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

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14. ABSTRACT

In the Navy's Phase IV environmental compliance planning, the potential effects on marine mammals and sea turtles from at-sea training and testing conducted by the U.S. Navy and U.S. Coast Guard are quantified and reported. Analysis of the potential effects of underwater sound sources—impulsive and non-impulsive—and research on various methodologies has produced a refinement of the Navy's standard model for assessing the effects of underwater sound on marine mammals and sea turtles—the Navy Acoustic Effects MOdel (NAEMO). NAEMO is used to assess the level of behavioral disturbance and physiological effects—e.g., temporary threshold shift and auditory injury due to the emission of sounds and impulses—predicted for individual virtual marine mammals and turtles that are likely to be in the vicinity of at-sea training and testing activities. Estimated effects are analyzed for each marine mammal and sea turtle species and/or stocks present in the area to inform the assessment of potential impacts. The NAEMO output shows the types of effects predicted for each training and testing event by area, season, species, and stock. Effects from pile driving are not currently modeled in NAEMO, but the quantitative methods used to estimate impacts due to pile driving are described.

15. SUBJECT TERMS

acoustic impacts, fishes, impulsive sources, pile driving acoustic effects, marine mammals, Navy Acoustic Effects MOdel (NAEMO), Navy training and testing, range-to-effect quantitative analysis, sea turtles, sonar, U.S. Coast Guard training and testing

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LIST OF ABBREVIATIONS AND ACRONYMS

3S2	Sea Mammals and Sonar Safety
Action Proponents	U.S. Department of the Navy and the U.S. Coast Guard
AFTT	Atlantic fleet training and testing
AG	airgun
AINJ	auditory injury
ANSI	American National Standards Institute
AUTEC	Atlantic Undersea Test and Evaluation Center
BAART	Bioacoustic Analysis and Applied Research Team (NIWC)
BB	broadband
BRF	behavioral response function
BST	Bottom Sediment Type (database)
CASS	Comprehensive Acoustic Simulation System
CASS/GRAB	Comprehensive Acoustic Simulation System/Gaussian Ray Bundle
CDC	continuous duty cycle
dB	decibel
DC	duty cycle
E0–E17	explosive bin number
EIS	environmental impact statement
F	frequency
FFT	fast Fourier transform
GEBCO	General Bathymetric Chart of the Oceans
GI	gastrointestinal
GIS	Geographic Information System
GRAB	Gaussian Ray Bundle
HCTT	Hawaii-California training and testing
HDC	high duty cycle
HF	high-frequency
HFBL	High-Frequency Bottom Loss (database)
HFEVA	High-Frequency Environmental Acoustics (database)
HYCOM	Navy Hybrid Coordinate Ocean Model
Hz	Hertz
IFFT	inverse fast Fourier transform
LDC	low duty cycle
LF	low-frequency
LFBL	Low-Frequency Bottom Loss (database)
LOA	letter of authorization
MB	medium band
MDC1–6	medium duty cycles 1–6
MEM	military expended materials
MEPP	Mission Environmental Planning Program
MF	mid-frequency
MSMT	Marine Species Modeling Team
NAEMO	Navy Acoustic Effects MOdel
NB	narrowband
NOAA	National Oceanic and Atmospheric Administration

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

nbr	number
NEPM	non-explosive practice munitions
NEW	net equivalent weight
NIWC	Naval Information Warfare Center
NM	nautical miles
NMFS	National Marine Fisheries Service
NMSDD	Navy Marine Species Density Database
NUWC	Naval Undersea Warfare Center
NWIC	Naval Information Warfare Center
OCW	otariids and other non-phocid marine carnivores in water
OD	omnidirectional
OEIS	overseas environmental impact statement
OPAREA	operating area
$p_{brf}(0.5)$	0.50 point on the behavioral response function
$p_{brf}(0.9)$	0.90 point on the behavioral response function
PCW	phocid carnivores in water
PMRF	Pacific Missile Range Facility
PTS	permanent threshold shift
RAM	Range-Dependent Acoustic Model
REFMS	Reflection and Refraction in Multilayered Ocean/Ocean Bottoms with Shear Wave Effects
RL	received level
rms	root-mean-square
SEL	sound exposure level
SL	source level
SMGC	Surface Marine Gridded Climatology (database)
SOCAL-BRS	Southern California Behavioral Response Study
SPL	sound pressure level
SPL_{peak}	peak sound pressure level
SPL_{rms}	root-mean-square sound pressure level
SS	non-explosive impulsive source other than airgun
TL	transmission loss
TNT	trinitrotoluene
TR	technical report
TTS	temporary threshold shift
U.S.	United States
UDC	ultra-low duty cycle
VACAPES	Virginia Capes
VDC	very-high duty cycle
VHF	very-high-frequency
VLF	very-low-frequency
WB	wide band
ZOI	zone of influence
μPa	micropascal

1. INTRODUCTION

The United States (U.S.) Department of the Navy and the U.S. Coast Guard (hereinafter jointly referred to as the Action Proponents) are required to assess the potential impacts of Action Proponent-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 (MMPA), and the Endangered Species Act (ESA). This report applies to all of the Phase IV 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 at-sea training and testing conducted by the Action Proponents. Phase IV is the fourth phase of the Navy's environmental compliance planning, covering similar types of training and testing activities analyzed in Phase III.

The Navy has invested considerable effort and resources in analyzing the potential impacts of underwater sound sources (e.g., impulsive and non-impulsive). Research on various methodologies and collaboration with subject matter experts has led to a refinement by the Navy of a standard model for assessing the impacts of underwater sound on marine mammals and sea turtles—the Navy Acoustic Effects MOdel (NAEMO).

NAEMO is used to assess the level of behavioral disturbance and physiological impacts—e.g., temporary threshold shift (TTS) and auditory injury (AINJ) due to the emission of sounds and impulses—predicted for individual marine mammals and turtles that are likely to be in the vicinity of training and testing activities conducted by the Action Proponents. Estimated effects are analyzed for each marine mammal and sea turtle species and/or stocks present in the area to assess potential impacts.

The NAEMO output shows the types of impacts estimated for each training and testing event by area, season, species, and stock.

Impacts from pile driving cannot currently be modeled in NAEMO. The quantitative methods used to estimate impacts due to pile driving are described in this report.

Four technical reports (TRs) that provide details on the quantitative process and show specific data inputs to the models are listed below:

- "Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase IV)" (U.S. Department of the Navy 2024a) describes the development of criteria and thresholds used to estimate impacts and is referred to herein as the criteria and thresholds TR.

- "U.S. Navy Marine Species Density Database Phase IV for the Hawaii-California Training and Testing Study Area" (U.S. Department of the Navy 2024c) and "U.S. Navy Marine Species Density Database Phase IV for the Atlantic Fleet Training and Testing Study Area" (U.S. Department of the Navy, in press) describe the spatial density models for each species or stock in these study areas and are referred to herein as the density TRs. The densities were updated with new data for each modeling effort, and figures in each density report show the change in spatial density for each species since the prior analysis (U.S. Department of the Navy 2017a, 2017b). Any substantial changes affecting the quantified impacts in this analysis are discussed for each stock in this report.

- "Dive Distribution and Group Size Parameters for Marine Species Occurring in the U.S. Navy's Atlantic and Hawaii-California Training and Testing Study Areas" (U.S. Department of the Navy 2024b) describes the dive profile and other behavioral characteristics of each species and is referred to herein as the dive profile TR.

2. NAVY ACOUSTIC EFFECTS MODEL (NAEMO) OVERVIEW

NAEMO is developed and managed by the Marine Species Modeling Team (MSMT) at the Naval Undersea Warfare Center (NUWC), Division Newport, RI. In addition to being the Navy's standard model for assessing acoustic effects on marine mammals and sea turtles, NAEMO serves as a data entry point for activity information and as a repository for modeling results. NAEMO is also the primary database for military expended materials (MEM) and stressor tracking. NAEMO consists of modules accessed via a graphical user interface. Training and testing activities are defined in NAEMO as scenarios with specific platforms, sources, targets, devices, and MEM. Scenarios are further refined into events that account for the locations where the scenarios occur and how often they occur. Section 3 describes the data inputs to NAEMO, and Section 4 describes the implementation of and outputs from each of the NAEMO modules. Section 2.1 describes the major changes or shifts from Phase III to the current phase, Phase IV, reported herein.

2.1 IMPROVEMENTS FROM PHASE III TO PHASE IV

- Density estimates have been updated as described in the density TRs for each study area (U.S. Department of the Navy 2024c, in press).

- Environmental data has been updated to reflect the best available science. Information on the resources that provide this data is given in Section 3.1.

- The acoustic source binning process has been updated to more accurately group similar sources and use the parameters of the bin for propagation. Some sources are modeled at slightly different propagation parameters than in Phase III. The updated binning process is described in detail in Section 3.7.

- Non-impulsive broadband sources were defined as any source with a frequency range spanning more than two octaves. These sources were binned into broadband source bins (Section 3.7.2) and broken out into sub-bins at every octave within the frequency range. Each sub-bin was propagated and simulated separately, more accurately capturing the frequency spectrum associated with these sources. In Phase III, broadband sources were modeled at a single frequency—the geometric mean of the low and high range—which did not provide as comprehensive a representation of the frequency profile. Details on the non-impulsive broadband source bins can be found in Section 3.7.2.

- An animal avoidance process was developed and integrated into the Animat Processor (Section 4.4) in NAEMO. This process reduces the sound exposure level (SEL), defined as the accumulation for a given animat (i.e., a virtual animal), by reducing the received sound pressure levels (SPL) of individual exposures based on a spherical spreading calculation from sources on each unique platform in an event. The onset of avoidance was based on the behavioral response functions. Avoidance speeds and durations were informed by a review of available exposure and baseline data. In prior phases, avoidance was not modeled in NAEMO. Instead, 95% of the permanent threshold shift (PTS), now referred to as AINJ, predicted by NAEMO was assumed to be reduced to the TTS due to avoidance (Blackstock et al. 2017). This reduction was based on avoiding the AINJ zone of a moving MF1 source (i.e., a hull-mounted surface ship sonar as defined in NAEMO). The avoidance process in Phase IV is described in detail in Section 4.4.2.2.
- The similitude equation used for impulsive modeling has been updated to reflect the most current version applicable to underwater explosions. This update is described in Section 4.1.3.

