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Quantifying Acoustic Impacts on Marine Mammals and Sea Turtles: Methods and Analytical Approach for Phase III Training and Testing

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NAVSEA WARFARE CENTERS NEWPORT

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LIST OF ABBREVIATIONS AND ACRONYMS

AFTT	Atlantic Fleet Training and Testing
ASW	Anti-submarine Warfare
BRF	Behavioral Response Function
CASS	Comprehensive Acoustic Simulation System
dB	Decibels
dB re 1 µPa	Decibels referenced to one micropascal
EIS	Environmental Impact Statement
FFT	Fast Fourier Transform
GRAB	Gaussian Ray Bundle
HF	High-Frequency
HSTT	Hawaii- Southern California Training and Testing
HYCOM	Hybrid Acoustic Coordinate Ocean Model
Hz	Hertz
IFFT	Inverse FFT
kHz	Kilohertz
KM	Kilometer(s)
LF	Low-Frequency
M	Meter(s)
MF	Mid-Frequency
NAEMO	Navy Acoustic Effects Model
NMFS	National Marine Fisheries Service
NMSDD	Navy Marine Species Density Database
NUWC	Naval Undersea Warfare Center
OAML	Ocean and Atmospheric Master Library
OEIS	Overseas Environmental Impact Statement
PTS	Permanent Threshold Shifts
REFMS	Refraction in Multilayered Ocean/Ocean Bottoms with Shear Wave Effects
RMS	Root-Mean-Square
SEL	Sound Exposure Level
SPL	Sound Pressure Level
SWFSC	Southwest Fisheries and Science Center
TNT	Trinitrotoluene
TTS	Temporary Threshold Shifts
U.S.	United States

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1. INTRODUCTION

The United States (U.S.) Department of the Navy (Navy) is required to assess potential impacts of Navy-generated sound in the water on protected marine species in compliance with applicable laws and regulations, including the National Environmental Policy Act, Executive Order 12114, the Marine Mammal Protection Act, and the Endangered Species Act. This report applies to all of the Navy's Phase III Study Areas as described in each Environmental Impact Statement (EIS)/ Overseas Environmental Impact Statement (OEIS) and describes the methods and analytical approach to quantifying the number of potential effects to marine mammals and sea turtles as a result of the Navy's at-sea training and testing.

The Navy has invested considerable effort and resources analyzing the potential impacts of underwater sound sources (i.e., impulsive and non-impulsive sources on marine mammals and sea turtles). Research on various methodologies, collaboration with subject matter experts, and a review by the Center for Independent Experts have led to the Navy's refinement of a standard Navy model for assessing the impacts of underwater sound, the Navy Acoustic Effects Model (NAEMO).

NAEMO is used to assess the level of behavioral disturbance and physiological impacts (e.g., temporary and permanent threshold shifts [TTS and PTS, respectively]) predicted for individual marine mammals and turtles likely to be in the vicinity of Navy training and testing activities. The Navy then applies factors to account for animals that would avoid high level sound exposures (e.g., TTS or PTS) since these levels are greater than those that may cause a behavioral reaction, which in most cases would include moving away from the sound source (DeRuiter et al., 2013; Southall et al., 2012). The Navy also accounts for mitigation measures designed to avoid or reduce marine mammal and sea turtle exposure to explosives and high-intensity sound. Predicted impacts are then assigned to the marine mammal stocks that are present in the area to assess potential impacts at the stock level.

The predicted impacts are stored and examined in spreadsheets via pivot tables, charts, and graphs. Output shows the types of impacts predicted for each Navy training and testing activity by area, season, and species. To summarize and report, predicted impacts for each species and stock are summed across all of the projected activities (training and testing are summed separately in most Study Areas) and then rounded to the nearest integer.

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2. NAVY ACOUSTIC EFFECTS MODEL OVERVIEW

NAEMO serves as a data entry point for Navy activity information and as a repository for modeling output and estimated effects. NAEMO consists of modules accessed via a graphical user interface. Navy training and testing activities were defined in NAEMO as scenarios with specific platforms, sources, targets, and military expended materials. Scenarios were further refined into events, which also accounted for location and frequency of events. Section 3 describes the data inputs to NAEMO and Section 4 describes the implementation and outputs from each of the NAEMO modules.

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3. DATA INPUTS

The Navy used specific information about environmental conditions, best available marine mammal and sea turtle data, and projected Navy activities within each Study Area to run NAEMO and quantify potential impacts on marine mammals and sea turtles. Environmental data include information about bathymetry, seafloor composition (e.g., rock, sand), and factors that vary throughout the year, such as wind speed and underwater sound speed profiles. Marine mammal and sea turtle data include densities, group sizes, and dive profiles. Lastly, the details of Navy training and testing activities were collected, which included location, rate of occurrence, and source characteristics.

3.1. Navy Training and Testing Activities

NAEMO uses a hierarchy to group Navy training and testing events for analysis. The broadest category includes the primary mission areas (e.g., air warfare, amphibious warfare, etc.). The activities that fall within these categories are further refined in NAEMO as "scenarios," which include data on the number of platforms, types and numbers of impulsive and non-impulsive sources, and source duration. Scenarios are then further defined as "events," which include details on location and frequency of occurrence. This section also provides additional information on how scenario and event definitions are implemented in NAEMO.

3.1.1. Locations and Modeling Areas

Activities were modeled in range complexes, testing ranges, pierside locations, transit lanes, and other representative areas where training or testing may occur. Location restrictions were incorporated when applicable (i.e., minimum or maximum depth and distance from shore).

3.1.2. Platforms

Platforms include aircraft, submarines, surface ships, unmanned vehicles, and stationary structures (e.g., moored platforms). Typical platform speed and depth are accounted for in NAEMO. The number and types of platforms that participate in a given scenario can vary due to numerous factors, including deployment schedules, number of ships assigned to a strike group, specific testing objective, and planned or unplanned maintenance of ships and systems. The quantitative modeling uses the average number of platforms that would be used during a typical scenario. For example, if three to five surface ships normally participate in a given anti-submarine warfare exercise, the representative modeling scenario for this event would consist of four surface ships. The composition of this exercise represents the average number of anti-submarine warfare-equipped ships and types of sonar that would be used during a typical anti-submarine warfare exercise.

3.1.3. Sources

Acoustic sources were divided into two categories, impulsive and non-impulsive. Impulsive sounds feature a rapid increase to high pressures, followed by a rapid return to static pressure. Impulsive sounds are often produced by processes involving a rapid release of energy or mechanical impacts (Hamernik & Hsueh, 1991). Explosions and air gun impulses are examples of impulsive sound sources. Non-impulsive sound sources include sonar and other transducers, which lack the rapid rise time of impulsive sources and can have durations longer than those of impulsive sounds.

In addition to impulsive and non-impulsive, sources can be categorized as either broadband (producing sound over a wide frequency band) or narrowband (where the energy is within a single one-third octave band). Typically, broadband is equated with impulsive sources, and narrowband with non-impulsive sources, although non-impulsive broadband sources, such as acoustic communications equipment and certain countermeasures, were also modeled. All non-impulsive sources were modeled using the geometric mean frequency. All impulsive sources were modeled using the time series of the pressure amplitude, including air guns.

3.1.3.1. Non-Impulsive Source Classes

Hundreds of common Navy sources were compiled into NAEMO in the Navy Sound Source Data file. These were reduced to the active sources that were applicable to quantitative modeling. These include explosive and non-explosive impulsive sources and non-impulsive sources (sonar and other transducers). Explosive impulsive sources were placed into bins based on net explosive weights. Each non-explosive impulsive source was assigned its own unique bin. Non-impulsive sources were grouped into bins that were defined in accordance with their fundamental acoustic properties such as frequency, source level, beam pattern, and duty cycle. Each bin was characterized by the most conservative parameters for all sources within that bin. Specifically, bin characteristics for non-impulsive sources were selected based on (1) highest source level, (2) lowest geometric mean frequency, (3) highest duty cycle, and (4) largest horizontal and vertical beam patterns. The specific source class bins proposed for use and the total annual usage under each alternative are provided in each EIS/OEIS.

The use of source classification bins provides the following benefits:

- Provides the ability for new sensors or munitions to be covered under existing environmental compliance documentation, as long as those sources fall within the parameters of a "bin;"
- Allows analysis to be conducted in a more efficient manner, without any compromise of analytical results;
- Simplifies the source utilization data collection and reporting requirements anticipated under Marine Mammal Protection Act authorizations;
- Ensures a conservative approach to all impact estimates, as all sources within a given class are modeled at the lowest frequency, highest source level, longest duty cycle, or largest net explosive weight within that bin; and
- Provides a framework to support the reallocation of source usage (hours/explosives) between different source bins, as long as the total numbers of takes remain within the overall analyzed and authorized limits. This flexibility is required to support evolving Navy training and testing requirements, which are linked to real-world events.

Some sources were removed from quantitative analysis because they are not anticipated to result in takes of protected species. This included sources with low source level, narrow beamwidth, downward-directed transmission, short pulse lengths, frequencies above known hearing ranges of marine mammals and sea turtles, or some combination of these factors.

3.1.3.2. Impulsive Sources

The steep pressure rise that characterizes impulsive sources and their potential for structural injury are the reason they are evaluated differently than are non-impulsive ones. Impulsive sources are further classified into explosive and non-explosive impulsive sources.

The following terms were used to collect data on impulsive sources:

1. Source Depth—the depth at which an impulse source goes off.
2. Net Explosive Weight—for explosive sources, the trinitrotoluene (TNT) equivalent weight of explosive material in the source.

3. Source Signature—the pressure time series of the source at a nominal distance of 1m. The explosive signatures are taken from the similitude equations (equations 4-2 through 4-4) based on net explosive weight, whereas the non-explosive signatures are taken from real-world data.
4. Cluster Size—the number of rounds fired (or buoys dropped) within a very short duration.
5. Count—the number of sources or clusters of sources deployed during a scenario.

Explosive impulsive sources include the following types of devices: mines, mine countermeasure systems, projectiles, rockets, missiles, bombs, torpedoes, underwater demolition explosives, ship shock trial charges, impulsive sonobuoys, and littoral warfare line charges. A list and qualitative descriptions of impulsive sources can be found in each EIS/OEIS. Non-explosive impulsive sources include air guns and combustive sound sources.

3.1.3.3. Non-Impulsive Sources

Non-impulsive sources are sonars and other transducers and include the following types of devices: submarine sonars, surface ship sonars, helicopter dipping sonars, torpedo sonars, active sonobuoys, countermeasures, underwater communications, tracking pingers, unmanned underwater vehicles and their associated sonars, and other devices. Qualitative descriptions can be found in each EIS/OEIS.

The following terms were used to collect data on non-impulsive sources:

1. Source Depth—the depth at which a source goes active.
2. Source Level—the sound level of a source at a nominal distance of 1 meter, expressed in decibels referenced to one micropascal (dB re 1 µPa).
3. Nominal Frequency—typically, the geometric mean of the frequency bandwidth.
4. Source Directivity—the source beam was modeled as a function of a horizontal and a vertical beam pattern.
    a. The horizontal beam pattern was defined by two parameters:
        i. Horizontal Beamwidth—the width of the source beam in degrees measured at the 3-decibel (dB) down points in the horizontal plane (assumed constant for all horizontal steer directions).
        ii. Relative Beam Angle—the direction in the horizontal plane that the beam was steered relative to the platform's heading (direction of motion) (typically 0°).
    b. The vertical beam pattern was defined by two parameters:
        i. Vertical Beamwidth—the width of the source beam in degrees in the vertical plane measured at the 3-dB down points (assumed constant for all vertical steer directions).
        ii. Depth/Elevation Angle—the vertical orientation angle relative to the horizontal.
5. Ping Interval—the time in seconds between the start of consecutive pulses for a non-impulsive source.
6. Pulse Length—the duration of a single non-impulsive pulse, specified in milliseconds. Duty cycle is defined as ping length/ pulse interval × 100%.
7. Signal Bandwidth—the geometric mean frequency is the square root of the product of the frequencies defining the frequency band (equation 3-1),

$$f_{gm} = (f_{min} \times f_{max})^{0.5}, \quad (3\text{-}1)$$

where, f_{max} is the upper cutoff frequency and f_{min} is the lower cutoff frequency.

Many of these system parameters are classified and cannot be provided in an unclassified document. Each source was modeled utilizing representative system parameters based on the non-impulsive source category within which it occurs.