3. NAEMO DATA INPUTS

The Navy uses specific information about environmental conditions, the best available marine mammal and sea turtle data, and the projected activities within each study area to run NAEMO and quantify the potential effects on marine mammals and sea turtles. Environmental data includes information about bathymetry, seafloor composition (e.g., rock or sand) and factors that vary throughout the year, such as surface wind speeds and oceanographic properties. Marine mammal and sea turtle data includes densities, group sizes, dive profiles, and criteria for behavioral and physiological responses to sound. Finally, the details of training and testing activities planned by the Action Proponents are collected, including location, rate of occurrence, and platforms and sources involved.

3.1 PHYSICAL ENVIRONMENT DATA

The physical environment data described herein plays an important role in the acoustic propagation used in the modeling process. Since accurate in-situ measurements cannot be used to model activities that will 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 are part of the Oceanographic and Atmospheric Master Library (OAML). See Table 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 1. To capture environmental variability, NAEMO extracts information from these databases along radials extending out from each source location.

Table 1. OAML environment data

Parameter	Database
Bathymetry	Digital Bathymetric Database Variable-Resolution (DBDB-V), Version 7.7 (Level 0)
	General Bathymetric Chart of the Oceans (GEBCO)
Coastline	Derived from bathymetry data
Seafloor composition	Re-Packed Bottom Sediment Type (BST), Version 2.0 (includes High-Frequency Environmental Acoustics (HFEVA), Version 1.0)
	Low-Frequency Bottom Loss (LFBL), Versions 12.1 and 12.2*
	High-Frequency Bottom Loss (HFBL), Version 3.0*
Wind speed	Surface Marine Gridded Climatology (SMGC), Version 2.0
Oceanography	Navy Hybrid Coordinate Ocean Model (HYCOM), Version 3.1

*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.

3.1.1 Bathymetry

The bathymetry is obtained at the highest resolution available, ranging from 0.05 to 2.0 arcminutes. The bathymetry is also used to generate the coastline, as well as small geographic features such as breakwaters. DBDB-V is the preferred bathymetric data source within NAEMO, but GEBCO is used when the resolution or range is insufficient for modeling.

3.1.2 Seafloor Acoustic Properties

For each modeled area, the bottom type and the associated geo-acoustic parameters are extracted in accordance with the guidelines specified in Table 2. These data are extracted at the highest available resolution, ranging from 0.1 to 5.0 arcminutes.

Table 2. Bottom type and geo-acoustic parameter extraction guidelines

Frequency (f)	Database
$f < 1$ kHz	LFBL*
$1 \text{ kHz} \leq f \leq 10$ kHz	HFBL[†]
$f \geq 10$ kHz	Bottom Sediment Type (BST)

*LFBL: Low-Frequency Bottom Loss
[†]HFBL: High-Frequency Bottom Loss

3.1.3 Wind Speed

All wind speed data are extracted once per season from the SMGC data at the highest available resolution of 1°. Wind speed is directly related to the roughness of the sea surface, which controls the reflection and scattering angles of acoustic rays interacting with the ocean surface.

3.1.4 Oceanography

Navy HYCOM data consists of temperature, salinity, and depth. For each timeframe, this data is extracted at the highest resolution—0.08 arc-degrees—over the extent of the modeled area.

3.2 MARINE MAMMAL AND SEA TURTLE DATA

Density estimates, group sizes, and stock estimates are all utilized for distribution of marine mammals and sea turtles throughout the study area. In NAEMO, marine species are represented by "animats," which are artificial or virtual animals used during modeling (Dean 1998). Marine species densities are needed to estimate the number of animals of each species that may be present within a specific area and timeframe. Details on the density data used for the Phase IV analyses are provided in the density TR for each study area (U.S. Department of the Navy 2024c, in press). The density data used in NAEMO comes from the Navy Marine Species Density Database (NMSDD). An NMSDD report is prepared for each study area. These reports are available online at https://www.nepa.navy.mil/fleetprojects/. Marine mammals and sea turtles are typically categorized by species in the NMSDD. Many marine mammal species are divided into stocks based on life history and genetic structure for management purposes. Marine mammal stock proportions within the species densities are provided by the Mission Environmental Planning Program (MEPP) of NUWC Division Newport. Distributions are created for stocks when available and are otherwise modeled at the species level.

3.2.1 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 by accounting for statistical uncertainty around the group size estimate. Group sizes are handled differently in each study area, based on data availability and the recommendations of the research groups that provide the density information. The typical group sizes of each species are delivered by the research groups that provide the density data, which can be found in the density TR for each study area (U.S. Department of the Navy 2024c, in press).

3.2.2 Dive Profiles

NAEMO accounts for depth distributions by changing the depth of each animat during the simulation process according to the typical depth pattern observed for each species. This information is presented as a percentage of time that the animal typically spends at each depth in the water column. The dive profiles for each species are shown in the dive profile TR for each study area (U.S. Department of the Navy 2024b).

3.2.3 Avoidance Factors

NAEMO does not simulate horizontal animat movement during an event. However, NAEMO approximates marine mammal avoidance of high sound levels due to exposure to sonars in a one-dimensional calculation that scales how far an animat would be from a sound source based on sensitivity to disturbance, swim speed, and avoidance duration. These avoidance factors are provided in the avoidance process outlined in Section 4.4.2.2.

3.2.4 Criteria and Thresholds for Assessing Impacts

Criteria and thresholds for assessing the impact of acoustic stressors and explosives on marine mammals and sea turtles were updated as described in the criteria and thresholds TR (U.S. Department of the Navy 2024a). While the metrics to assess auditory, physiological, and behavioral impacts are unchanged, the thresholds for effect have been revised based on updated science.

3.3 TIMEFRAME DEFINITIONS

The majority of training and testing activities are not limited to a specific month of a season. Therefore, most of the scenarios are modeled for year-round activity. A seasonal approach was adopted to meet this requirement, given the impracticality of modeling each scenario for every month. The timeframe definitions in Phase IV are the same as employed in Phase III; these definitions (see Table 3) are dictated by region and the presence of marine mammals and sea turtles as determined by the density TR for each study area (U.S. Department of the Navy 2024b, in press). Seasons are defined by the available density data and the minimum number of timeframes that characterize the species distribution over 1 year. The number of timeframe designations could vary based on the detail of the available data. For the Atlantic Ocean, the timeframe designations are designated by the traditional four seasons; for the Pacific and Arctic Oceans the seasons are designated as warm and cold.

Table 3. Modeling timeframes

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

3.4 TRAINING AND TESTING ACTIVITIES

NAEMO uses a hierarchy to group Action Proponent training and testing activities for analysis. The broadest category includes the primary mission areas (air warfare, amphibious warfare, etc.). The activities that fall within these categories are further refined in NAEMO as “scenarios” that include data such as the number of platforms, types and numbers of impulsive and non-impulsive sources, and source durations. Scenarios are then further defined as “events,” which include details on location and frequency of occurrence. Additional information on how scenarios and event definitions are implemented in NAEMO is provided in the subsequent sections.

3.5 LOCATIONS AND MODELING AREAS

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

3.6 SOURCES

Acoustic sources are divided into two categories—impulsive and non-impulsive. Impulsive sounds feature a rapid increase to high pressures, followed by a rapid return to static pressures. Impulsive sounds are often produced by processes involving a rapid release of energy or mechanical impacts (Hamernik and Hsueh 1991). Explosions and airgun impulses are examples of impulsive sound sources. Non-impulsive 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.

3.6.1 Non-impulsive Sources

Non-impulsive sources are sonars and other transducers. This category includes the following types of devices: submarine sonars, surface ship sonars, helicopter dipping sonars, torpedo sonars, active sonobuoys, acoustic countermeasures, mine hunting sonars, navigation sonars, underwater communications, tracking pingers, and unmanned underwater vehicles and their associated sonars. Qualitative descriptions can be found in the EIS/OEIS for each study area (U.S. Department of the Navy, n.d.-a, n.d.-b).

Non-impulsive sources are considered broadband in NAEMO if the bandwidth spans more than two octaves. These sources are modeled at one-octave frequency steps from the minimum to the maximum defined frequency (see Section 3.7.2 for more details). Non-impulsive narrowband sources are modeled using the geometric mean frequency.

The following terms are used for the data collected on non-impulsive sources:

1. <u>Source level</u>: The sound level of a source at a nominal distance of 1 meter, expressed in decibels (dB) referenced to 1 micropascal (dB re 1 μPa) for underwater sources.

2. <u>Frequency range</u>: The minimum and maximum frequencies used in operation.

3. <u>Source directivity</u>: The source beam is modeled as a function of horizontal and vertical beam patterns.

    a. The horizontal beam pattern is defined by two parameters:

        i. <u>Horizontal beamwidth</u>: 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 steering directions).

        ii. <u>Relative beam angle</u>: 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 is 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 steering directions).

   ii. Depth/elevation angle: The vertical orientation angle relative to the horizontal.

4. Pulse interval: The time in seconds between the start of consecutive pulses for a non-impulsive source.

5. Pulse length: The duration of a single non-impulsive pulse, specified in milliseconds. The duty cycle (expressed as a percentage) is defined as $100 \times (\text{ping interval}/\text{pulse length})$, where the pulse length is expressed in seconds for purposes of the calculation.

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 bin within which it occurs. Source bins are discussed in Section 3.7.

3.6.2 Impulsive Sources

Impulsive sources are generally broadband. A pressure time series (the source signature) represents the source at the activation location, and the spectrum of the source signature determines the contribution of each frequency in the bandwidth. For explosive sources, the source signature is calculated with the similitude equation (Swisdak 1978) at a distance of 1 meter. For airguns and other non-explosive impulsive sources, the source signature is provided by operators of the source. The steep pressure rise that characterizes impulsive sources and their potential for structural injury are the reason these sources are evaluated differently from non-impulsive ones. Impulsive sources are further classified into explosive and non-explosive sources.

The following terms are used for the data collected on impulsive sources:

1. Source depth: The depth at which the impulsive source activates.

2. Net explosive weight: For explosive sources, the trinitrotoluene (TNT) equivalent weight (in kg) of explosive material in the source.

3. Source signature: The pressure time series of the source at a nominal distance of 1 meter. The explosive signatures are taken from the similitude equations based on net explosive weight, whereas the non-explosive signatures are taken from real-world data.

4. Cluster size: The number of emissions (e.g., 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, explosive torpedoes, underwater demolition explosives, ship shock trial charges, impulsive sonobuoys, and littoral warfare line charges. Non-explosive impulsive sources include airguns and compact sound sources. Qualitative descriptions of impulsive sources can be found in the EIS/OEIS (U.S. Department of the Navy, n.d.-a, n.d.-b).

3.7 SOURCE BINS

Hundreds of common Navy sources were compiled into the NAEMO database. These include explosive and non-explosive impulsive sources as well as non-impulsive sources (sonars and other transducers). NAEMO does not model sources based on their specific parameters. Instead, sources are categorized into “bins” that have representative characteristics used for propagation modeling.

The use of source bins provides the following benefits:

- Provides the ability for new sensors or munitions to be covered under existing authorizations, as long as those sources fall within the parameters of an authorized 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 MMPA authorizations
- Favors a conservative approach for propagation, since sources within a given bin are modeled at the highest source level, longest duty cycle, or largest net explosive weight within that bin
- Provides a framework to support the reallocation of source usage (hours/counts) between different source bins, as long as the total number of effects remain within the overall analyzed and authorized limits. This flexibility is required to support evolving training and testing requirements, which are linked to real-world events.

3.7.1 Non-impulsive Narrowband Source Bins

Non-impulsive sources that operate within a range of frequencies of less than two octaves are treated as narrowband sources. In previous analyses, these sources were grouped into bins that were defined by their acoustic properties or, in some cases, their purpose or application. For Phase IV analyses, binning by purpose or application is abandoned, and sources are binned based only on their fundamental acoustic properties, such as frequency, source level, beam pattern, and duty cycle.

Bins are created from the unique combinations of these four acoustic properties, each of which is segmented into distinct categories. For each acoustic property, the categories span the entire range of the corresponding acoustic parameters so that all existing and future Action Proponents’ sources are covered. There are 9 categories for the frequency (F), 8 categories for the source level (SL), 11 categories for the duty cycle (DC), and 4 categories for the beam pattern. The categories for the SL, DC, and beam pattern properties are designed with no overlap. The frequency property includes a lower and upper boundary, and the maximum value in a frequency category is equal to the minimum value in the subsequent frequency category. A source that has a maximum frequency boundary that sits on the shared value between two bins will be assigned to the lower frequency bin, which allows a source to be objectively assigned to one bin. The full list of categories within the acoustic properties is given below:

- Frequency: F1–F9
- Source level: SL1–SL8
- Duty cycle: UDC, LDC, MDC1, MDC2, MDC3, MDC4, MDC5, MDC6, HDC, VDC, CDC
- Beam pattern: NB, MB, WB, OD

The bins are named based on combinations of the acoustic property divisions listed above, e.g., F1SL1-MDC1-OD. Sources are placed in bins based on how their acoustic properties align with the frequency, source level, duty cycle, and beam pattern divisions listed above in order to model the greatest potential effects. Each bin is modeled at the upper bound of the bin's source level, duty cycle, and beam pattern. The frequency property for a bin is modeled at the geometric mean of the lower and upper bound of the bin's frequency range. This can result in sources being modeled at a lower frequency than in previous phases, which is generally conservative because sound will typically propagate farther at lower frequencies. However, modeling at lower frequencies can sometimes result in less conservative estimates of effects if the lower frequency coincides with a less sensitive part of a species' audiogram. Refer to the criteria and thresholds TR (U.S. Department of the Navy 2024a) for more information on the species' audiograms and Sections 4.1.3 and 4.4.2.3 for details on how frequency weighting is applied in NAEMO.

Overall, there is appropriate resolution in the acoustic property divisions to ensure that bin parameters closely match those of the sources contained in them. The combination of the four acoustic property parameters described above allow for 3,168 potential unique bins. Although most of the Phase IV study areas use only sources that fall into a small number of these potential bins, the binning construct allows for easy addition of bins as required. For written reports such as the EIS/OEIS and the letter of authorization (LOA) request, non-impulsive narrowband bins are grouped by their frequency category (low, medium, high, or very high) and their source level category (low, medium, or high), which results in 12 source categories.

In many cases, sources that previously fell into one purpose-based bin now fall into multiple bins. Likewise, sources with similar acoustic parameters that were previously sorted into separate bins owing to different purposes now share a bin. As a result, the new bins do not represent a one-for-one replacement, which means that a crosswalk table between the old bins and new bins is not possible. An exception to the new naming convention was retention of "MF1" to represent the hull-mounted surface ship sonar that was previously in the MF1 bin. The retention of this name allowed clear comparisons to past analyses. The other exceptions to the bin rule are the addition of MF1 bins (i.e., MF1K, MF1C, and MF1S) as naming conventions for other hull-mounted surface ship sonar sources that are similar to MF1 but require their own bins.

3.7.2 Non-impulsive Broadband Source Bins

Non-impulsive sources that operate within a range of frequencies greater than two octaves are grouped into unique broadband bins that are separated into sub-bins with frequencies spaced at one-octave intervals. The number of sub-bins is defined by Equation (1).

$$N = \log_2 \frac{f_h}{f_l}, \tag{1}$$

where *N* is the number of sub-bins rounded down to the nearest integer, f_h is the high-frequency cutoff, and f_l is the low-frequency cutoff. Starting at the lowest frequency, sub-bins cover a full octave. The last bin may not be a full octave, depending on the value of f_h. The sound level of each sub-bin is defined by Equation (2).

$$SL_s = SL - 10\log_{10} N, \tag{2}$$

where SL_s is sub-bin sound level, and SL is the original source sound level. Each sub-bin is modeled at the geometric mean frequency of the sub-bin. The sub-bins are treated as separate sources on the same platform during the simulation stage and then combined into a single source during the animat processing stage (formerly known as postprocessing in Phase III).

Non-impulsive broadband source bins are designated as "BB" followed by a number (e.g., BB8). For written reports such as the EIS/OEIS and the LOA request, these broadband bins are only referred to by the frequency categories they span (e.g., low frequency (LF), mid-frequency (MF), LF-to-MF, etc.).

3.7.3 Impulsive Source Bins

Explosive impulsive sources are placed into bins based on the TNT net equivalent weights (NEW). To place a source in a bin, the NEW of the source is rounded up to the nearest bin NEW. The NEWs for the bins are defined in Table 4.

Each non-explosive impulsive source (e.g., airgun) is assigned its own unique bin. Airgun bins are designated "AG" followed by a number corresponding to the peak SPL pressure in dB (e.g., AG175). Non-explosive impulsive sources other than airguns, are considered "special source sources" and assigned to bins designated as "SS" followed by a number (e.g., SS2).

Table 4. Explosive bins and net equivalent weight of TNT

Bin	Net Equivalent Weight of TNT (lb)
E0	0.1
E1	0.25
E2	0.5
E3	2.5
E4	5.0
E5	10.0
E6	20.0
E7	60.0
E8	100.0
E9	250.0
E10	500.0
E11	675.0
E12	1,000.0
E13	1,500.0
E14	4,000.0
E15	7,500.0
E16	15,000.0
E17	60,000.0

3.7.4 De Minimis and Inactive Source Bins

Some sources were removed from quantitative analysis because they are not expected to result in effects on protected species and/or they are required for ship safety and navigation. Sources that are not expected to result in effects are categorized into a de minimis or inactive bin. These include sources that were considered de minimis in Phase III, sources with a very low source level, and sources having very high frequencies above the known hearing ranges of marine mammals and sea turtles. Sources that are characterized as de minimis or inactive are not modeled.

In Phase IV, there are five de minimis and inactive bins, named and defined as follows:

1. <u>De minimis</u>: Non-explosive sources that emit a sound or impulse but are considered to have a negligible effect
2. <u>E0</u>: De minimis impulsive sources with such a low energy that they are considered to have a negligible effect
3. <u>Passive</u>: Systems that do not emit sound
4. <u>NEPM</u>: Non-explosive practice munitions that have counterparts that are explosive
5. <u>Inert</u>: Objects that have no design or alternate design to cause them to explode or emit noise

Non-impulsive sources are considered de minimis if (1) the source was considered de minimis in Phase III, (2) the source is used for ship safety and navigation, (3) the geometric mean frequency of the source is greater than 200 kHz, or (4) the source level is less than 160 dB. Impulsive sources are considered de minimis if the source has a NEW of 0.1 lb or less; these sources are placed in the E0 bin. Additionally, there are several types of inactive sources used by the Action Proponents that do not emit an impulse or sound but are tracked through the model: passive, non-explosive practice munitions (NEPM), and inert.

3.8 MODELING EVENT INPUTS

3.8.1 Model Box Size

Each modeling scenario is connected to a modeling area (see Section 3.5) to create a modeling event. The platforms within the scenario are randomly distributed throughout the modeling area. The modeling areas can be quite large (e.g., range complexes and operation areas), and randomly spreading platforms throughout a modeling area could situate the platforms tens, if not hundreds, of nautical miles (NM) apart. Because platforms included in the same modeling event are intended to interact during the exercise, it would be inaccurate to model them without that proximity. NAEMO accounts for this by applying a model box size. The model box size creates a rectangular shape, in NM, that is randomly placed within the user-selected modeling area (e.g., OPAREA or range complex). All the platforms within the modeling event are randomly distributed within the model box for each iteration.