3.2. Physical Environment Data

The physical environment data described below play an important role in the acoustic propagation used in the modeling process. Since accurate *in-situ* measurements cannot be used to model activities that occur in the future, historical data are used to define a typical environmental state for propagation analysis. Because acoustic activities rely heavily on the accuracy of propagation loss estimates, the Navy has invested heavily in measuring and modeling the relevant environmental parameters. The results of this effort are databases with global measurements of these environmental parameters that comprise part of the Oceanographic and Atmospheric Master Library (OAML; Table 3-1). The distribution of OAML data is restricted to organizations within the Department of Defense and its contractors. The versions of the OAML databases within NAEMO are provided in Table 3-1. In order to capture environmental variability, NAEMO extracts information from the databases discussed below every 5 kilometers (km) along transects radiating out from each source location.

Table 3-1. Oceanographic and Atmospheric Master Library Environmental Databases

Parameter	Database
Bathymetry	Digital Bathymetric Database Variable-Resolution Version 5.4 (Level 0)
Seafloor Composition	Re-Packed Bottom Sediment Type Version 2.0 (includes High-Frequency Environmental Acoustics Version 1.0)
	Low-Frequency Bottom Loss Version 11.1*
	High-Frequency Bottom Loss Version 2.2*
Wind Speed	Surface Marine Gridded Climatology Version 2.0
Sound Speed Profile	Navy Hybrid Acoustic Coordinate Ocean Model (HYCOM) Version 2.2

*Low-frequency and high-frequency bottom loss databases are used to capture the variability of bottom sediment to absorb or reflect energy from high-frequency and low-frequency sound sources.

3.2.1. Bathymetry

Bathymetry can affect sound propagation in a variety of ways. In a shallow area, an acoustic ray will have more interaction with the bottom, which will absorb some of the sound energy. The slope of the seafloor determines the angle at which an acoustic ray will be reflected off the bottom. Within a typical modeling area, bathymetry tends to be the environmental parameter that varies the most. It is not unusual for water depths to vary by an order of magnitude or more in these areas. Bathymetry was obtained at the highest resolution available, ranging from 0.05-2.0 arc-minutes. Since propagation loss is determined along paths radiating out from an analysis point, bathymetry was extracted radially to align with these paths.

3.2.2. Seafloor composition

Seafloor composition can affect acoustic propagation calculations. For example, a muddy bottom absorbs more energy and a rocky bottom reflects more energy. However, this factor's impact on propagation tends to be limited to waters on the continental shelf and the upper portion of the slope because sound is more likely to reach the bottom in these areas. The primary acoustic propagation paths in deep water do not usually involve any interaction with the bottom, whereas in shallow water, bottom loss variability can play a larger role. This is especially true if the sound speed profile directs all propagation paths to interact with the bottom. For each modeled area, bottom type and the associated geo-acoustic parameters were extracted in accordance with the guidelines specified in Table 3-2. These data were extracted at the highest available resolution of one degree.

Table 3-2. Geo-Acoustic Parameter Guidelines as a Function of Acoustic Source Frequency

Frequency (f)	Database
f < 1 kHz	Low-Frequency Bottom Loss
1 kHz ≤ f < 1.5 kHz	Low-Frequency Bottom Loss and High-Frequency Bottom Loss
1.5 kHz ≤ f < 4 kHz	High-Frequency Bottom Loss
f ≥ 4 kHz	Bottom Sediment Type

3.2.3. Wind Speed

All wind speed data were extracted from the Surface Marine Gridded Climatology data at the highest available resolution of one degree. Wind speed data are directly related to other environmental parameters, primarily the sound speed. For example, wind in a downward refracting environment would not likely create a significant change in results because of the relatively short propagation ranges characterized by minimal surface interaction. In the case of a surface duct with correspondingly long propagation ranges and associated surface interaction, however, wind speed could have significant impact on the resultant propagation ranges.

3.2.4. Sound Speed Profiles

Navy Hybrid Acoustic Coordinate Ocean Model (HYCOM) sound speed profile data consist of temperature, salinity, and depth. For each scenario, these data were extracted at the highest resolution, 0.08 arc-degrees, over the extent of the modeled area. The sound speed throughout the water column is calculated from temperature, salinity, and pressure with the Chen-Millero-Li sound speed equation (Chen & Millero, 1977).

The spatial variability of the sound speed profiles is generally minimal within the modeling areas. The presence of a strong oceanographic front, in which temperature and salinity vary rapidly over a small geographic area, is a noteworthy exception to this rule. To a lesser extent, variability in the depth and strength of a surface duct can be of some importance to sound speed. In the mid-latitudes, the most significant variation in the sound speed profile is seasonal. For this reason, activities that occur year-round were modeled with two or four seasons, depending on the Study Area.

An example sound velocity profile is shown in Figure 3-1, spaced 10 km along a single transect in the Virginia Capes Range Complex. In shallow water, sound velocity varies primarily with temperature and salinity. At greater depths the temperature is more uniform so increases in sound velocity are primarily due to increases in pressure.

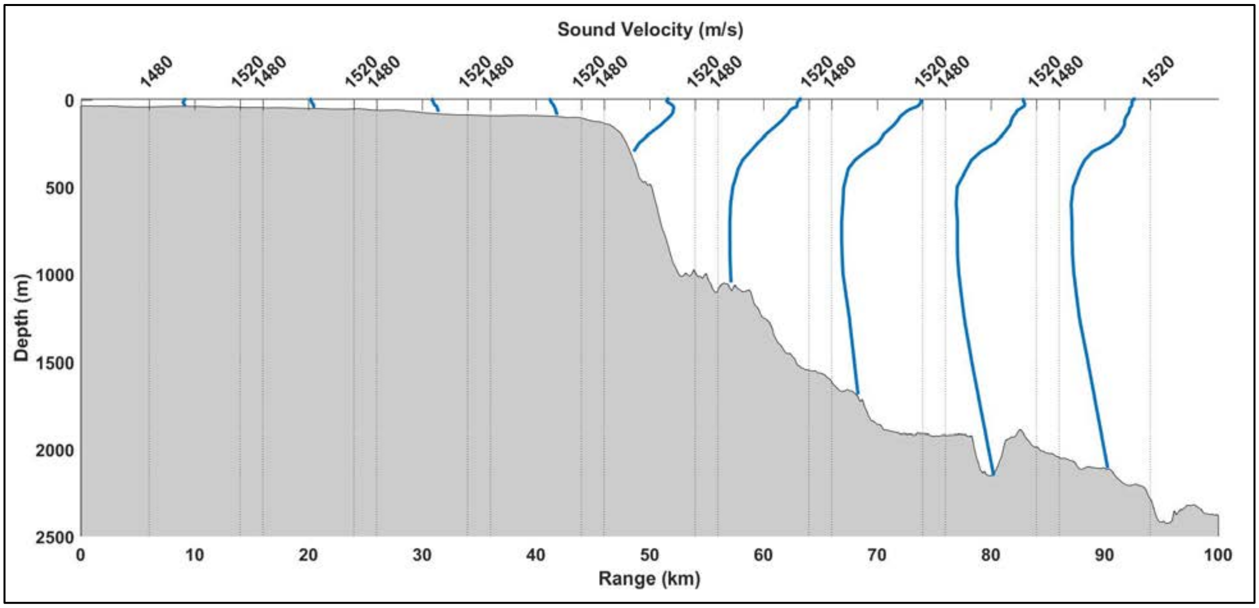

Figure 3-1. Sample Sound Speed Profile

3.2.5. Seasonal Definitions

The majority of Navy activities are not limited to a specific month or season. Therefore, most of the scenarios were modeled year-round. A seasonal approach was adopted to meet this requirement, given the impracticality of modeling each scenario for every month. The seasonal definitions that were employed were dictated by region and marine mammal and sea turtle presence (Table 3-3); this is described in the density technical report for each Study Area (e.g., U.S. Department of the Navy, 2017a, 2017b). The seasonal averages were generated by linearly averaging the data for the months within a given season.

Table 3-3. Seasonal Definitions

Season		Dates
Warm	Summer	1 June – 31 August
	Fall	1 September – 30 November
Cold	Winter	1 December – 28/29 February
	Spring	1 March – 31 May

3.3. Marine Mammal and Sea Turtle Data

Marine mammal and sea turtle input data include density estimates, group sizes, dive profiles, body masses, and stock/guild information (when necessary). In NAEMO, marine species are represented by "animats," which are virtual animals used during modeling (Dean, 1998). Marine mammal densities are needed to estimate the number of animals of each species that may be present within a specific area and timeframe and from that the number of animals that could be affected by non-impulsive or impulsive activities. Details on the density data used for the Phase III analyses are provided in the Navy Marine Species Density Database (NMSDD) and described in the density technical report for each Study Area (e.g., U.S. Department of the Navy, 2017a, 2017b).

3.3.1. Group Size

Many marine mammals are known to travel and feed in groups. NAEMO accounts for this behavior by incorporating species-specific group sizes into the animat distributions, and accounting for statistical uncertainty around the group size estimate. Group sizes were handled differently in each Study Area, based on data availability and the recommendations of the research groups that provided density information. For example, in the AFTT Study Area, mean group sizes and the associated standard deviations were collected for each species via literature search. Mammals were distributed in groups of a size that varied according to an inverse Gaussian distribution defined by the group size mean and standard deviation. For HSTT, NWTT, and the Mariana Islands Training and Testing (MITT) Study Area, simulations, group size mean, and standard deviation were collected from a combination of survey data from the density data source and a literature review. The standard deviations were incorporated by randomly selecting a value from the Poisson or lognormal distribution defined by the mean group size and standard deviation provided. The density data sources also specified which species' group size followed a Poisson or lognormal distribution.

3.3.2. Depth Distributions

NAEMO accounts for depth distributions by changing each animat's depth during the simulation process according to the typical depth pattern observed for each species. Depth distribution information was collected via literature search. This information is presented as a percentage of time the animal typically spends within various depth bins in the water column. During a simulation, each animat's depth is changed every 4 minutes to a value randomly selected by the probability density function described by its depth distribution. At this time, NAEMO does not simulate horizontal animat movement during an event.

3.3.3. Guild and Stock Breakouts

Marine mammals and sea turtles are typically categorized by species in the NMSDD. NAEMO has adopted the same format for its results, with the exception of species that are grouped into guilds or stocks. In some cases, species can be difficult to distinguish from one another during surveys at sea and are only reported as a group of similar species, or "guilds," which are processed in NAEMO as would be a species. The proportion of each species within each guild is estimated based on sightings where species can be determined. Based on these proportions, predicted impacts on guilds are separated out to the species level. Similarly, many species within each Study Area are divided into multiple stocks based on life history and genetic stock structure for management purposes. For some stocks, like island-associated stocks in Hawaii, there is enough survey information to support stock-specific density models. In these cases, a density layer for the stock is provided and is modeled independently of other stocks. In other cases, predicted impacts were assigned by stock, as opposed to the species as a whole.

In the Study Areas for the Atlantic Fleet Training and Testing (AFTT) and Hawaii-Southern California Training and Testing (HSTT) EIS/OEISs, the stock and guild reassignment process described above was performed after acoustic impacts were estimated in NAEMO. Following AFTT and HSTT analyses, an update to the process was implemented for the Northwest Training and Testing (NWTT) Study Area, where stock and guild composition was accounted for before impacts were estimated. Where necessary, guilds were broken down to species and species were broken down to stocks prior to modeling (see section 4.2). The broken out species and stocks were then modeled individually in NAEMO. Compared to previous methods, this approach allowed NAEMO to better account for geographic variation in the proportion of each stock or species expected in a Study Area. For example, there are three stocks of humpback whale in the NWTT Study Area: Hawaiian, Mexican, and Central American. Off the coast of Washington, the proportions of these stocks are 53%, 42%, and 5%, respectively. South of Washington, these proportions are 0%, 90%, and 10%. Geographic variations in species and guild composition such as this will be captured in NAEMO going forward, if applicable and if data is available.

3.4. Criteria and Thresholds for Assessing Impacts

Criteria and thresholds to assess impacts on marine mammals and sea turtles are synthesized from published study results. The *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)* technical report (U.S. Department of the Navy, 2017c) provides details on the derivation of the Navy's current impact criteria. These criteria and thresholds are used to assess potential effects to marine mammals and sea turtles in the analysis process.

Upper and lower frequency limits will be used for each marine mammal hearing group and sea turtles so that sonar and other transducers with the majority of their energy above or below these limits would not be considered for acoustic effects to those species (Table 3-4).