The activity in which the event is categorized has a default box size that is used unless modified by the user. Typical box sizes are 5x5, 15x15, 30x30, and 60x60 NM. A 0x0 size bypasses the model box creation so that NAEMO will distribute the platforms throughout the modeling area. 0x0 model boxes are often required for modeling in smaller, coastal areas. 0x0 model boxes are also used where depth or distance from shore restrictions (Sections 3.8.2 and 3.8.3, respectively) make it impossible to fit a rectangular box within the allowed modeling space.

3.8.2 Depth Restrictions

Certain naval exercises only occur in areas shallower or deeper than a prescribed depth. NAEMO considers these constraints for modeling and allows a minimum or a maximum depth to be input. If a depth restriction is used, the selected modeling area is trimmed based on the bathymetric contours of the minimum and/or maximum. The model box will be randomly placed within the updated modeling area created by the depth restriction.

3.8.3 Distance from Shore Restrictions

Some naval exercises are required to take place close to or far away from the shore. NAEMO accounts for such restrictions by providing a “distance from shore restriction” input. If selected, the modeling area is trimmed along a distance contour based on the study area coastline. Both a minimum and a maximum distance from shore restriction can be selected. The model box will be placed randomly in the updated modeling area created by the distance from shore restriction.

3.8.4 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 can participate in a given type of activity can vary depending on the type of training or testing.

For each iteration, the platforms selected in a modeled event will be placed randomly within the model box inside the modeling area at the start of the simulation. Their starting orientations and paths are also randomized for every iteration, and the platforms will move at the speeds and depths defined in the scenario. If a platform encounters a model box boundary as it moves within the area, it will reflect off the boundary at the same angle. Platforms will move around the model box for the duration of the modeling scenario.

3.8.5 Sources

Sources within the NAEMO database, as described in Section 3.6, can be added to platforms within a modeling scenario. Each source included has a defined count and cluster as defined in Section 3.6.2. Typically, clusters of more than one source are only associated with impulsive sources. For example, an explosive source with a count of two and a cluster of four will model four detonations simultaneously at two independent time steps. Sources with counts greater than one can apply a defined spacing that determines how much time will pass between the activation/detonation for each count. If undefined, each count will activate or detonate randomly within the modeling scenario duration.

Non-impulsive sources must be assigned a duration for the time that they will be active. During the active time, the source will be modeled based on the pulse interval and pulse length defined by the source bin. Impulsive sources are not assigned durations.

Each source added to a platform has an associated activation/detonation location. The possible activation/detonation locations are defined as follows:

- Underwater
- At surface
- Above surface (<30 feet)
- Low altitude (30–500 feet)
- Medium altitude (500–15,000 feet)
- High altitude (>15,000 feet)

The sources tagged as underwater, at surface, or above surface activation/detonation locations are considered for modeling. Sources that are at surface or above surface are modeled at a depth of 0.1 meter. Sources with an underwater activation/detonation location are modeled at the depth equal to the sum of the defined platform and source depths if the source is not launched. Launched sources are considered independent of the platform during simulation and are modeled at the defined source depth only. All sources are modeled using the propagation parameters of the source bin.

3.9 NON-MODELED EVENT INPUTS

Several inputs to scenarios/events modeled in NAEMO are available that do not affect modeling. Such inputs include targets, devices, and military expended material (MEM) that would be used in naval exercises in conjunction with or independent of the modeled sources. Although targets, devices, and MEM are not being used within the model, it is necessary to track data associated with these items to account for expended material or stressors that may have an environmental impact. `Percent used` is the percentage of naval exercises that the scenario/event represents in which an item is utilized, and `percent recovered` is the percentage of used items that are recovered.

3.9.1 Targets

Targets are items such as mine shapes, ship hulks, or surface floats that are often aimed at by operators during training and testing activities. Targets may be partially or completely recovered after use, and each target in the NAEMO database has a default `percent recovered`. Targets included in a scenario have a default `percent used` of 100%, though a target may actually only occasionally be used within the scenario. The default `percent recovered` and `percent used` can both be modified. These data do not impact the modeling but are considered in NAEMO in order to track the associated MEM and stressors. The number of targets expended is compiled and reported, as scaled by both the `percent used` and `percent recovered`, for each study area in the Phase IV modeling effort.

3.9.2 Devices

Devices are items such as lasers, radar, and electromagnetic emitters that are actively used during a naval exercise but do not produce sound themselves. Devices included in a scenario are assigned a `percent used` that is 100% by default. This value can be modified to reflect how often that device is included in the naval activity. Devices have no impact on modeling but are considered for their associated stressors. These stressors are compiled and reported for each study area in the Phase IV modeling effort.

3.9.3 Military Expended Materials (MEM)

The Action Proponents report the amount of material that is expended (i.e., left in the ocean) during training and testing exercises. The MEM can be associated with a platform, source, target, or device, but it can also be added to a scenario separately if it is not directly associated with one of these four. The NAEMO database is built with automatic associations between platforms, targets, sources, and devices and the MEM that is typical for them. When any platform, source, target, or device is added to a scenario, its MEM is automatically added as well. The MEM inherits the `percent used` from the feature it is associated with. For example, all of the MEM linked to a target that is used 50% of the time in a scenario will have `percent used` = 50% applied.

3.9.4 Stressors

The term "stressors" refers to a broad category of environmental hazards that may occur to marine animals during naval activity—such as physical disturbance, strike, entanglement, or ingestion—and are tracked in NAEMO. Platforms, sources, targets, devices, and MEM can be associated with stressors, and these links are built into the NAEMO database. Stressors cannot be added to a scenario directly, but they are automatically linked based on the components included.

4. NAEMO ANALYSIS

This section discusses the NAEMO acoustic analysis: the acoustic propagation, marine species distribution, simulation process, and output.

4.1 ACOUSTIC PROPAGATION

NAEMO generates acoustic propagation data within a given modeling location by using event definitions to extract source bin characteristics and environmental data. Propagation by source bin and depth are modeled at geographic coordinates, called "analysis points," which are strategically distributed throughout the study area to capture changes in physical environmental characteristics. Variations in those data, outlined in Section 3.1, can have significant impacts on sound propagation.

Bathymetry affects sound propagation in a variety of ways. Energy from acoustic rays interacting with the ocean subsurface is absorbed into the subsurface, scattered due to the roughness of the subsurface particles (e.g., large rocks or small grains of sand), and/or reflected at an angle depending on the slope of the bathymetry. Because these interactions are more common in shallow areas, the analysis point distribution near the coast is denser to capture any rapid changes in bathymetry.

Seafloor composition affects propagation calculations because it determines how much energy will be absorbed, scattered, and/or reflected. For example, a muddy bottom absorbs more energy than it reflects, and a rocky bottom reflects more energy than it absorbs. This impact on propagation is more prominent in waters on the continental shelf and the upper portion of the slope where sound is more likely to reach the bottom. This is especially true if the sound speed profile directs all propagation paths toward interaction with the bottom. The primary acoustic propagation paths in deep water rarely involve interaction with the bottom.

Surface interactions, such as scattering and reflection, are influenced by wind speeds that determine surface roughness. For example, wind in a downward refracting environment would not likely create a significant change in transmission loss because of the relatively short propagation ranges characterized by minimal surface interaction. However, propagation in shallow regions or during conditions that confines acoustic rays to the near surface (e.g., surface ducts) could be significantly impacted by wind speed.

Sound speed throughout the water column is calculated from temperature, salinity, and pressure with the Chen-Millero-Li sound speed equation (Chen and Millero 1977), which is the Navy standard for calculating oceanic sound speed in general conditions.

The spatial variability of the sound speed profiles is generally minimal within the modeling areas. The presence of a strong oceanographic eddy or 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 are modeled with two or four seasons, depending on the study area (Section 3.3).

Figure 1 shows an example of a sound speed profile. At depths shallower than approximately 1 km, the sound speed varies primarily with variations in temperature and salinity. At greater depths, changes in the sound speed are primarily due to the increase in pressure with depth.

For each analysis point, the Navy's standard propagation model—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 the simulation process. For impulsive sources, CASS/GRAB is used to calculate several sound metrics that are provided to the simulation process as input.

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

The CASS/GRAB model is used to determine the propagation characteristics for acoustic sources with frequencies greater than 100 Hertz (Hz). CASS was described in (Keenan and Gainey 2015) 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 OAML-certified model for active sonar analysis between 100 Hz and 500 kHz. NAEMO uses CASS/GRAB for frequencies as low as 25 Hz for impulsive modeling. Though it is not OAML approved for this frequency, Weinberg and Keenan (1996) showed that CASS/GRAB predicts the general trend of propagation loss well compared to other propagation loss models.

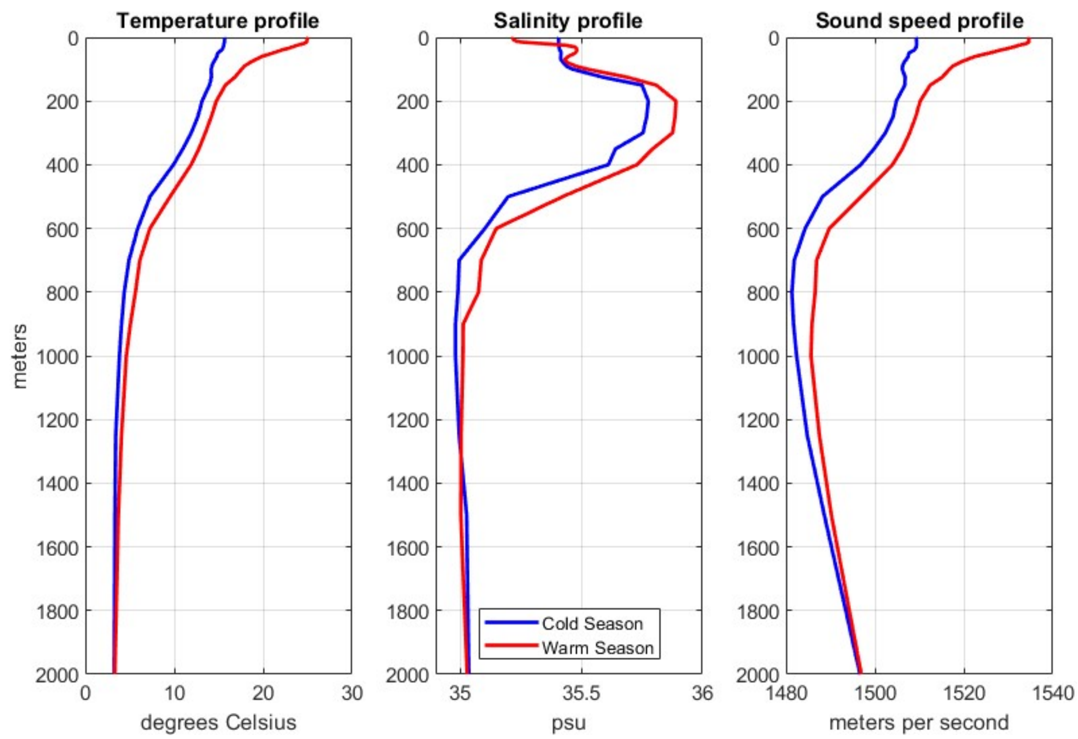


Figure 1. Examples of vertical profiles of temperature (left), salinity (middle), and sound speed (right) in the mid-latitude open ocean down to 2,000 meters from archived HYCOM data for cold (blue) and warm (red) seasons

4.1.1 Comprehensive Acoustic Simulation System/Gaussian Ray Bundle

To determine the received level at an animat, NAEMO analysis uses CASS in the passive propagation mode—that is, for one-way propagation—rather than in 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, refraction, 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.

The role of GRAB in the propagation model is to group eigenrays into families based on their surface/bottom bounce and vertex history (see Figure 2). 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 (i.e., the source angle, arrival angle, travel time, phase, and amplitude) are integrated 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 3 shows the representative eigenrays for the families shown in Figure 2. The total received energy at the receiving point (depth of 50 meters, range of 1.4 km) 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. Further, as with most other propagation models except finite-element-type models, CASS/GRAB does not accommodate diffraction or the propagation of sound around bends.

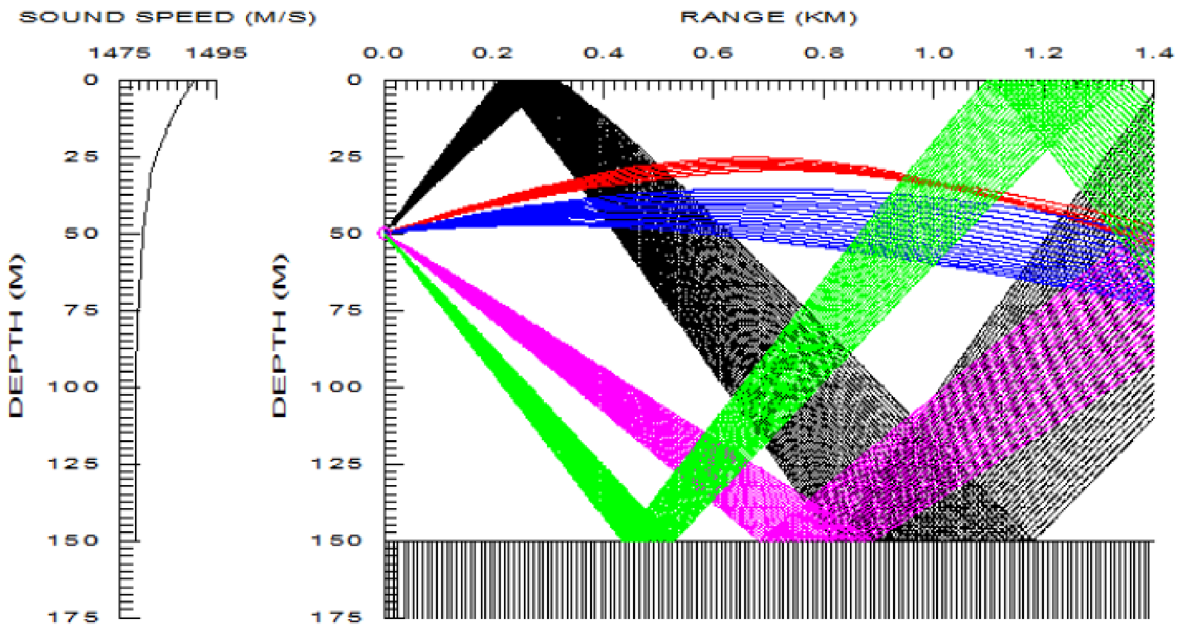


Figure 2. Colors represent distinct families of eigenrays identified by GRAB.

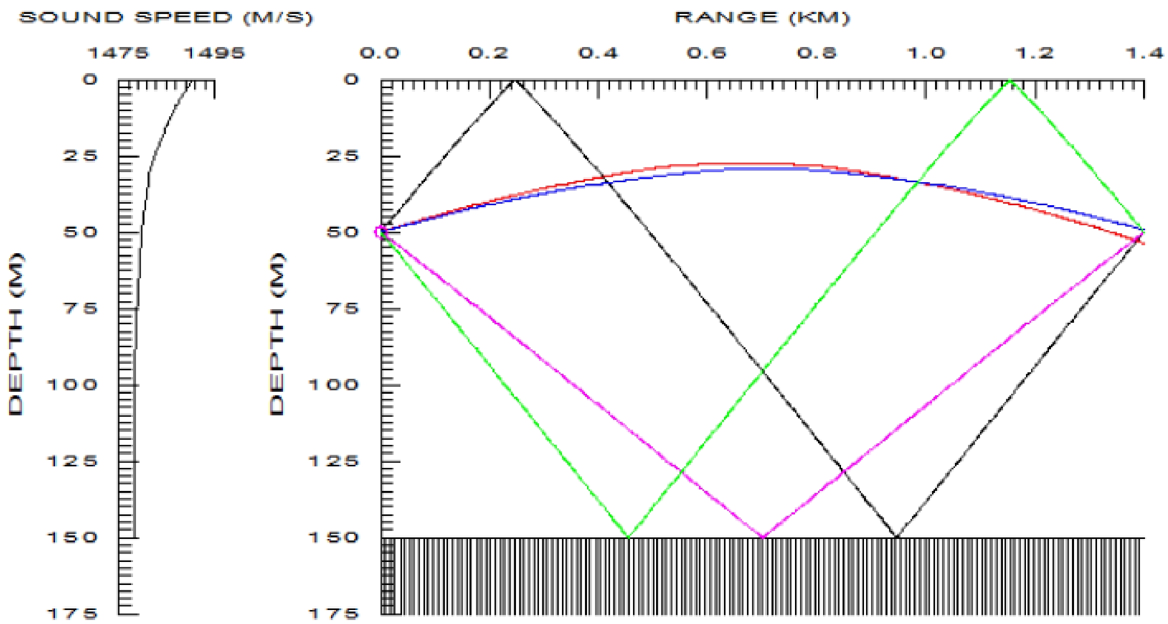


Figure 3. Representative eigenrays for the ray families in Figure 2

CASS/GRAB generates a table of depth range points with an associated received level per location and per source bin. For non-impulsive source bins, these received levels are used as input into the simulation process (Section 4.3), whereas further transformations are required for impulsive source bins, as described in Section 4.1.3.

CASS/GRAB is the most practical model to use for impulsive analysis. To evaluate some of the necessary metrics for explosives, a pressure time series is needed. The only other range-dependent models that can provide a pressure time series are so computationally intensive that the number of computations required renders them impractical.

4.1.2 Non-impulsive Propagation

NAEMO includes the following features for non-impulsive propagation:

- Acoustic analysis points are imported into NAEMO. The number of equally spaced radials (bearing angles) is specified for each analysis point. The number used (9, 18, 36, or 72) depends on how quickly the environmental parameters change; the number generally increases as analysis points are placed closer to shore.

- Environmental data is extracted along each radial originating from each analysis point out to 100 km. Bathymetry is extracted with the best resolution available, while the other environmental parameters are updated every 5 km along the radial.

- Bin information for the sources in the event is extracted: frequency, vertical beamwidth, pulse length, and source depth. Source level and duty cycle are not applied until the simulation step because they are independent of propagation loss.

- NAEMO produces a range-dependent transmission loss table for each radial based on each analysis point. The table is a function of receiver depth and range, which corresponds to the location of an animat relative to the source and applied in the Simulator (Section 4.3.2). The range and depth resolution is set by the NAEMO user.

4.1.2.1 Range-Dependent Acoustic Model (RAM)

The Range-Dependent Acoustic Model (RAM) propagation model is used for some non-impulsive modeling. Detailed descriptions of the RAM model and its governing equations can be found in (Collins 1993). RAM has been incorporated into the Navy Standard Parabolic Equation Model, version 6.0.1.

In NAEMO analysis, the RAM propagation model is used to determine the propagation characteristics for acoustic sources with frequencies of less than 100 Hz and at water depths of less than 50 meters. These selected values guarantee that at least one wavelength from the modeled bin frequencies of less than 100 Hz will fit within the 50-meter depth restriction.