Table 3-4. Lower and Upper Cutoff Frequencies for Marine Species Hearing Groups for Sonar and Other Transducers Used for Phase III Acoustic Analysis

Hearing Groups	***Limit (Hertz)***	
	Lower	***Upper***
Low-Frequency Cetaceans (Mysticetes)	5	30,000
Mid-Frequency Cetaceans	50	200,000
High-Frequency Cetaceans	100	200,000
Phocid Pinnipeds (In-Water)	50	80,000

Table 3-4. Lower and Upper Cutoff Frequencies for Marine Species Hearing Groups for Sonar and Other Transducers used for Phase III Acoustic Analysis (Cont'd)

Hearing Groups	***Limit (Hertz)***	
	Lower	***Upper***
Otariid Pinnipeds, Sea Otters, Polar Bears, Walruses, and Sirenians (In-Water)	20	60,000
Sea Turtles	5	2,000

Explosives, air guns, impact pile driving, and vibratory pile driving have significant acoustic energy within all groups' hearing ranges; therefore, it is not necessary to apply frequency limits to these broadband sound sources.

4. NAVY ACOUSTIC EFFECTS MODEL

The following sections discuss the acoustic analysis, marine species distribution, simulation, and outputs from each of the NAEMO modules.

4.1. Acoustic Analysis

In NAEMO, the Acoustic Builder module generates propagation data. First, it uses event definitions from NAEMO to extract source characteristics and environmental data for a given location. It then uses a standard resolution for a set of propagation analysis points in the event's location (e.g., 0.1 degree in the AFTT Study Area). For each analysis point, the Navy's standard propagation model (the Comprehensive Acoustic Simulation System/Gaussian Ray Bundle (CASS)/(GRAB) is run to generate a sound field for each source in the scenario. For non-impulsive sources the sound field data are saved in NAEMO and subsequently provided as input to Scenario Simulator. For impulsive sources CASS/GRAB is used to calculate several sound metrics which are provided to Scenario Simulator as input.

4.1.1. Comprehensive Acoustic Simulation System/ Gaussian Ray Bundle

The CASS/GRAB propagation model was used for all impulsive and non-impulsive modeling. Detailed descriptions of the CASS/GRAB model and its governing equations can be found in Keenan and Gainey (2015); Weinberg and Keenan (1996).

The CASS/GRAB model is used to determine the propagation characteristics for acoustic sources with frequencies greater than 150 Hertz (Hz). Keenan and Gainey (2015) described CASS as "a linear acoustics, range-dependent, ray-based eigenray model that calculates arrival structure, sound pressure, reverberation, signal excess, and probability of detection." It has been accepted as the Navy standard and Ocean and Atmospheric Master Library (OAML)-certified model for active sonar analysis between 150 Hz and 500 kilohertz (kHz). For impulse modeling CASS/GRAB is used for frequencies as low as 25 Hz. Though it is not OAML approved for this frequency, Weinberg and Keenan (1996) showed that CASS/GRAB predicted the general trend of propagation loss well compared to other propagation loss models.

NAEMO analyses use CASS in the passive propagation mode, that is, one-way propagation, rather than the active mode, which uses two-way propagation. CASS uses acoustic rays to represent sound propagation in a medium. As acoustic rays travel through the ocean, their paths are affected by mechanisms such as absorption, reflection, and reverberation, including backscattering, and boundary interaction. The CASS model determines the acoustic ray paths between the source and a particular location in the water. The rays that pass through a particular point are called eigenrays.

GRAB's role in the propagation model is to group eigenrays into families based on their surface/bottom bounce and vertex history (Figure 4-1). For example, a ray that bounces off the surface and then off the ocean floor would be in a different family than a ray that bounces off the floor first and then the surface. Rays with no boundary interaction would be in yet another family. Once the eigenrays have been grouped into families, the ray path properties are integrated (source angle, arrival angle, travel time, phase, and amplitude) to determine a representative ray for each family. These properties are weighted prior to integration so that rays closer to the desired target depth have more weight. Each representative eigenray, based on its intensity and phase, contributes to the complex pressure field, and hence, to the total energy received at a point. The total received energy at a point is calculated by summing the modeled eigenrays. Figure 4-2 shows the representative eigenrays for the families shown in Figure 4-1. The total received energy at the receiving point (50 m depth, 1.4 km range) is calculated by summing the representative eigenrays. CASS/GRAB accommodates surface and bottom boundary interactions but does not account for side reflections that would be a factor in a highly reverberant environment, such as a depression or canyon, or in a man-made structure, such as a dredged harbor. Additionally, as with most other propagation models except finite-element-type models, CASS/GRAB does not accommodate diffraction or the propagation of sound around bends.

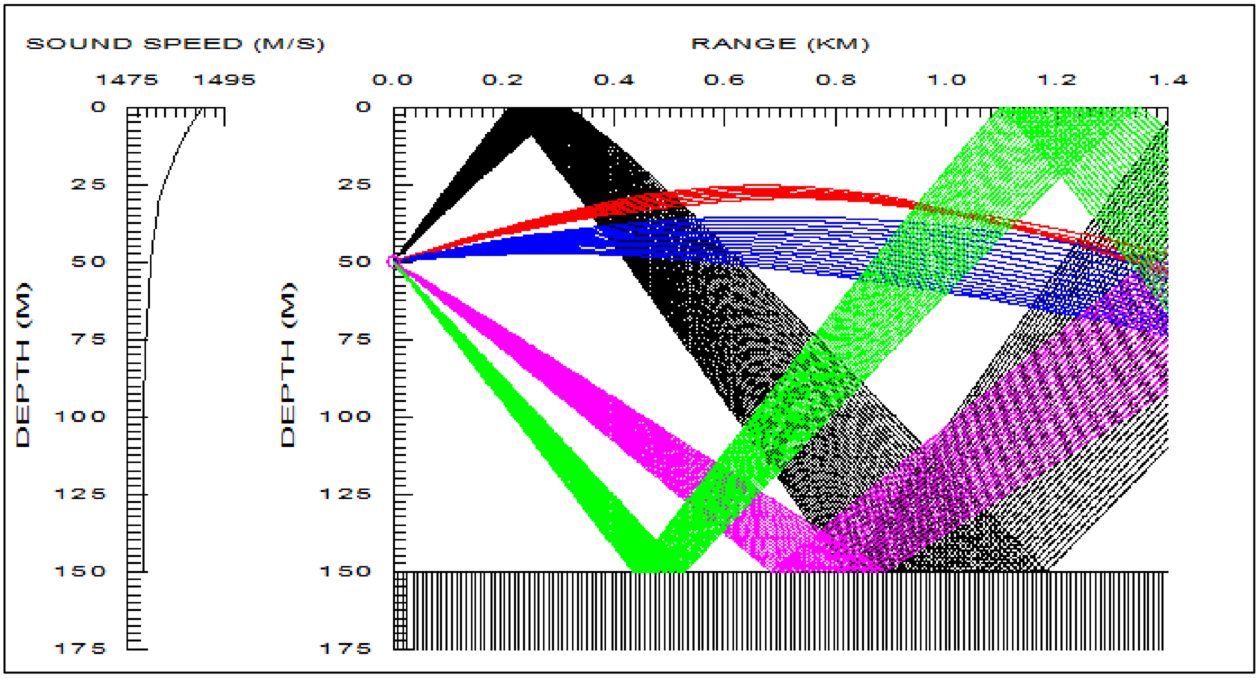

Figure 4-1. Colors Represent Distinct Families of Eigenrays Identified by GRAB

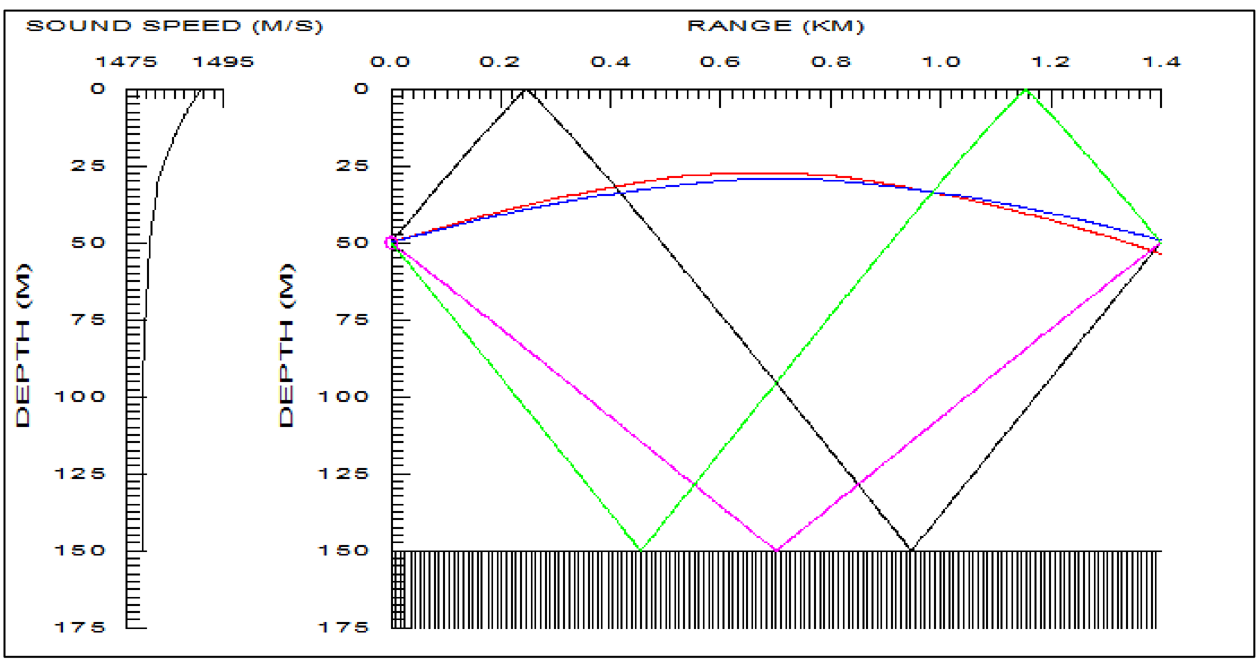

Figure 4-2. Representative Eigenrays for the Ray Families in Figure 4-1

CASS/GRAB generates a table of depth range points with an associated received level per location and per source. For non-impulsive sources, these received levels are used as input into Scenario Simulator (Section 4.3.2), whereas for impulsive sources, further transformations are required, as described in Section4.1.3.

CASS/GRAB is the most practical model to use for impulsive analysis. In order to evaluate some of the necessary metrics for explosives, a pressure time series is needed. The only other range-dependent models that can provide time information are so computationally intensive that given the number of computations required it would take too long to complete the analysis. For Phase II impulsive modeling, the Reflection and Refraction in Multilayered Ocean/Ocean Bottoms with Shear Wave Effects (REFMS) model was used. Though it was range-independent and not OAML-certified, REFMS was the best available model at the time. CASS/GRAB is a more logical model to use because it does not have these issues. Additionally the impulse model using CASS/GRAB has compared favorably with data (Deavenport & Gilchrest, 2015), though it should be noted that the data were for small explosives at short ranges. Data for large explosions and long ranges are needed to fully validate the model.

4.1.2. Non-Impulsive Model

The following features were included in Acoustic Builder for non-impulsive events:

- Events can be visually inspected and verified before modeling begins. For example, Acoustic Builder allows the user to view an event's geographic location, range complex, platforms, sources, bathymetry, modeling boxes, and local species distributions.
- Users can select analysis points to be run by CASS/GRAB. This can be done automatically by giving Acoustic Builder spacing between points, which it uses to create a grid of equally spaced analysis points. Or, users can manually select analysis points.
- Acoustic Builder provides a graphical user interface for CASS/GRAB and runs the propagation model at every analysis point selected.
- Acoustic propagation is run along 18 equally spaced radials (bearing angles) from an analysis point to 100 km, or until the received level has reached 100 dB.

4.1.3. Impulsive Model

The impulsive model used in the Navy's current analysis described in this report is an upgrade from previous modeling efforts. The model uses CASS/GRAB to create a frequency band-limited transfer function that is combined with a similitude source signature to obtain a pressure time series. Advantages of using CASS/GRAB over REFMS include:

- CASS/GRAB is OAML approved, REFMS is not.
- CASS/GRAB can vary environmental parameters with range, more accurately representing the environment.
- CASS/GRAB has a built in absorption model.
- CASS/GRAB is more numerically stable.