4.1.3 Impulsive Propagation

The impulsive propagation method 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. The impulsive propagation method used in the Navy's current analysis described in this report is OAML approved. The impulsive propagation method produces five metrics to characterize the sound received by animats: (1) peak sound pressure level (SPL_{peak}), (2) root-mean-square (rms) sound pressure level (SPL_{rms}), (3) sound exposure level (SEL), (4) calf impulse, and (5) adult impulse. The sound pressure level is the logarithm of the ratio of sound pressure to a relative pressure (1 µPa). The peak sound pressure level is the maximum SPL over time. The SPL_{rms} is an average sound level—a metric applied only to modeling of airguns. The SEL represents both the SPL of a sound as well as its duration. The calf impulse and adult impulse metrics are the integrals of positive pressure over a brief period and a function of animat mass. These impulse metrics are applied only 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 modeled as an instantaneous phenomenon (Deavenport and 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 it with a similitude source signature (Deavenport and Gilchrest 2015). The transfer function is constructed as given by Equation (3).

$$H(t) = \Sigma_{n=1}^{N} A_n e^{i\omega\tau_n + \phi_n} \, , \tag{3}$$

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 pascals, τ_n is the arrival time of path n in seconds, and ϕ_n is the phase of path n in radians. 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 (typically 32,768 samples per second) and the longest arrival time. Additionally, it is approximated that the sound pressure levels, arrival times, and phases are identical within one-third-octave bins defined from 25–12,800 Hz for the typical sampling rate. 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 as defined in Table 2.

Explosive source signatures are modeled by similitude equations (Swisdak 1978) given by

$$S(t) \;=\; P_m\, e^{-\frac{t}{\theta}}\,, \tag{4}$$

where P_m is the amplitude of the initial shock wave in Pascals, θ is the time decay constant in seconds, and t is the time in seconds after the initial shock wave arrives. P_m and θ can be expressed by Equations (5) and (6) from (Swisdak 1978).

$$P_m = k_p \left(\frac{\sqrt[3]{W}}{r}\right)^{a_p}\,, \tag{5}$$

and

$$\theta = k_\theta \sqrt[3]{W} \left(\frac{\sqrt[3]{W}}{r}\right)^{a_\theta}\,, \tag{6}$$

where r is the distance from the source in meters, W is the net TNT equivalent weight in lb, and the coefficients k_p, k_θ, a_p, and a_θ are specific to a given explosive type. The signature is modeled at 1 meter from the source. The length of the source signature similitude signal is cut off at the time when the SPL time series is first below 100 dB. For non-explosive sources, the source signature $S(t)$ is not determined by an equation but by data provided by Navy operators. The final pressure time series $P(t)$ for explosive sources is determined by Equation (7).

$$P(t) = \mathrm{IFFT}\big(\mathrm{FFT}\big(H(t)\big) \cdot \mathrm{FFT}\big(S(t)\big) \cdot R^{-0.13}\big)\,, \tag{7}$$

where FFT is the fast Fourier transform (FFT, IFFT is the inverse fast Fourier transform, and R is the slant range (the three-dimensional distance between the source and receiver). The term $R^{-0.13}$ is a correction factor that accounts for the losses associated with energy dissipated at the shock front as well as the usual absorption losses associated with linear acoustics (Barash and Goertner 1967; Deavenport and Gilchrest 2015). Medwin and Clay (1977) attributed the similitude correction 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 airguns. For the SEL calculation, $P(t)$ is weighted by the auditory response function, which modifies the equation as shown in Equation (8).

$$P_w(t) = \mathrm{IFFT}\big(w(f) \cdot \mathrm{FFT}\big(H(t)\big) \cdot \mathrm{FFT}\big(S(t)\big) \cdot R^{-0.13}\big)\,, \tag{8}$$

where $w(f)$ is the auditory weighting function for each hearing group as a function of frequency, and the correction factor is applied only for explosive impulsive sources. The weighted and unweighted time series calculations are intermediate steps in calculating the five previously mentioned metrics. The peak sound pressure level $\mathrm{SPL}_{\mathrm{peak}}$ is given by Equation (9).

$$\mathrm{SPL}_{\mathrm{peak}} = 20 \log_{10}\left(\frac{\max\left(P(t)\right)}{P_{\mathrm{ref}}}\right), \tag{9}$$

where the reference pressure P_{ref} is 1 μPa. The rms sound pressure is given by Equation (10).

$$\mathrm{SEL}_{\mathrm{rms}} = 10 \log_{10}\left(\frac{\int_{t_l}^{t_u}(P(t)^2 dt)}{P_{\mathrm{ref}}^2 t_{\mathrm{ref}}}\right), \tag{10}$$

where the reference duration t_{ref} is 1 second, and t_l and t_u are chosen such that 90% of the sound energy is between t_l and t_u. The total sound exposure level is the cumulative effect of the weighted sound energy for each hearing group, given by

$$\mathrm{SEL}_C = 10 \log_{10}\left(\frac{\int(P_w(t)^2 dt)}{P_{\mathrm{ref}}^2 t_{\mathrm{ref}}}\right). \tag{11}$$

For explosive impulsive sources, the impulse I is calculated for both adults and calves by Equation (12).

$$I = \int_0^{\mathrm{T}} P(t)\, dt\,, \tag{12}$$

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

1. 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;
2. The lung volume in liters is 3% of the mass of the animal in kilograms; and
3. As the animal dive, the lungs undergo isothermal compression.

These assumptions lead to the formula in Equation (13) for the 20% lung resonance.

$$T = \frac{\sqrt[3]{1.8 \times 10^{-4} \pi^2 M P_1}}{\sqrt[6]{P_0^5}} \sqrt{\frac{\rho}{3\gamma}}, \tag{13}$$

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, 18, or 36 equally spaced radials from an analysis point to 100 km. The number of radials used depends on how quickly the environmental parameters change; the number generally increases as analysis points are placed closer to shore. Each of the above metrics is summarized in tables for each bearing, range, and depth to be used in the impulsive simulator.

4.1.3.1 NAEMO Impulsive Modeling Comparison with Experimental Data

Prior to Phase III modeling, the data from the NAEMO explosive modeling process were compared to experimental data collected at the Virginia Capes (VACAPES) Range Complex and at the Silver Strand Training Complex (Deavenport and Gilcrest 2015). For the data comparisons, the explosive charge sizes (less than 24-lb NEW) used for the experiments were at the lower end of the spectrum of charge sizes modeled in NAEMO. Furthermore, the water depths and measurement distances (less than 10 meters of water depth and a maximum of 1,700 meters from the source) were relatively small compared to the Phase III predicted range-to-effect distances of interest. Nonetheless, the comparisons made between the experimental data and the NAEMO model data showed good correlation of peak pressures, which indicated that the NAEMO impulsive modeling process is in agreement with experimental data for the limited datasets used for the comparisons. Additional experimental data for several charge sizes have since been collected at various sites, but not all of it has been compared to NAEMO predictions. For more recent data that has been compared to NAEMO, the peak pressures also generally correlate well. To conduct a full 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-effect distances.

4.1.3.2 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 because of the limited datasets available for the wide range of explosive charge sizes being modeled in Phase IV. As with any theoretical representation, there are limitations and assumptions that must 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 NEW of TNT, the valid range reported is from 3.4 to 138 MPa. Converting the pressure maximum into charge size produces a NEW of TNT of 28.8 lb, which is equivalent to Phase IV impulsive bin E5. Charge sizes above this weight would thus fall outside 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 was conducted using the NAEMO modeling process. For each analysis, the peak pressure was computed at various ranges along radials from the source location and compared to the theoretical value based on similitude. The comparison showed good agreement between the NAEMO 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.

4.1.3.3 Surface Effects for Near-Surface Detonations

The impulsive modeling approach used in NAEMO cannot account for the highly nonlinear effects of cavitation and surface blowoff that would exist in the real world. To approximate these effects, a series of modeled analyses was conducted with the charge depths defined at varying distances from the free surface. The results of these simulations were compared to modeling using the numerical Reflection and Refraction in Multilayered Ocean/Ocean Bottoms with Shear Wave Effects (REFMS) tool. Based on these comparisons, a depth of 0.1 meter was chosen as the representative depth of near-surface detonations.

4.1.3.4 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 as to 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 one-third-octave bins, model each bin separately, and then combine the outputs from each bin to produce the overall effects of the impulsive source. When the bins are created, some bins 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 wavelengths may be too large in comparison to the water depth. RAM is used for non-impulsive sources in such conditions, but it is unsuitable for impulsive sources because its output lacks the temporal information required for the approach detailed above. Because of the small number of scenarios in which these conditions may occur as well as the initial comparisons made to the shallow-water data, it was determined that using CASS/GRAB in these conditions had a negligible impact on the estimated effects produced by NAEMO's modeling process.

4.2 MARINE SPECIES DISTRIBUTIONS

Marine mammals and sea turtles are distributed into study areas with multiple iterations generated for each species to account for statistical uncertainty in the density estimates. The distributed animats (i.e., artificial or virtual animats used during modeling) function as a dosimeter, recording energy received from all sources that were active during a scenario. Each iteration varies according to the standard error associated with the density estimate as provided by the density TR for each study area (U.S. Department of the Navy 2024b, in press). 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 stock 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, a standard deviation was not provided.

NAEMO considers the mean group size, the standard deviation, the minimum and maximum number of animals in a group, and the distribution type when creating animat distributions. The distribution types specified include log-normal, Poisson, or constant distributions. Animats are distributed in groups of a size that varies according to an inverse Gaussian distribution defined by the group size mean and standard deviation. The standard deviations are incorporated by randomly selecting a value from the Poisson or log-normal distribution defined by the mean group size and standard deviation provided. For constant distributions, all group sizes are forced to the mean group size provided.

The distribution of animats in NAEMO starts with the extraction of species density estimates from the NMSDD for a given area and month. To incorporate statistical uncertainty surrounding density estimates into NAEMO, 10 distributions are produced for each species per month, each of which varies 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 for a given iteration:

- 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 are determined specific to each study area. If the density estimate does not have a corresponding standard deviation, the density remains constant at the mean for every iteration.

- The density estimate (animals/km^2) for each cell is multiplied by the cell 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 the mean and standard deviation of the group size (see Section 3.2.1). 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.

These steps result in a series of data files containing the month, location, and bathymetry at the location of each animat placed within the modeling area. The standard deviation is only used to vary the total number of animats in the entire region.