The impulsive model used in the Navy's current analysis described in this report is OAML approved. The impulsive model uses five metrics to describe the sound received by animats: peak sound pressure level ($\mathrm{SPL_{peak}}$), root mean square sound pressure level ($\mathrm{SPL_{rms}}$), sound exposure level (SEL), calf impulse, and adult impulse. Sound pressure level (SPL) is the logarithm of the ratio of sound pressure to a relative pressure. The peak sound pressure level is the maximum SPL over time. The root-mean-square (RMS) pressure level is an average SPL over the duration of the signal. The ($\mathrm{SPL_{rms}}$) criteria are only applied to air guns and behavioral effects on sea turtles. Sound exposure level represents both the SPL of a sound as well as its duration. Impulse is the integral of positive pressure over a brief time period. Impulse is a function of animat mass and is calculated for both calf and adult. The impulse metric is only applied to explosive impulses.

The main difference between impulsive and non-impulsive modeling is that the impulsive signal is time-dependent, whereas the pressure field for non-impulsive sources is modelled as an instantaneous phenomenon (Deavenport & Gilchrest, 2015). This is because impulsive signals are time-dependent processes characterized by a rapid rise and subsequent fall in pressure. The time dependence is incorporated by using outputs from CASS/GRAB to build a transfer function, and convolving this with a similitude source signature as described below (Deavenport & Gilchrest, 2015).

The first step is to use eigenray information from CASS/GRAB to create a transfer function of the form:

$$H(\omega) = \sum_{n=1}^{N} A_n e^{i\omega\tau_n + i\phi_n} \tag{4-1}$$

where ω is frequency ($2\pi f$ in Hz), N is the number of arrival paths, A_n is the received level for path *n* in Pa, τ_n is the arrival time (s) of path *n*, and ϕ_n is the phase (rad) of path *n*. This transfer function represents the instantaneous pressure field of the impulse, transformed so that it can be convolved with the source signature. The frequency resolution is determined by the sampling rate (32,768 samples per second) and the longest arrival time. Additionally, it is approximated that the levels, arrival times, and phases are identical within 1/3 octave bins defined from 25-16,384 Hz. CASS/GRAB is run at each of these frequencies to get the necessary eigenray information. Before running CASS/GRAB, bottom loss tables are computed in each frequency domain defined in table 3-2.

Explosive source signatures are modeled by similitude equations (Friedlander, 1946);

$$P_{sim}(t) = P_m e^{-\left(\frac{t}{2\theta}\right)} \cdot \left(1 - \left(\frac{t}{2\theta}\right)\right), \tag{4-2}$$

where, P_m is the amplitude of the initial shock wave in Pa, θ is the time decay constant in *s*, and t is the time after the initial shock wave arrives in s. P_m and θ can be expressed by Swisdak (1978);

$$P_m = K \cdot \left(\frac{\sqrt[3]{W}}{r}\right)^{\alpha}, \tag{4-3}$$

$$\theta = K_2 \cdot \sqrt[3]{W} \cdot \left(\frac{\sqrt[3]{W}}{r}\right)^{\alpha_2}, \tag{4-4}$$

where, r is the distance from the source in m, W is the net explosive weight of TNT in kg, and coefficients (K, K_2, α, and α_2) are specific to a given explosive type. The signature is modeled as 1 m from the source. The length of the signal is assumed to be 50ms, to ensure that all of the energy is accounted for. The pressure time series $P(t)$ is then determined by;

$$P(t) = \mathrm{IFFT}(\,H(\omega) \times \mathrm{FFT}(P_{sim}(t))) \times \,R^{-0.13}, \tag{4-5}$$

where, FFT and IFFT indicate the Fast Fourier Transform (FFT) and the Inverse Fast Fourier Transform (IFFT), and R is the slant range (the three-dimensional distance between the source and receiver). The $R^{-0.13}$ is a correction factor believed to account for the losses associated with energy dissipated at the shock front as well as the usual absorption losses associated with linear acoustics (Barash & Goertner, 1967; Deavenport & Gilchrest, 2015). Also see Medwin and Clay (1977), in which similitude correction is attributed to “excess attenuation at the shock front.” This correction factor is specific to TNT and is not applied to non-explosive impulsive sources such as air guns. For the SEL calculation $P(t)$ is weighted by the auditory response function, which modifies the equation to;

$$P_w(t) = \mathrm{IFFT}(\,M(\omega) \times H(\omega) \times \mathrm{FFT}(P_{sim}(t))) \times \; R^{-0.13}, \tag{4-6}$$

where, $M(\omega)$ is the auditory weighting function for each hearing group. Calculation of the weighted and unweighted time series are intermediate steps in calculating the five previously mentioned metrics. The equation for the peak sound pressure level is given by;

$$\mathrm{SPL_{peak}} = \; 20 \times \log\left(10^6 \times \max\big(P(t)\big)\right), \tag{4-7}$$

where, the 10^6 is multiplied by the pressure to convert to μPa, since the reference pressure is 1 μPa. The root mean square sound pressure is given by;

$$\mathrm{SPL_{rms}} = \;\; 20 \times \log\left(10^6 \times \sqrt{\tfrac{1}{t_u - t_l}\textstyle\int_{t_l}^{t_u}[P(t)]^2 dt}\right), \tag{4-8}$$

where, t_l and t_u are chosen such that 90% of the sound energy is between t_l and t_u. The sound exposure level is the cumulative effect of the weighted sound energy for each hearing group, given by;

$$\mathrm{SEL} = \; 10 \times \log\left(10^6 \times \int_0^{t_f} [P_w(t)]^2 dt\right), \tag{4-9}$$

where, t_f is the length of the received signal.

For explosive impulsive sources, the impulse is calculated for both adults and calves by:

$$I = \int_0^T P(t)dt \tag{4-10}$$

where T is determined by either the duration of the first positive impulse or 20% of the mammal's lung resonance period (Goertner, 1982). Between these two estimates, NAEMO selects whichever time period is shorter. The formula for the 20% lung resonance period of a mammal can be derived under the following three assumptions:

- The excitation of the lung cavity is approximated by the radial oscillation response of an equal volume spherical air bubble in water subjected to the same pressure wave.
- The lung volume in liters is 3% of the mass of the animal in kilograms.
- As the animal dives the lungs undergo isothermal compression.

These assumptions lead to the following formula for the 20% lung resonance:

$$T = \sqrt{\frac{\rho}{3\gamma}} \times \frac{(1.8 \times 10^{-4}\pi^2 M P_1)^{1/3}}{{P_0}^{5/6}}, \tag{4-11}$$

where, ρ is the density of water, γ is the adiabatic exponent for air, M is the animal mass, P_1 is the atmospheric pressure, and P_0 is the hydrostatic pressure (Goertner, 1982).

Propagation for impulsive sources is run along 9 equally spaced radials from an analysis point to 30 km. The range is extended to 100 km if any of the metrics are still above threshold at 30 km. Each of the above metrics are summarized into tables for each bearing, range, and depth to be used in the impulsive simulator.

4.2. Marine Species Distribution Builder

Marine mammals and sea turtles are distributed into simulation areas, and multiple iterations (see Section 4.3.1) are run for each species to account for statistical uncertainty in the density estimates. Each iteration varies according to the standard error associated with the density estimate (e.g., U.S. Department of the Navy, 2017a, 2017b). The density data are provided as a geographic grid (typically 10 km x 10 km) in which each cell is assigned a species density (animals/km^2). One density grid for each species or guild was provided. In many cells, a standard deviation was provided with the density estimate. However, for areas where density predictions were made for non-surveyed areas, the density cells were so far away from any survey measurement that the estimated statistical uncertainty would not be meaningful. In these cases, standard error was not provided. Group size and dive profiles were taken into account and are discussed in Sections 3.3.1 and 3.3.2. As described in Section 3.3, animats were used during modeling to function as a dosimeter, recording energy received from all sources that were active during a scenario.

The distribution of animats in NAEMO starts with the extraction of species density estimates from the NMSDD for a given area and month. In order to incorporate statistical uncertainty surrounding density estimates into NAEMO, 30 distributions were produced for each species for each season, each of which varied according to the standard deviations provided with the density estimates. The following steps are then taken to distribute the animats within the defined modeling space.

- In each cell, the density estimate for that iteration is determined by randomly selecting a single value from a distribution defined by the density estimate (the mean of the distribution) and its standard deviation. These definitions were determined specific to each Study Area (e.g., for the HSTT Study Area, a lognormal distribution was used; for the AFTT Study Area, a compound Poisson-gamma distribution was specified in the density regression model). If the density estimate did not have a corresponding standard deviation, the density remained constant at the mean for every iteration.
- The density estimate (animals/km^2) for that iteration is multiplied by the cells' area (km^2) to obtain the total number of animats in that cell.
- The total number of animats in each cell is summed across the entire area to determine the total number of animats in the entire area.
- Animats are placed into groups according to mean and standard deviation of group size (see Section 3.3.1). Groups are created until total abundance is reached.
- Groups of animats are then distributed into cells according to the probability density function defined by the original density estimates provided.
- Stock/Species breakouts: If the density layer defines a species or guild of species that needs to be segmented for management purposes (e.g. a density provided as a guild needs to be split into species, or a density provided as a species needs to be split into stocks), distributed animats are separated into the necessary units. This is done probabilistically, according to the expected proportion of each unit present in a given area. This step was only part of the Marine Species Distribution Builder for the NWTT Study Area.

These steps result in a series of data files containing the time, location, and depth of each animat placed within the modeling area. The standard deviation was only used to vary the total number of animats in the entire region. This is necessary because, as a consequence of extrapolating the regression models into areas without survey measurements, the statistical uncertainty in these cells was substantially higher than in areas with survey measurements. An unrealistically high number of animats was often selected for these cells, which warped the population's spatial distribution.

4.3. NAEMO Simulation Process

The NAEMO simulation process combines all of these previously defined data and estimates the acoustic effects on marine mammals and sea turtles. The first module, Scenario Simulator, combines scenario definitions from Scenario Builder, data created in Acoustic Builder, and animat distributions created in Marine Species Distribution Builder to produce a record in NAEMO of the sounds received by each animat. The second module, Post Processor, reads the record created by Scenario Simulator, applies the frequency-based weighting functions, and conducts a statistical analysis to estimate effects associated with each marine mammal and sea turtle group based on the specified criteria thresholds. Results from each analysis are stored in NAEMO. The third and final module, Report Generator, provides a mechanism to assemble all of the individual species exposure records created by Post Processor and computes annual effect estimates. Estimated annual effects can be grouped by activity, season, and geographic region before outputting the results to comma-separated text files that can be used for further examination of the data. The following sections provide additional information for each module.

4.3.1. Monte Carlo Simulation Approach

Estimation of effects in NAEMO is accomplished through Monte Carlo simulations. This approach was chosen to account for the variability inherent in many factors of testing and training events such as platform location and movement, precise location of modeling area, and instantaneous distributions of marine mammals and sea turtles. Additionally, NAEMO incorporates individual animat movement vertically in the water column at a specified displacement frequency for sufficient sampling of the depth dimension. Individual animats are not moved horizontally within NAEMO. The location of an event is randomly selected within a specified modeling area. NAEMO uses unique iterations of the simulated animal populations in each simulation, which allows it to provide sufficient sampling in the horizontal dimensions for statistical confidence. Monte Carlo simulations also produce statistically independent samples, which allows for the calculation of metrics such as standard error and confidence intervals. Thirty Monte Carlo simulations are run per event, per species, and per season. In each simulation, the following factors are randomly selected:

- Modeling box (the area to which platforms are restricted)
- Geographic location of animats
- Depth of each animat (updated at 4 minute intervals during simulation)
- Platform start location within the modeling box
- Platform track (unless platform is stationary or its track is defined by waypoints)
- Time that sources first go active (unless timing is specified in scenario definition)

4.3.2. Scenario Simulator

The purpose of Scenario Simulator is to determine the level of sound received by each animat. This module references the scenario definition in NAEMO to determine the starting location, direction, and depth of each platform. Scenario Simulator then steps through time and interrogates each of the platform sources to determine which sources are actively emitting sound during that time step.

The simulation begins with a time equal to zero and progresses incrementally in 1-second steps until the end of the scenario. For each active source, the beam pattern area and direction of sound source emission is computed. The beam pattern area is calculated from the horizontal beam pattern and maximum propagation distance, which are stored in the source table in NAEMO. For example, the area for a source with a ninety-degree horizontal beam pattern and a maximum propagation distance of 100 km would equate to a quarter of a circle whose radius is 100 km. The beam pattern direction is based on the direction of travel of the platform and any offsets defined for the horizontal beam pattern. The next step in the process identifies all animats that fall within each defined beam pattern area.

Propagation data are computed at multiple points within each modeling box to account for platforms moving during the simulation (Section 4.1). The exception to this is scenarios that involve only stationary platforms. At each time step, the position of each platform is compared to the locations of each propagation analysis point to determine the closest propagation file.

For each animat identified in the beam pattern, a lookup in the sound source propagation file is performed to determine the received sound level for that animat. The lookup is conducted based on the bearing and distance from the platform to the animat and the depth of the animat. The closest matching point within the propagation file is used.

Simulation output for each animat is stored in NAEMO. These outputs include simulation time, platform name, source name, source mode name, source mode frequency, source mode level, ping length, platform location (latitude/longitude), platform depth, species name, animal identification number, animal location (latitude/longitude), animal depth, animal distance from source, and sound received levels. A single animat may have one or more entries in the data file at each time step depending on the number of sources determined to be within hearing distance.

4.3.3. Post Processor

Post Processor uses output from Scenario Simulator to compute the impact of events on each marine mammal and sea turtle group. Criteria and thresholds (Section 3.4) are applied to Monte Carlo simulations which are then combined to provide a mean estimate of effects for each event.

4.3.3.1. Non-Impulsive Sources

For non-impulsive sources, Post Processor uses two metrics to describe sound received by animats, SPL and SEL. Post Processor computes maximum SPL and accumulated SEL over the entire duration of the event for each animat. The maximum SPL, which is used to determine behavioral effects, is simply the maximum received level reported in Scenario Simulator. Accumulated SEL is used to determine PTS and TTS and represents the accumulation of energy from all time-steps and from multiple source exposures. For SEL, the appropriate auditory weighting functions defined by the marine mammal and sea turtle criteria (Section 3.4) are applied to adjust the received levels. SEL is given by;

$$\mathrm{SEL}_{s,t} = \mathrm{SPL}_{\mathrm{weighted},t} + 10 \times \log(PL_s), \qquad (4\text{-}12)$$

where, s is source s, t is time t, $\mathrm{SPL}_{\mathrm{weighted},t}$ is the received level adjusted by the species auditory weighting function at time t, and PL_s is the pulse length of source s. The SEL values are then power summed across time to give a cumulative SEL for each source;

$$\text{Cumulative SEL}_s = 10 \times \log\left(\sum_{t=1}^{n} 10^{\text{SEL}_{s,t}/10}\right) \quad (4\text{-}13)$$

where, n is the number of time steps for the given source. After these calculations, the cumulative SEL is once more power summed across sources for each animat to determine the final cumulative SEL. A mean number of SPL and SEL simulated exposures are computed for each 1-dB bin. The mean value is based on the number of animats exposed at that dB level from each track iteration. The Behavioral Response Function (BRF) curve is applied to each 1-dB SPL bin to compute the number of behaviorally affected animats per bin. The number of behaviorally affected animats per bin is summed to produce the total number of behavioral effects.

Mean 1-dB bin SEL exposures are then summed to determine the number of instances in which PTS and TTS thresholds were exceeded. PTS values represent the cumulative number of animats affected at or above the PTS threshold. TTS values represent the cumulative number of animats affected at or above the TTS threshold and below the PTS threshold. Each animat can only be reported under a single criterion (e.g., once an animat is reported for PTS, it would not additionally be reported under TTS or behavioral). Behavioral effects are only computed for animats that experience two or more pulses.

4.3.3.2. **Impulsive Sources**

For impulsive sources five metrics are used to describe the sound received by animats: peak sound pressure level (SPL_{peak}), root mean square sound pressure level (SPL_{rms}), SEL, calf impulse, and adult impulse. SPL_{rms} is applied to behavioral effects for turtles and behavioral effects from airguns for all species. Calf and adult impulses are only applied to explosive sources. SEL is a cumulative metric and is adjusted if a group of sources is in a cluster where *c* is the cluster size. This is then power summed over all clusters of sources to get the final cumulative SEL for the animat.

$$\text{SEL}_c = \text{SEL} + 10 \times \log(c) \quad (4\text{-}14)$$

Unlike non-impulsive sources, criteria for mortality and injury to animats is evaluated. Mortality and lung injury are determined by calf and adult impulse. Gastrointestinal injury is driven by (SPL_{peak}). Both TTS and PTS have duel metrics: SPL_{peak} and SEL. Only one of these metrics needs to be above threshold to trigger TTS or PTS. Behavioral effects are primarily based on a single SEL metric with the exceptions of effects from airguns and effects on turtles. Behavioral effects are only computed for counts greater than one.

4.3.3.3. **Navy Acoustic Effects Model Output**

All scenarios analyzed in NAEMO were evaluated as single events occurring within a given season and location. Scenarios that occurred over multiple seasons and locations were modeled for each combination of season and location. The annual estimated effects for a single scenario are determined by taking the average of all seasons and locations modeled for that scenario. To create the average effects, each scenario was multiplied by a factor based on the number of seasons, locations, and events per season that scenario would be conducted. Each factored scenario effect is then summed together to produce the average scenario effect. Total annual effects resulting from all scenarios modeled are then the summation of each scenario’s averaged effect.

Scenarios that may not occur every year are the exception to this methodology. Non-annual scenarios were modeled in multiple locations and seasons to provide coverage for all possible conditions, but these scenarios occur only one time within a given year. Therefore, the maximum effects from all modeled locations and seasons are used in place of the average values. To compute the maximum requires using a multiplication factor of one for each location and season and then determining the maximum per species effect from all locations and seasons.

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5. PILE DRIVING ACOUSTIC EFFECTS ANALYSIS

The Navy performed a quantitative analysis to estimate the number of times that marine mammals and sea turtles could be affected by pile driving and extraction used during proposed activities. A similar method was used to determine the ranges to specific effects for fishes. The analysis took into account:

- *Proposed Activity*: details of the activity, such as the number of pile strikes and number of days.
- *Criteria and Thresholds*: sound levels used to predict potential behavioral response, TTS, and PTS effects from pile driving.
- *Acoustic Parameters*: underwater sound levels, frequencies produced, and the environmental parameters controlling sound propagation in the surf zone/nearshore environment.
- *Marine Species Density*: number and distribution of marine mammals and sea turtles.
- *Mitigation and Avoidance*: mitigation effectiveness and the animal's ability to avoid the zones of higher sound levels.

This information was used in an 'area*density' model where the areas within each footprint (i.e., zone of influence [ZOI]) that encompasses each potential effect (i.e., behavioral response, TTS, and PTS) are calculated for a given day's activities. Then these areas were multiplied by the density of each marine species within the nearshore environment to estimate the number of effects to each species. Since the same animal can be 'taken' every day (i.e., 24-hour reset time), the number of predicted effects from a given day were multiplied by the number of days for that activity. This generated a total estimated number of effects over the entire activity per species and stock. The effectiveness of mitigation measures and the animal's ability to move away from the area of potential behavioral reaction were also considered, especially in regard to the accumulation period for the SEL that was used to predict TTS/PTS effects.

5.1. Proposed Activity

In AFTT and HSTT, construction of an Elevated Causeway System would involve intermittent impact pile driving over approximately 20 days. The size of the pier used in an Elevated Causeway System event is assumed to be a maximum of 1,520 ft. long, requiring 119 supporting piles. Crews work 24 hours a day and would drive approximately six piles in that time period. Each pile takes approximately 15 minutes to drive, with time taken between piles to reposition the driver. When training events that use the Elevated Causeway System are complete, the structure would be removed using vibratory extraction over approximately 10 days. Crews would remove approximately 12 piles per 24-hour period, each taking about six minutes to remove. Table 5-1 summarizes the pile driving and pile removal activities that would occur during a 24-hour period.

Table 5-1. Summary of Pile Driving and Removal Activities per 24-Hour Period

Method	*Piles Per 24-Hour Period*	*Time Per Pile*	*Total Estimated Time of Noise Per 24-Hour Period*
Pile Driving (Impact)	6	15 minutes	90 minutes
Pile Removal (Vibratory)	12	6 minutes	72 minutes

5.2. Criteria and Thresholds

See the *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)* technical report (U.S. Department of the Navy, 2017a) for a comprehensive discussion on how the criteria and thresholds were derived. Additionally, this report includes detailed information on frequency weighting and hearing groups.

Because impact pile driving produces impulsive noise, impulsive criteria were used to assess the onset of TTS and PTS for these sources. Weighting functions specific to each hearing group were used to weight the received sound level before the weighted level was compared to the thresholds for PTS and TTS. Vibratory pile removal produces continuous, non-impulsive noise. Therefore, the non-impulsive criteria were used to assess the onset of TTS and PTS. Due to the low source levels for vibratory pile extraction, frequency weighting was not deemed necessary for this noise type (i.e., unweighted source levels were already well below weighted thresholds). Existing the National Marine Fisheries Service (NMFS) risk criteria were applied to estimate behavioral effects from impact and vibratory pile driving.

5.3. Acoustic Parameters

Impact pile driving and vibratory pile extraction were recorded during an Elevated Causeway System installation and removal (Illingworth and Rodkin, 2015, 2017). Transmission loss (TL) was assumed to be TL = 16.5 * Log_{10} (range) based on these measurements. The measured source levels are shown in Table 5-2.

Table 5-2: Elevated Causeway System Pile Driving and Removal Underwater Sound Levels

Pile Size &Type	*Method*	*Average Sound Levels at 10 m (SEL per individual pile)*
24-in. Steel Pipe Pile	Impact[1]	192 dB re 1 µPa SPL peak 182 dB re 1 µPa^{2}s SEL (single strike)
24-in. Steel Pipe Pile	Vibratory[2]	146 dB re 1 µPa SPL rms 145 dB re 1 µPa^{2}s SEL (per second of duration)

[1]Illingworth and Rodkin (2017), [2]Illingworth and Rodkin (2015)
Notes: in.: inch; SEL: Sound Exposure Level; SPL: Sound Pressure Level; rms: root mean squared; dB re 1 µPa: decibels referenced to 1 micropascal

Table 5-3 shows the weighting factors that were used in this analysis for impact pile driving based on the averaged difference between weighted and unweighted levels from multiple recorded strikes. These factors were derived from the weighting functions and were added to the threshold for each hearing group before ranges to potential TTS/PTS effects from impact pile driving were determined. Frequency weighting was not used for behavioral response criteria or vibratory pile extraction.

Table 5-3. Weighting Factors Applied to Each Hearing Group for Impact Pile Driving (Applies to TTS/PTS only)

Marine Species Hearing Groups	*Weighting Factor as Measured for Impact Pile Driving (cSEL)*
Low-Frequency Cetaceans	1
Mid-Frequency Cetaceans	24
High-Frequency Cetaceans	29
Phocids (In-Water)	8
Otariids (In-Water)	8
Sea Turtles	4

cSEL: cumulative sound exposure level

Ranges to potential effects (i.e., behavioral response, TTS, and PTS) were calculated based on the TL reported above. The threshold for a given effect was subtracted from the source level to find the TL needed to reach that specific threshold. For PTS and TTS from impact pile driving the weighted threshold was found by adding the PTS or TTS threshold i with the species hearing group appropriate weighting factor from Table 5-4. The metric used to estimate PTS and TTS effects was cumulative sound exposure level (cSEL), which increases with signal duration based on cSEL = single strike SEL + 10 * Log_{10}(# strikes) for impact pile driving, or similarly: cSEL = one second SEL + 10 * Log_{10}(# seconds) for vibratory pile extraction. Single strike and single second SELs are provided in Table 5-4 and Table 5-5 for impact and vibratory, respectively. Thirty-five strikes were used to represent 60 seconds of impact pile driving (further justification of 60-sec duration provided below) and vibratory pile extraction was accumulated for 360 seconds per pile. The source levels that were used for the behavioral response criteria or any potential effects from vibratory pile extraction (i.e., PTS, TTS, or behavioral response) were not weighted. Once the difference between the source level and the appropriate criteria was found, the range to this TL was solved using: TL = 16.5 * Log_{10} (range). This provided a single-pile range to effects for each effect category and each marine species group. The ranges to effects for impact pile driving and vibratory pile extraction are given in

Table 5-4 and Table 5-5, respectively. Note that ranges to PTS and TTS for impact pile driving were based on 60 seconds of activity. This is discussed further in the *Mitigation, Standard Operating Procedures, and Avoidance* section below.