4.3 SIMULATION PROCESS

The NAEMO simulation process combines the event, sound propagation, and animat distribution data to estimate the acoustic effects on marine mammals and sea turtles. Events are visually inspected and verified before modeling begins. An event's geographic locations, modeling boxes, platforms, sources, bathymetry, and local species distributions can be reviewed to validate modeling viability and provide a quality assurance check to align reality with the model.

The NAEMO Simulator combines scenario definitions, propagation data, and animat distributions to produce a record in NAEMO of the sounds received by each animat.

4.3.1 Monte Carlo Simulation Approach

Estimation of effects in NAEMO is accomplished through Monte Carlo simulations. This approach is unchanged from Phase III to Phase IV. The Monte Carlo approach uses repeated random sampling to account for the variability inherent in many factors of training and testing events, such as the precise location of modeling area, platform location and movement, and instantaneous distributions of marine mammals and sea turtles. The location of an event is randomly selected within a specified modeling area (Section 3.8.1). 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 the calculation of metrics such as standard error and confidence intervals. A total of 120 Monte Carlo simulations are run per event, per species, and per year, in which the iterations are evenly distributed across seasons. 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 the platform is stationary or its track is defined by waypoints)
- Time that the sources first go active (unless timing is specified in scenario definition)

4.3.2 Simulator

The purpose of the Simulator is to determine the level of sound received by each animat. This module first references the scenario definition in NAEMO to determine the depth of each platform and source; then it randomizes the starting location and direction within the modeling box. The exception to this randomization is when a platform is set to run on a defined track, where it will start at the same point at the start of the track in each iteration. The Simulator then steps through time and interrogates each of the platform sources to determine which sources are actively emitting sound during each 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 activation time (ping), the horizontal beam pattern area and the direction of the sound source emission is computed. The horizontal beam pattern area is calculated from the horizontal beam pattern of the source and the maximum propagation distance, which are both stored in the source table in NAEMO. For example, the area for a source with a 90° 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 vertical beam pattern is already taken into account in the propagation loss calculation. 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 within each defined horizontal beam pattern area for each ping. For each animat identified in the beam pattern of a ping, a table lookup in the propagation data is performed to determine the received sound level for that animat. The lookup is conducted based on the source bin parameters, bearing and distance from the platform to the animat, and the depth of the animat. NAEMO incorporates individual animat movement vertically in the water column at a specified displacement frequency for sufficient sampling of the depth dimension. Animat depths are changed every 4 minutes based on the species' dive profile, although no dive paths are simulated and there is no correlation between an animat depth and the subsequent depth. Individual animats are not moved horizontally within NAEMO. The radial from the closest bearing from the closest matching analysis point (Section 4.1) within the propagation database is used. If the closest radial is outside the horizontal beam pattern area, the animat receives no sound from that ping. Only sound exposures that exceed 100 dB are recorded.

Broadband sources are broken out into their one-octave sub-bins (Section 3.7.2) and treated as independent transmissions in the Simulator. However, since each ping is coming from the same source, every ping of a sub-bin from a broadband source will go off at the same time and bearing. The source level for each sub-bin is reduced to adjust for the additional transmissions so that they recombine to the true source level of the bin. Only exposures from the broadband sub-bins that exceed 100 dB are recorded.

The Simulation module output for each animat is stored in NAEMO. These outputs include simulation time, platform name, platform location (latitude and longitude), platform depth, source name, source mode name, source mode frequency, source mode level, pulse length, species name, animat identification number, animat location (latitude and longitude), animat depth, animat 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 producing exposures that exceed 100 dB for that animat.

4.4 ANIMAT PROCESSOR

The NAEMO Animat Processor reads the records produced by the 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 (U.S. Department of the Navy 2024a, in press).

The Animat Processor uses output from the Simulator to compute the effects of events on each marine mammal and sea turtle group. Criteria and thresholds (Section 3.2.4) are applied to the Monte Carlo simulations. In each iteration, animats that receive a sound level above a criterion's threshold are recorded as an effect. For animats that exceed multiple criteria thresholds, the most severe impact is recorded. For example, once an animat is reported for AINJ, it would not additionally be reported under TTS or behavioral, even if all criteria thresholds were exceeded. Results from each analysis are stored in the NAEMO database for later retrieval.

4.4.1 Impulsive Sources

For impulsive sources, the Animat Processor primarily uses three metrics to describe sound received by animats: SPL, SEL, and impulse. The Animat 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 TTS, AINJ, and gastrointestinal (GI) effects, is simply the maximum received level reported in the Simulator. The accumulated SEL is used to determine behavioral effects, TTS, and AINJ; the accumulated SEL represents the accumulation of energy from all time steps and from multiple source exposures. For the SEL, the appropriate auditory weighting functions defined by the marine mammal and sea turtle criteria (Section 3.2.4) are applied to adjust the received levels during propagation (see Equation (12)). AINJ values represent the cumulative number of animats affected at or above the AINJ thresholds. TTS values represent the cumulative number of animats affected at or above the TTS thresholds and below the AINJ thresholds. The Animat Processor for impulsive sources also uses the impulse (see Equation (13)) received by each animat to determine the slight lung injury and mortality metrics. For airguns, there are alternative metrics that use SPL_{rms} for some types of effects.

4.4.1.1 Avoidance in Impulsive Modeling

The avoidance methods encompass the non-impulsive process. An equivalent avoidance process was not implemented in impulsive modeling. The decision to omit avoidance from impulsive modeling was due to a lack of data on certain source count spacing. The Phase III versions of NAEMO randomized the times at which different counts of the same impulsive source went active owing to the irrelevance of the time spacing on stationary animats. That spacing would be critical to any avoidance process because the period between counts is the time an animat would have to increase its approximated distance from the platform. Because this data was not attainable during model development, an avoidance method for impulsive modeling was not implemented for the Phase IV at-sea modeling efforts.

4.4.2 Non-impulsive Sources

For non-impulsive sources, the Animat Processor uses two metrics to describe sound received by animats—SPL and SEL. The Animat Processor computes the SEL accumulation and maximum SPL over the duration of the event for each animat to determine the probability that the animat received either AINJ or TTS and whether there is a probability of a behavioral response in either case.

4.4.2.1 Broadband Sub-bin Recombination

For simulations that feature broadband sources, the first step of the Animat Processor is to combine the concurrent sub-bin transmissions. Broadband bins are broken up by octaves so that each sub-bin is modeled at a different frequency. Individual sub-bin transmissions are independently weighted based on the weighting function for the specific species exposed. The weighting is not applied until the SEL accumulation calculation step. The received level (RL) is then calculated based on a logarithmic power sum, as given by Equation (14).

$$\mathrm{RL} = 10\log_{10}\sum 10^{rl_n/10}\,, \tag{14}$$

where RL is the combined received level and rl_n *is* the received level of sub-bin n. Broadband sources are handled in the same way as narrowband sources after this step.

4.4.2.2 Avoidance

The Navy continues to refine NAEMO between each phase of the at-sea environmental compliance planning process through improved modeling methodologies, collaboration with subject matter experts, and lessons learned from prior phases. Incorporating animal avoidance (defined below) into NAEMO is a process improvement identified by the Navy during Phase IV planning:

- Avoidance: At close ranges to high sound levels, avoidance of the area immediately around the sound source is one of the behavioral responses assumed for marine mammals. "Avoidance" refers to a marine mammal avoiding a high-intensity sound exposure by moving horizontally out of the immediate injury zone for subsequent exposures (i.e., not wide-scale area avoidance).

- Note: Sea turtles do not avoid in NAEMO.

NUWC Division Newport and the Naval Information Warfare Center (NIWC) Pacific Bioacoustic Analysis and Applied Research Team (BAART) have collaborated to develop a method for calculating avoidance within NAEMO. This approach is predicated on two assumptions:

- An animat is able to localize the bearing of the sound source with relation to itself

- An animat is able to increase its distance from the source at a continuous rate, based on swim speed and elapsed time

The approach within NAEMO mathematically simulates an animat moving away from a sound source since animats are assigned stationary locations in a simulation.

Avoidance calculations are conducted within the Animat Processor, introduced in Section 4.4. During this step, NAEMO will read the data output file from the Simulator, described in Section 4.3.2, and apply an avoidance formula prior to estimating the number and severity of impact for each species or stock of marine mammals, based on their specified criteria thresholds.

Species-specific information, such as avoidance swim speeds, have been added to the NAEMO database. This data is combined with simulation data already calculated within NAEMO to approximate how far an animal would have been able to move from its stationary location at the time of a given exposure as well as the sound level that would be expected at this approximated location.

The Phase IV approach is to conduct all avoidance calculations within NAEMO. This approach was selected because it captures a more accurate representation of avoidance by using the received sound levels, distance to platform, and species-specific criteria to calculate potential avoidance for each animat.

4.4.2.2.1 Animat Avoidance Thresholds

During the animat distribution process (Section 4.2), each animat is randomly assigned a value between zero and one with a precision to two decimal places (i.e., 0.00–1.00). This value is carried through the simulation process with each animat modeled by the Animat Processor. Applying this random value during the distribution maintains consistency throughout the modeling effort and allows the reproducibility of results in the event of remodeling. Remodeling is sometimes necessary to make corrections or changes to scenarios or events based on review of initial results. This animat-specific value is converted to a dB level in the Animat Processor by sampling for that number along the behavioral response function (BRF) for the behavioral group of that species. The avoidance response threshold is based on the SPL in units of dB and use the Phase IV BRFs. The calculated dB level is the avoidance threshold for each animat, and an avoidance response will be triggered when an animat is simulated to receive a sound exposure that exceeds their unique threshold.

A minimum avoidance threshold is applied for each species. This minimum threshold corresponds to an assigned value of 0.50, or the 50% point along the BRF. For animats whose avoidance threshold is below the 0.50 point on the BRF ($p_{brf}(0.5)$), the avoidance threshold is increased to the dB level corresponding to $p_{brf}(0.5)$. This minimum threshold ensures that animats do not initiate avoidance at relatively low received levels.