Table 5-4: Range to Potential Effects from Impact Pile Driving for Each Hearing Group

Hearing Group	***Impact Pile Driving PTS (m)***	***Impact Pile Driving TTS (m)***	***Impact Pile Driving Behavioral Response (m)***
Low-Frequency Cetaceans	65	529	870
Mid-Frequency Cetaceans	2	16	870
High-Frequency Cetaceans	65	529	870
Phocids (In-Water)	19	151	870
Otariids (In-Water)	2	12	870
Sea Turtles	2	19	107

Note: TTS and PTS ranges are based on 60 seconds of impact pile driving. Range to behavioral response is based on highest received level and therefore does not include a time component.
m: meters

Table 5-5: Range to Potential Effects from Vibratory Pile Extraction for Each Hearing Group

Hearing Group	***Vibratory Pile Extraction PTS (m)***	***Vibratory Pile Extraction TTS (m)***	***Vibratory Pile Extraction Behavioral Response (m)***
Low-Frequency Cetaceans	0	3	376
Mid-Frequency Cetaceans	0	4	376
High-Frequency Cetaceans	7	116	376
Phocids (In-Water)	0	2	376
Otariids (In-Water)	0	0	376
Sea Turtles	0	0	0

5.4. Marine Species Density

The exposures estimated from the Elevated Causeway System analysis relied upon the assumption that marine mammals are uniformly distributed within the ocean waters adjacent to the proposed event locations. In reality, animal presence in the surf zone and nearshore waters is known to be patchy and infrequent with the exception of a few coastal species (e.g., bottlenose dolphins). These densities were derived from the Navy's Marine Species Density Database (NMSDD). Note, only densities for species with estimated impacts are shown. All other species were deemed to be extralimital to the nearshore/surf zone environment, or had densities so low as to produce no estimated effects in the analysis.

5.5. Mitigation, Standard Operating Procedures, and Avoidance

For impact pile driving, the mitigation zone (see Table 5-6) extends beyond the average ranges to PTS for all hearing groups; therefore, mitigation will help prevent or reduce the potential for exposure to PTS. The impact pile driving mitigation zone also extends beyond or into a portion of the average ranges to TTS; therefore, mitigation will help prevent or reduce the potential for exposure to all TTS or some higher levels of TTS, depending on the hearing group. Vibratory pile extraction has shorter impact ranges than impact pile driving; therefore, the mitigation zone will extend further beyond the average ranges to PTS, and further beyond (or into, depending on hearing group) the average ranges to TTS during vibratory pile extraction.

The small size of the mitigation zone and its close proximity to the observation platform will result in a high likelihood that Lookouts would be able to detect marine mammals and sea turtles throughout the mitigation zone. With regard to the post-sighting wait periods, the 30-min. recommencement wait period would cover the average dive times of the marine mammal species that could be present in the mitigation zone.

Table 5-6: Procedural Mitigation for Pile Driving

Procedural Mitigation Description
<u>Stressor or Activity</u> • Pile driving and pile extraction sound during Elevated Causeway System training
<u>Resource Protection Focus</u> • Marine mammals • Sea turtles
<u>Number of Lookouts and Observation Platform</u> • 1 Lookout positioned on the shore, the elevated causeway, or a small boat
<u>Mitigation Zone Size and Mitigation Requirements</u> • 100 yd. around the pile driver: o 30 min. prior to the start of the activity, observe the mitigation zone for floating vegetation (if floating concentrations of detached kelp paddies and *Sargassum* are found in the Study Area), marine mammals, and sea turtles; if observed, delay the start of impact pile driving or vibratory pile extraction until the mitigation zone is clear. o During the activity, observe the mitigation zone for marine mammals and sea turtles; if observed, cease impact pile driving or vibratory pile extraction. o The Navy will allow a sighted marine mammal or sea turtle to leave the mitigation zone prior to the initial start of the activity (by delaying the start) or during the activity (by not recommencing pile driving or pile extraction) until one of the following conditions has been met: (1) the animal is observed exiting the mitigation zone; (2) the animal is thought to have exited the mitigation zone based on a determination of its course, speed, and movement relative to the pile driving location; or (3) the mitigation zone has been clear from any additional sightings for 30 min.

As described in Chapter 2 (Description of Proposed Action and Alternatives) of the AFTT and HSTT EIS/OEIS documents, the Navy implements standard operating procedures for pile driving safety. Due to pile driving system design and operation, the Navy performs soft starts during impact installation of each pile to ensure proper operation of the diesel impact hammer. During a soft start, the Navy performs an initial set of strikes from the impact hammer at reduced energy before it can be operated at full power and speed. This standard operating procedure may “warn” marine mammals and sea turtles and cause them to move away from the sound source before impact pile driving increases to full operating capacity. This should reduce their exposure to higher levels of individual pile strikes thereby reducing their cumulative SEL.

Based on best available science regarding animal reaction to sound, selecting a reasonable SEL calculation period is necessary to more accurately reflect the time period an animal would likely be exposed to the sound. Mitigation effectiveness and animal avoidance of higher sound levels were both factored into the impact pile driving analysis as most marine mammals and sea turtles should be able to easily move away from the expanding ZOI of TTS/PTS within 60 seconds especially considering the soft start procedure. Alternatively, the animal should avoid the zone altogether if they are outside of the immediate area upon startup. As shown in Table 5-4, the TTS zone for all mid-frequency cetaceans, otariids, and sea turtles is well within the 100 yd. mitigation zone for impact pile driving. Phocids (HSTT only) have a 60-second TTS range of 151 m, only slightly longer than the mitigation zone and well within the behavioral reaction range of 830 m. Therefore, most phocids (harbor seals and elephant seals in HSTT) would be expected to avoid sound levels well below those that could cause TTS. Low and high-frequency cetaceans both have 60-second ranges to TTS of 529 m, which is farther than the mitigation zone. However, LF cetaceans (i.e., mysticetes) and most HF cetaceans, such as *Kogia* spp. and Dall’s porpoise, are not expected in the nearshore/surf zone environment where these activities are proposed. The harbor porpoise (HF cetacean) has demonstrated avoidance of low levels of underwater noise and will likely avoid well beyond ranges to TTS. Of the LF and HF cetaceans, only Dall’s porpoise has estimated behavioral responses from HSTT proposed Elevated Causeway System activities.

5.6. Calculating Number of Effects per Species and Stock

The analysis uses a simple ‘area*density’ model to estimate numbers of behavioral response, TTS, and PTS per species and stock. The zone of influence (ZOI) for an effect is the area that encompasses the sound levels at or above a threshold for that given effect to the threshold for the next higher-order effect. For example, the ZOI for TTS is the area where sound levels meet or exceed the TTS threshold but are still below the PTS threshold. The number of times an animal may be affected was found by multiplying these ZOIs by the density of marine species in the area.

To calculate the total ZOI, first the single pile ZOI was needed. Since Elevated Causeway System pile driving activities occur in the surf/nearshore environment and animals would generally be seaward of this, the area of a half-circle was calculated with a range (i.e., radius) to each effect category as shown in Table 5-4 and Table 5-5 for impact pile driving and vibratory pile extraction, respectively. The single pile ‘ring-shaped’ ZOI for each effect was then found by subtracting the next smaller effect area (i.e., higher order effect; TTS ZOI = TTS Area - PTS Area).

Marine mammals and sea turtles are likely to leave the immediate area of pile driving and extraction activities and be less likely to return as activities persist. However, some ‘naïve’ animals may enter the area during the short period of time when pile driving and extraction equipment is being re-positioned between piles. Therefore, an animal “refresh rate” of 10% was selected. This means that 10% of the single pile ZOI was added for each consecutive pile within a given 24-hour period to generate the daily ZOI per effect category. These daily ZOIs were then multiplied by the number of days of pile driving and pile extraction and then summed to generate a total ZOI per effect category (i.e. behavioral response, TTS, PTS).

These total ZOIs were then multiplied by the density of marine species to produce estimates of the number of times animals of each species could be affected. With the exception of bottlenose dolphins, all marine mammals that could be near both AFTT and HSTT Elevated Causeway System activities are likely to belong to a single stock per species. Therefore, all effects to a given species were assigned to that stock. Bottlenose dolphins were already divided into stocks within the densities for HSTT, so no further calculations were necessary. The AFTT densities only provided a single value for bottlenose dolphins (species), so the effects per stock were estimated by parsing the effects by the proportion of each stock represented in each Elevated Causeway System location.

6. MITIGATION EFFECTIVENESS

As described in Chapter 5 (Mitigation) of each Phase III EIS/OEIS, the Navy implements mitigation measures to avoid or reduce potential impacts of training and testing activities on biological and cultural resources. Mitigation measures are typically organized into two categories: procedural mitigation measures and mitigation areas. For Study Areas that have a terrestrial component, a third mitigation category would include mitigation for terrestrial resources, which generally includes ordnance, targeting, or other access restrictions.

The Navy implements procedural mitigation measures for applicable activities whenever and wherever they occur within an applicable Study Area. Procedural mitigation measures are tailored to each specific stressor or training and testing activity category and generally involve: (1) the use of one or more trained Lookouts to diligently observe for specific biological resources within a mitigation zone, (2) requirements for Lookouts to immediately communicate sightings of specific biological resources to the appropriate watch station for information dissemination, and (3) requirements for the watch station to implement mitigation until a pre-activity commencement or during-activity recommencement condition has been met. An example of a procedural mitigation measure is powering down or ceasing the transmission of active sonar in response to a sighting of a marine mammal in a mitigation zone. Mitigation zones are areas at the surface of the water (measured as the radius from a stressor) within which applicable training or testing activities will be ceased, powered down, or modified to protect specific biological resources from an auditory injury (PTS), non-auditory injury (from impulsive sources), or direct strike (e.g., vessel strike) to the maximum extent practicable. The Navy developed each mitigation zone to be the largest area Lookouts can reasonably be expected to observe during typical activity conditions (i.e., the most environmentally protective) and within which the Navy can commit to implementing mitigation without impacting safety, sustainability, and the ability to meet mission requirements.

NAEMO estimates acoustic and explosive effects without considering mitigation. Therefore, it overestimates impacts on marine mammals and sea turtles. To account for mitigation for marine mammals and sea turtles, the Navy conservatively (i.e., erring on the side of underestimating effectiveness) quantifies the potential for procedural mitigation to reduce model-estimated PTS to TTS for exposures to non-impulsive sources and reduce model-estimated mortality to injury for exposures to impulsive sources.

6.1. Mitigation Effectiveness Factors

The Navy assumes that a Lookout will not be 100 percent effective at detecting all individual marine mammals and sea turtles within a mitigation zone due to the inherent limitations of observing marine species, and because the likelihood of sighting individual animals is largely dependent on the following: observation conditions, such as time of day, sea state, mitigation zone size, observation platform; and animal behavior, such as amount of time an animal spends at the surface of the water. This is particularly true for sea turtles, small marine mammals, and marine mammals that display cryptic behaviors (e.g., surfacing to breathe with only a small portion of their body visible from the surface). To account for these variables, the Navy quantitatively assessed the effectiveness of its mitigation measures on a per-scenario basis using the following four factors:

- Species Sightability
- Observation Area
- Visibility
- Positive Control

The Navy used the equation below to calculate a mitigation effectiveness score for each species for each training and testing scenario based on the mitigation effectiveness factors.

$$\text{Mitigation Effectiveness} = \text{Species Sightability } [0–1] \times \text{Observation Area } [0, 0.5, 1] \times \text{Visibility } [0.25, 0.5, 0.75, 1] \times \text{Positive Control } [0, 0.5, 1] \quad (5\text{-}1)$$

6.1.1. Species Sightability

The ability to detect marine mammals and sea turtles is dependent on the animal's presence at the surface and the characteristics of the animal that influence its sightability. The Navy considered applicable data from the best available science to numerically approximate the sightability of marine mammals and determined that the standard "detection probability," referred to as g(0), is most appropriate. Detection probabilities are derived from systematic line-transect surveys based on species-specific estimates for vessels and aerial platforms. Estimates of g(0) are available in peer-reviewed reports, typically from research conducted by NMFS Regional Science Centers.

There are two components of g(0): perception bias and availability bias (Marsh & Sinclair, 1989). Perception bias accounts for marine mammals that are on the transect line and detectable but are missed by the observer. Various factors influence the perception bias component of g(0), including species-specific characteristics (e.g., behavior, appearance, group size, blow characteristics), viewing conditions (e.g., sea state, wind speed, wind direction, wave height, glare), observer characteristics (e.g., experience, fatigue, concentration), and platform characteristics (e.g., pitch, roll, speed, height above water). To derive estimates of perception bias, typically an independent observer looks for marine mammals missed by the primary observers. From that data, an estimate of the probability that animals are missed by the primary observers is determined. The second component of g(0), availability bias, reflects the probability of an animal being at the surface within the survey track. Availability bias accounts for animals that are missed because they are not available for detection when the survey platform passes by. This generally occurs more often with deep diving whales (e.g., sperm whales, beaked whales).

When available, values for g(0) used by the Navy took into account perception bias, availability bias, and Beaufort sea state. The values were derived through vessel surveys (Barlow, 2015, 2016; Palka, 2006) and aircraft surveys (Carretta et al., 2000; Fuentes et al., 2015; Hain et al., 1999; Miller et al., 1998; Palka, 2006; Seminoff et al., 2014). Surveys to determine g(0) have not been performed for all species in each Study Area. For species without available g(0) values, the Navy assigned surrogate species based on morphology, group size, and typical species behaviors.

Line-transect surveys and Navy training and testing activities are conducted for fundamentally different purposes. Differences exist between the areas observed, number of observers, observation tools and techniques, and types of observer experience. The Navy assessed these differences and determined that using g(0) values derived from line-transect surveys is the best available scientific basis (i.e., statistically-derived values) for its species sightability factors. Using these g(0) values is an appropriate and conservative approach that underestimates the protection afforded by the Navy's mitigation measures for the reasons discussed below.

During line-transect surveys, there are typically two primary observers. Line-transect observers are trained marine biologists who have extensive experience observing for marine mammals and sea turtles in varying field conditions. During Navy training and testing, there are routinely between one to four Navy Lookouts designated to observe the mitigation zones. Additional Lookouts are designated during certain activities, such as ship shock trials in the AFTT Study Area, which has 10 Lookouts or trained marine species observers. During explosive activities, if additional platforms are participating, personnel positioned in those assets (e.g., safety observers, evaluators) will support observing the mitigation zone while performing their regular duties. During activities involving vessel movement, the Navy positions watch personnel to monitor for any indication of danger to the ship and the personnel on board. As a standard collision avoidance procedure, watch personnel also monitor for marine mammals that have the potential to be in the direct path of the ship. This can result in additional personnel observing a mitigation zone (e.g., during hull-mounted active sonar activities). To conservatively assess mitigation effectiveness, the Navy only accounts for the minimum number of Lookouts required for each activity. Therefore, the mitigation effectiveness factors may underestimate the likelihood that some marine mammals and sea turtles may be detected during activities that are supported by additional personnel who may also be observing a mitigation zone. Navy Lookouts are not trained marine biologists; however, Lookouts are required to complete the NMFS-approved Marine Species Awareness Training and have significant experience looking for objects (including marine mammals) on the water's surface to ensure safety of ships and aircraft.

Line-transect observers and Navy Lookouts generally use similar observation tools, including a combination of naked-eye scanning, scanning with hand-held binoculars, and if available, scanning with high-powered pedestal-mounted binoculars on larger vessels. Scanning techniques differ due to the different fundamental purposes of line-transect surveys and observations during Navy training and testing activities. Line-transect surveys are typically used to estimate cetacean and turtle abundance, and as such, are designed to cover a survey area uniformly in a straight line or grid pattern. Each primary line-transect observer looks for marine species in the forward 90-degree quadrant on their side of the survey platform and scans the water from the vessel out to the limit of the available optics (i.e., the horizon). A systematic line-transect survey is designed to sample broad areas of the ocean and generally does not retrace the same area during a given survey. Therefore, line transect observers have a limited opportunity to detect animals present at the surface during a single pass along their trackline. Because Navy Lookouts focus their observations on established mitigation zones, their area of observation is typically much smaller than that observed during line-transect surveys. The mitigation zone size and distance to the observation platform varies by Navy activity. For example, during hull-mounted mid-frequency active sonar activities, the mitigation zone extends 1,000 yd. from the ship hull. During explosive bombing activities, the mitigation zone is 2,500 yd. around the intended target, which is located directly beneath the firing platform. Navy mission requirements determine the operational parameters for participating aircraft (altitude, flight path, and speed) and vessels (course and speed). Some Navy training and testing activities are stationary or occur within a localized area. During these activities, Lookouts generally scan the same area of water during the activity, which offers a continuous opportunity to sight animals at that location, including animals that may have initially been underwater and not available to be seen.

Line-transects are conducted at a constant speed, typically around 10 knots for vessels, during daylight hours. Surveys are typically scheduled for a season when the weather and sea state are most likely to provide favorable sighting conditions. However, observers may be required to collect data in high sea states up to Beaufort 6 and during periods of rain and fog, which may reduce marine mammal detections due to poor visibility (Barlow, 2006). During Navy training and testing, speeds of most large naval vessels generally range from 10 to 15 knots to limit fuel consumption; however, ships will, on occasion, operate at higher speeds within their specific operational capabilities. For some activities, such as hull-mounted mid-frequency sonar events, training and testing in both good visibility (e.g., daylight, favorable weather conditions) and low visibility (e.g., nighttime, inclement weather conditions) is vital because environmental differences between day and night and varying weather conditions affect sound propagation and the detection capabilities of sonar. Other activities, such as sinking exercises, are only conducted during daylight hours for safety purposes. Detection probabilities derived from surveys in less than ideal conditions are reflected in the g(0) values used by the Navy (Barlow, 2003; Barlow & Forney, 2007).

6.1.2. Observation Area

The Navy conservatively assessed the likelihood that Lookouts would be able to visually observe the range to PTS (for non-impulsive sources) or mortality (for impulsive sources) for each training or testing scenario. This is influenced by the size of the predicted impact ranges, location of the mitigation zone in proximity to the observation platform, type of observation platform (e.g., pier, small boat, large vessel, helicopter, fixed-wing aircraft), and number of Lookouts. The Navy also considered the objectives of each training and testing scenario to determine the opportunities for and capabilities of Lookouts to continuously visually observe the impact range. For a simplified example, large-caliber gunnery activities involve vessels firing projectiles at targets located up to 6 NM down range, whereas medium-caliber gunnery activities involve vessels or aircraft firing projectiles at targets located up to 4,000 yd. down range. Therefore, a scenario involving explosive large-caliber gunnery would generally receive a lower score relative to a scenario involving explosive medium-caliber gunnery based on the proximity of the mitigation zones to the observation platforms.

Observation Area = portion of impact range that can be continuously observed during an event (5-2)

- If the entire impact range can be continuously visually observed, then *Observation Area* = 1.
- If over half the impact range can be continuously visually observed, then *Observation Area* = 0.5.
- If less than half the impact range can be continuously visually observed, then *Observation Area* = 0.

6.1.3. Visibility

The Navy conservatively assessed the likelihood that a training or testing scenario would be conducted during periods of reduced visibility, such as during rain, high wind, high sea state, or at night. If a scenario could be conducted during periods of reduced visibility, then the effectiveness score was reduced by the sum of the individual visibility reduction factors. This is a conservative approach because most events that could occur during periods of low visibility do so infrequently. Although activities that occur at night under certain moon phases (e.g., full) could result in clear nighttime visibility, this was not accounted for in the analysis structure. The visibility reduction factors were derived from data input into the Navy's Acoustic Effects Model database by training and testing stakeholders.

Visibility = 1 – sum of individual visibility reduction factors (5-3)

- The percentage of time the scenario could occur at night would result in a *visibility reduction factor* = 0, 0.25, or 0.50
- If the scenario could occur in high sea state (Beaufort sea state of 4 or higher), then *visibility reduction factor* = 0.25
- If the scenario could occur in fog, rain, or high wind, then *visibility reduction factor* = 0.25
- If the scenario could occur in high sea state and fog, rain, or high wind, the visibility reduction factor was not summed to equal 0.50. To avoid doubling the reduction in visibility from inclement weather on the whole, the maximum *visibility reduction factor* due to high sea state and fog, rain, and high wind is 0.25.

6.1.4. Positive Control

The Navy assessed the ability for sources to be positively controlled in response to a marine mammal or sea turtle sighting in a mitigation zone. Most active sonars are positively controlled, and mitigation can be implemented within a few seconds after the operator has been notified of a sighting. Other sound sources are not positively controlled, such as explosives with time-delay fuses (i.e., the detonation cannot be terminated once the fuse is initiated due to human safety concerns). The positive control factor was derived from data input into the NAEMO database by training and testing stakeholders.

Positive Control = positive control factor of sound sources involving mitigation (5-4)

- If there is a single source involving mitigation within a scenario and it is under positive control, or there are multiple sources involving mitigation within a scenario and all are under positive control, then *Positive Control* = 1
- If there are multiple sources involving mitigation within a scenario and no more than one source is not under positive control (e.g., torpedo), then *Positive Control* = 0.5
- If there is a single source involving mitigation within a scenario and it is not under positive control, or there are multiple sources involving mitigation within a scenario and more than one source is not under positive control, then *Positive Control* = 0

6.2. Accounting for Mitigation Effectiveness

To quantify the number of marine mammals and sea turtles predicted to be sighted by Lookouts during implementation of mitigation in the range to PTS during a scenario involving non-impulsive sources and in the range to mortality during a scenario involving impulsive sources, the species-specific mitigation effectiveness score is multiplied by the model-estimated PTS or mortality impacts, as shown below.

Number of animals sighted = Mitigation Effectiveness x *Model-Estimated Impacts* (5-5)

The number of animals sighted is equivalent to the number of marine mammals and sea turtles that the Navy would avoid exposing to PTS (for non-impulsive sources) or mortality (for impulsive sources) during a scenario. To account for this in the marine mammal and sea turtle impact estimates, the Navy corrects the category of predicted impact by shifting that number of PTS impacts to TTS impacts for scenarios involving non-impulsive sources, and shifting that number of mortality impacts to non-auditory injury impacts for impulsive sources. The Navy does not change the total number of estimated impacts to a marine mammal or sea turtle species to account for mitigation, but instead reassigns a conservative number of impacts to a lower order effect. In other words, the Navy does not change the total number of animals predicted to experience impacts from each scenario or a Proposed Action as a whole.

Because the Navy takes a conservative approach to assessing procedural mitigation effectiveness, the actual realized benefit of the Navy's mitigation measures for marine mammals and sea turtles is not fully represented in the quantitative analysis. Examples of conservative assumptions used in this analysis include:

- The Navy calculates the *Observation Area* mitigation effectiveness factor as either 0, 0.5, or 1. Therefore, if the portion of the impact range that can be continuously observed is less than half, the entire scenario receives a mitigation effectiveness score of 0 and no impact adjustments are made. However, implementing mitigation during that scenario will still provide some level of impact avoidance, even though it is not accounted for numerically in the quantitative analysis.

- The Navy only accounts for mitigation based on the required number of Lookouts and does not account for other personnel or platforms participating in the activity that will support observing the mitigation zone.
- The Navy does not quantify the potential for mitigation to reduce model-estimated PTS for impulsive sources, TTS, behavioral impacts, or the total number of animals predicted to experience impacts from each scenario as a whole. Depending on the hearing group and activity, the Navy's mitigation zones extend beyond or into a portion of the average ranges to PTS for impulsive sources. Some mitigation zones also extend beyond or into a portion of the average ranges to TTS or behavioral impacts for sea turtles and certain marine mammal hearing groups. Therefore, the mitigation will provide a greater level of impact avoidance than what has been numerically accounted for in this quantitative analysis.
- The mitigation effectiveness analysis accounts for the fact that Lookouts will not be 100% effective at observing all individual animals. However, the analysis does not account for situations when the Navy implements mitigation for one observed sea turtle or marine mammal, while there are additional unobserved sea turtles or marine mammals beneath the surface. These unobserved animals would realize the same mitigation benefit as the observed animals; however, they are unaccounted for in this quantitative analysis.
- The benefits of mitigation areas and terrestrial mitigation measures are discussed qualitatively and are not factored into the quantitative analysis process or reductions in take for MMPA and ESA impact estimates. Marine mammal mitigation areas are designed to help avoid or reduce potential impacts during biologically important life processes within particularly important habitat areas. Therefore, the mitigation benefit is discussed in each EIS/OEIS in terms of the context of impact avoidance or reduction, when applicable.

7. AVOIDANCE BY ANIMALS OF HIGH SOUND LEVELS FROM SONAR AND OTHER TRANSDUCERS

NAEMO overestimates the number of marine mammals and sea turtles that would be exposed to sound sources that could cause PTS because the model does not consider horizontal movement of animats including avoidance of high intensity sound exposures. Therefore, the potential for animal avoidance is considered separately. At close ranges and high sound levels, avoidance of the area immediately around the sound source is one of the assumed behavioral responses for marine mammals. Animal avoidance refers to the movement out of the immediate injury zone for subsequent exposures, not wide-scale area avoidance. Various researchers have demonstrated that cetaceans can perceive the location and movement of a sound source (e.g., vessel, seismic source, etc.) relative to their own location and react with responsive movement away from the source, often at distances of 1 km or more (Au & Perryman, 1982; Jansen et al., 2010; Richardson et al., 1995; Tyack et al., 2011; Watkins, 1986; Würsig et al., 1998). A marine mammal's ability to avoid a sound source and reduce its cumulative sound energy exposure would reduce risk of both PTS and TTS. However, the quantitative analysis conservatively only considers the potential to reduce some instances of PTS by accounting for marine mammals swimming away to avoid repeated high-level sound exposures. All reductions in PTS impacts from likely avoidance behaviors are instead considered TTS impacts.

While in general, the louder the sound source the more intense the behavioral response, the proximity of a sound source and the animal's experience, motivation, and conditioning were also critical factors influencing the response_ENREF_11 outlined an approach to assessing the effects of sound on marine mammals that incorporates these contextual-based factors. They recommend considering not just the received level of sound, but also in what activity the animal is engaged, the nature and novelty of the sound (i.e., is this a new sound from the animal's perspective), and the distance between the sound source and the animal. They submit that this "exposure context," as described, greatly influences the type of behavioral response exhibited by the animal *(U.S. Department of the Navy, 2017c*).

An extensive review of literature on marine mammal behavioral responses to sonar and other transducers occurred for the development of behavioral response functions in the technical report titled *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)* (U.S. Department of the Navy, 2017c). Due to the breadth of marine mammal behavioral response literature, individual studies are not discussed in detail in the technical report. However, general conclusions can be drawn from the literature, such as the received sound level to which species will behaviorally respond:

- Odontocetes (mid- and high-frequency cetacean species groups): Responses occurred between 94 and 185 dB re 1 μPa with a mean response range between 126 and 169 dB re 1 μPa.
- Pinnipeds (phocid and otariid species groups): In water responses occurred between 125 and 185 dB re 1 μPa with a mean response range between 159 and 170 dB re 1 μPa.
- Mysticetes (low-frequency cetacean species group): Responses occurred between 107 and 165 dB re 1 μPa with a mean response range between 123 and 139 dB re 1 μPa.
- Beaked whales (mid-frequency cetacean species group): Responses occurred between 95 and 142 dB re 1 μPa.
- Harbor porpoise (high-frequency cetacean species group): 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.

- Sirenians (low-frequency cetacean species group [surrogate]): Due to a lack of behavioral response data for sirenians, behavioral response data from mysticetes are used as a proxy due to similarities in behavioral traits and distant taxonomic relation.

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.

For Phase III analyses, with the exception of the high-frequency cetacean species group, all other species groups including sea turtles have an in water weighted PTS threshold greater than or equal to 198 dB re 1 μPa^2 s for non-impulsive sources (U.S. Department of the Navy, 2017c). In addition, the majority of species groups have a weighted TTS threshold greater than 178 dB re 1 μPa^2s for non-impulsive sources. The high-frequency cetacean species group has lower TTS and PTS thresholds; however, the hearing group is comprised of some species that have exhibited a high level of sensitivity to human activity. For example, dwarf and pygmy sperm whales are not often observed at sea, but they are among the more frequently stranded cetaceans (Caldwell & Caldwell, 1989; Jefferson et al., 2008; McAlpine, 2009). Rare sightings indicate they may avoid human activity, and they are rarely active at the sea surface.

Generally, the sound levels necessary for animals to experience PTS are much higher than the behavioral response thresholds reported in the literature. Therefore, it is expected that animals would avoid repeated exposures and reduce cumulative sound energy exposure necessary to induce PTS. During the first few pings of a training or testing event, or after a pause in sonar activities, if animals are caught unaware and it was not possible to implement mitigation measures (e.g., animals are at depth and not visible at the surface) it is possible they could receive enough acoustic energy to suffer PTS. Based on nominal marine mammal and sea turtle swim speeds (i.e., 3 knots) and normal operating parameters for Navy vessels (i.e., 10–15 knots), it was determined that an animal can easily avoid PTS zones within the timeframe it takes an active sound source to generate one to two pings from a moving vessel-based source.

Animals present beyond the range to onset PTS for the first three to four pings are assumed to avoid any additional exposures at levels that could cause PTS. This equates to approximately 5 percent of the total pings or 5 percent of the overall time active; therefore, 95 percent of marine mammals predicted to experience PTS due to sonar and other transducers are instead assumed to experience TTS. Although some of the predicted impacts are re-categorized, the overall number of animals predicted to be affected is unchanged.

8. RANGE TO EFFECTS

8.1. NAEMO Impulsive Modeling Comparison with Experimental Data

The NAEMO Phase III explosive modeling process has been compared to experimental data collected in the Virginia Capes Range Complex and at the Silver Strand Training Complex areas. Additional experimental data have recently been collected at the Pu'uloa range site but has not been compared to NAEMO data. However, in all of the available experimental datasets, the explosive charge sizes (less than 24 lb. net explosive weight) used for these experiments are at the lower end of the spectrum of charge sizes being modeled in Phase III. Furthermore, the water depths and measurement distances (less than 10 m of water depth and a maximum of 1,700 m from the source) are relatively small compared to the Phase III predicted range to effects distances of interest. Nonetheless, the comparisons made between the experimental data and NAEMO model data showed good correlation of peak pressures indicating that the NAMEO impulsive modeling process is in agreement with experimental data for the limited datasets used for the comparisons. To fully conduct a validation of the NAEMO impulsive modeling process would require additional datasets for several of the larger charge sizes in multiple environmental conditions and at distances similar to the predicted range to effects distances.

8.2. Limitations with Using Similitude Equation

A theoretical representation of the impulsive source signatures defined by the similitude equation is used in NAEMO as input into the explosive modeling process. This approach was selected due the limited datasets available for the wide range of explosive charge sizes being modeled in Phase III. As with any theoretical representation, there are limitations and assumptions that need to be considered. One of the limitations identified by Swisdak (1978) is the range in pressure over which the similitude equation is valid. For explosives represented in net explosive weight of TNT, the valid range reported is from 3.4-to-138 MPa. Converting this into charge size produces a maximum net explosive weight of TNT of 28.8 lb., which is equivalent to Phase III impulsive bin E5. Charge sizes above this weight would then fall outside of the pressure range for which this equation is valid. Unfortunately, the reference for the pressure range is from unpublished data which makes it impossible to review. To provide confidence in the use of the similitude equation, both within the pressure range and above the stated maximum validity range, a series of analysis runs were conducted using the NAEMO modeling process. For each analysis the peak pressure was computed at various radial distances from the source location and compared to the theoretical value based on similitude. The comparison showed good agreement between the NAMEO model and the similitude equation peak pressures at each of the distances reviewed. Based on this evaluation, the use of the similitude equation to represent impulsive source signatures was determined to be acceptable for the purposes of the NAEMO simulations.

The similitude equation is based on a closed form approximation of the explosive shockwave that is produced during underwater detonations. The basic form of the equation only produces positive pressures which violates conservation of mass/energy laws. Further research done by the originator of the method has yielded a closed form approximation that can match both peak overpressure and also give under-pressure to restore balance to the system. The new modified similitude equation developed by Friedlander (1946) was subsequently used for the NAEMO model.

The effect on propagation due to changing from similitude to a Friedlander source signature was examined at two locations (shallow and deep) for a near surface 1,000 lb. net explosive weight charge. Generally, there is excellent agreement for both locations with respect to peak SPL and unweighted SEL. The vast majority of peak SPL is within 3 dB and SEL is within 2 dB. A harbor porpoise calf (5 lb.) was used to compare impulse. Comparisons in $\log_{10}(\mathrm{I})$ space show at most a factor of 101.5 (≈ 32) increase in the impulse. However, these differences are usually beyond the range at which 1% slight lung injury occurs. Within the range of effects of concern the change to the impulse is minimal.

8.3. Surface Effects for Near Surface Detonations

The impulsive modeling approach used in NAEMO cannot account for the highly non-linear effects of cavitation and surface blowoff that would exist in the real world. To approximate these effects a series of analyses were conducted with the charge depths defined at varying distances from the free surface. The results of these simulations were compared to modeling using the Reflection and REFMS. Based on these comparisons a depth of 0.1 m was chosen as the representative depth for near surface detonations.

8.4. Ray Trace Model Limitations

The NAEMO impulsive modeling process utilizes the Navy's CASS/GRAB model as developed by Weinberg and Keenan (1996). CASS/GRAB is the Navy's standard ray trace model for computing the propagation of sound in an underwater environment. As with any computational model there are inherent limitations on how and where the model should be used. One of these limitations is the frequency of the source being modeled compared to the overall water depths at the location of interest. In general, the wavelength of the source should be small compared to the water depth, bathymetric features, and any internal features such as ducts (Janson et al., 2010). The approach used in NAEMO to model broadband impulsive sources is to break up the signature into 1/3 octave bins and model each bin separately and then combine the outputs from each bin to produce the overall effects of the impulsive source. In creating these bins some of them will be centered at low-frequencies which can have relatively large wavelengths compared to some of the environments being modeled for underwater detonations. Under some conditions the wave lengths may be too large in comparison to the water depth. However, due to the small number of potential locations where this may occur and the initial comparisons made to the shallow water data, it was determined that there would be minimal impacts on the estimated effects and take numbers produced by NAEMO's modeling process.

9. RANGE TO EFFECTS FOR MARINE MAMMALS AND REPTILES

9.1. Impact Ranges for Sonar and Other Transducers

Ranges to PTS thresholds were examined for an exposure of 30 seconds since that was estimated to be the maximum amount of time a marine mammal would realistically be exposed to levels that could cause the onset of PTS based on platform (e.g., ship) speed and a nominal animal swim speed of approximately 1.5 m per second. Since any hull-mounted sonar, such as the SQS-53, engaged in anti-submarine warfare training would be moving at between 10–15 knots and nominally pinging every 50 seconds, the vessel will have traveled a minimum distance of approximately 257 m during the time between those pings (note: 10 knots is the speed used in NAEMO). As a result, there is little overlap of PTS footprints from successive pings, indicating that in most cases, an animal predicted to receive PTS would do so from a single exposure (i.e., ping). For all other bins (besides MF1), PTS ranges are short enough that marine mammals (with a nominal swim speed of approximately 1.5 m per second) should be able to avoid higher sound levels capable of causing onset PTS within this 30-second period.

For all other functional hearing groups (low-frequency cetaceans, mid-frequency cetaceans, and phocid seals and sirenia), 30-second average PTS zones are substantially shorter. A scenario could occur where an animal does not leave the vicinity of a ship or travels a course parallel to the ship; however, the close distances required make PTS exposure unlikely. For a Navy vessel moving at a nominal 10 knots, it is unlikely a marine mammal could maintain the speed to parallel the ship and receive adequate energy over successive pings to suffer PTS. Due to the lower acoustic thresholds for TTS versus PTS, ranges to TTS are longer. Therefore, successive pings can be expected to add together, further increasing the range to onset-TTS.

Marine mammal and sea turtle range to effects results for sonar and other transducers are included in their respective sections in each EIS/OEIS for all of the Navy's Phase III Study Areas.

9.2. Impact Ranges for Explosives

Ranges for explosives were determined by modeling the distance that noise from an explosion would need to propagate to reach exposure level thresholds specific to a hearing group that would cause behavioral response, TTS, PTS, and non-auditory injury as described in the technical report titled *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)* (U.S. Department of the Navy, 2017c). Range to effects is important information in not only predicting impacts from explosives, but also in verifying the accuracy of model results against real-world situations and determining adequate mitigation ranges to avoid higher level effects, especially physiological effects to marine mammals.

Modeled ranges for non-auditory injury considered varying propagation conditions, animal mass, and explosive bin (i.e. net explosive weight). For representative animal masses and explosive bins, the larger of the range to slight lung injury or gastrointestinal tract injury was used as a conservative estimate. Animals within water volumes encompassing the estimated range to non-auditory injury would be expected to receive minor injuries at the outer ranges, increasing to more substantial injuries, and finally mortality as an animal approaches the detonation point.

Ranges to the onset of auditory and behavioral effects are provided for a representative source depth and cluster size for each bin. For events with multiple explosions, sound from successive explosions can be expected to accumulate and increase the range to the onset of an impact based on SEL thresholds. Modeled ranges to TTS and PTS based on peak pressure for a single explosion generally exceed the modeled ranges based on SEL even when accumulated for multiple explosions. Peak pressure based ranges are estimated using the best available science; however, data on peak pressure at far distances from explosions are very limited.

Marine mammal and sea turtle range to effects results for explosives are included in their respective sections in each EIS/OEIS for all of the Navy's Phase III Study Areas.

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