Conversely, a maximum threshold of 0.90 brackets the avoidance thresholds, adjusting for animats that would not initiate avoidance at high SPLs. For animats whose avoidance threshold was above the 0.90 point on the BRF ($p_{brf}(0.9)$), the avoidance threshold was decreased to the dB level corresponding to $p_{brf}(0.9)$. Without this maximum threshold for the received level (RL), given by Equation (15), some animats receiving very high SPLs would never avoid.

$$\mathrm{RL_{threshold}} = \begin{cases} \mathrm{RL_{0.50}}, & \mathrm{RL_{threshold}} < \mathrm{RL_{0.50}} \\ \mathrm{RL_{threshold}}, & \mathrm{RL_{0.50}} < RL_{\mathrm{threshold}} < \mathrm{RL_{0.90}} \\ \mathrm{RL_{0.90}}, & \mathrm{RL_{threshold}} > \mathrm{RL_{0.90}} \end{cases} \tag{15}$$

where

$\mathrm{RL_{threshold}}$ = the randomly assigned animat-specific avoidance threshold,

$\mathrm{RL_{0.50}}$ = the species-specific minimum avoidance threshold,

$\mathrm{RL_{0.90}}$ = the species-specific maximum avoidance threshold.

4.4.2.2.2 Initiating an Avoidance Response

The Simulator creates a data file that contains the time, range to platform, and received level of every exposure for every animat within the modeling area. The Animat Processor then analyzes the exposures by animat and platform. For every sound-producing platform to which an animat is exposed, a unique avoidance response can occur.

To trigger an avoidance response, at least one of the exposures in the series of exposures from the sources on a platform must exceed the avoidance threshold established during the animat distribution process (Section 4.2). See Equation (16).

$$t_0 = t_{\mathrm{RL}_1 > \mathrm{RL}_{\mathrm{threshold}}}, \tag{16}$$

where t_0 is the time when the avoidance response begins, and $t_{\mathrm{RL}_1 > \mathrm{RL}_{\mathrm{threshold}}}$ is the first timestamp when the avoidance threshold is exceeded.

An animat is eligible for a single avoidance response to a given platform within a simulation. When an avoidance response is triggered, an animat is deemed to be in an active avoidance state.

4.4.2.2.3 Duration of an Avoidance Response

An animat will continue to be in an active avoidance state if it continues to be exposed to sound levels from a platform that exceeds its avoidance threshold, based on the original simulation data. The only limit on how long an animat can be in an avoidance state within a given 24-hour modeling iteration is the duration of the iteration.

If an animat is exposed to a sound level below its avoidance threshold while in an active avoidance state, it will switch into a residual avoidance state. The residual avoidance state accounts for the likelihood that an animal would not immediately stop avoiding when the sound levels fell below the threshold that initially triggered the response but would continue to avoid until it has sufficient evidence to suggest that source is no longer active or a threat. While in a residual avoidance state, an animat will continue to simulate movement away from a platform for a specified duration based on its behavioral hearing group.

An animat can return to an active avoidance state if it is exposed to a sound level that exceeds its threshold at a later point within the residual avoidance period. If an animat returns to an avoidance state, the duration of its residual period is reset when it next enters a residual avoidance state.

An animat will cease to simulate movement away from a source when the residual period has expired unless an above-threshold exposure returns it to an avoidance state.

4.4.2.2.4 Received Level Reductions During Avoidance

The Animat Processor interrogates the simulation data to create distinct avoidance responses for every animat. NAEMO does not construct swim paths in two-dimensional space, but it determines for how long an avoiding animat would move away from a platform based on the time spent above its avoidance threshold. Avoidance responses are unique to a platform, and there is no accounting for the spatial and acoustic interaction of different platforms within the simulation. The method for determining the start and end of an avoidance response is described in Sections 4.4.2.2.2 and 4.4.2.2.3.

Once the avoidance period is established, the received levels from each exposure within the response are reduced via a spherical spreading calculation. The simulated avoidance movement is one-dimensional in range, and the increased distance between the animat and the source is calculated based on a species-specific swim speed and the elapsed time since avoidance began by using Equation (17).

$$d_{\text{avoid}} = (t_{\text{avoid}} - t_0) * v\,, \tag{17}$$

where

d_{avoid} = distance traveled since avoidance response began,

t_{avoid} = timestamp of exposure in avoidance response,

t_0 = timestamp of exposure that triggered avoidance response,

v = species-specific avoidance swim speed.

The avoidance distance at each time step during the avoidance response is added to the original distance from the platform to the animat. Spherical spreading is applied to the received level of each exposure based on the distance traveled since the avoidance response began by using Equation (18).

$$\mathrm{RL}_{\text{adj}} = \mathrm{RL}_{\text{exp}} - 20\log_{10}\left(\frac{d_{\text{avoid}} + d_{\text{exp}}}{d_{\text{exp}}}\right), \tag{18}$$

where

RL_{adj} = adjusted received level based on spherical spreading reduction,

RL_{exp} = original received level of exposure within avoidance response,

d_{exp} = original distance from platform to animat of exposure within avoidance response.

4.4.2.2.5 Aftermath of an Avoidance Response

An animat's active and residual avoidance states encompass the entirety of an avoidance response, during which NAEMO approximates movement away from the platform. Once the simulated movement has concluded (i.e., the animat has not been exposed to a received level from the platform above its avoidance threshold for the duration of the residual period), an animat enters an evasion state and remains in that state for the rest of the given iteration. Animats in an evasion state are given credit for their recent avoidance response and "stay away" from the platform. Further movement away from the source is not simulated for an animat in an evasion state. Instead, the final reduced received level calculated within its avoidance response is considered the maximum received level that the animat can be exposed to from the platform that it avoided. Any subsequent exposure during an evasive state exceeding that value will automatically be set to the last reduced received level of the avoidance response, per Equation (19).

$$\mathrm{RL}_{\text{after}} = \begin{cases} \mathrm{RL}_{\text{after}} = \mathrm{RL}_f, & \mathrm{RL}_{\text{after}} > \mathrm{RL}_f \\ \mathrm{RL}_{\text{after}} = \mathrm{RL}_{\text{after}}, & \mathrm{RL}_{\text{after}} < \mathrm{RL}_f \end{cases}, \tag{19}$$

where

RL_{after} = the received level of exposures after avoidance has concluded,

RL_f = the adjusted received level of final exposure in the avoidance response.

4.4.2.2.6 Non-avoidance

Delphinids have a tendency to bow-ride naval platforms rather than avoid them. NAEMO accounts for this behavior by randomly assigning 5% of delphinid animats as bow riders. These animats are ineligible to exhibit an avoidance response to moving surface vessels within NAEMO, even if they are exposed to sound levels above their avoidance threshold. However, bow-riding animats are eligible to avoid any platform that is not a moving surface vessel. The 5% probability is an estimate, because data on the portion of delphinids that may be attracted to bow-riding a vessel while sonar is active is limited. NAEMO does not model attraction behavior (i.e., animats moving closer to a platform to bow-ride), and received levels are not modified for animats disqualified from avoiding moving surface vessels.

4.4.2.2.7 Species-Specific Avoidance Factors

Avoidance swim speeds and durations were estimated using values obtained from behavioral response studies for sonar and from studies of responses to other anthropogenic sound sources (see the appendix). Baseline (no-exposure) swim speed data were also obtained from behavioral response studies and other observational studies. Marine mammal species in the sensitive behavioral group (beaked whales and harbor porpoises) and minke whales have longer avoidance durations compared to other species. The avoidance durations of both beaked whales and minke whales were based primarily on behavioral response studies with controlled exposure experiments in which focal species were exposed to simulated tactical sonar.

Baird's beaked whales and Cuvier's beaked whales were exposed to intermittent simulated sonar signals (3.5–4 kHz) during the Southern California Behavioral Response Study (SOCAL-BRS) experiments (DeRuiter et al. 2013; Stimpert et al. 2014), and Northern bottlenose whales and minke whales were exposed to intermittent simulated sonar signals (1–2 kHz or 6–7 kHz) during the Sea Mammals and Sonar Safety studies (3S2) in Norway (Kvadsheim et al. 2012; Lam et al. 2016; Miller et al. 2015; Sivle et al. 2015; Wensveen et al. 2019). In these studies, many beaked whales avoided simulated sonar signals for the full duration of a sonar event, with some species like the Northern bottlenose whale avoiding for a minimum of 7 hours until their tags fell off (DeRuiter et al. 2013; Miller et al. 2015; Tyack et al. 2011). On the Atlantic Undersea Test and Evaluation Center (AUTEC) range, Blainville's beaked whales appeared to move off-range during sonar use and return only after the sonar transmissions stopped, sometimes taking several days to do so (Boyd et al. 2009; Henderson et al. 2015; Jones-Todd et al. 2021; Manzano-Roth et al. 2022; Manzano-Roth et al. 2016; McCarthy et al. 2011; Tyack et al. 2011). On the Pacific Missile Range Facility (PMRF), acoustic detections of Blainville's beaked whales and minke whales decreased substantially during sonar exposure (Harris et al. 2019; Jacobson et al. 2022; Martin et al. 2015).

It can take at least 5 days for minke whales to return to baseline conditions, whether that means vocalizing normally or returning to the affected area (Durbach et al. 2021; Harris et al. 2019).

Likewise, detection rates of Cuvier's and *Mesoplodont* beaked whales dropped both during and after an 8-day, multi-platform anti-submarine warfare training exercise and remained low 7 days after the exercise (Stanistreet et al. 2022). Harbor porpoises are also known to displace for the entirety of certain activities, particularly pile driving and construction events (Benhemma-Le Gall et al. 2021; Brandt et al. 2011; Dähne et al. 2014; Haelters et al. 2014; Thompson et al. 2010; Tougaard et al. 2005; Tougaard et al. 2009). Considering the field study limitations (e.g., tags falling off) and the evidence of sensitive species avoiding, or at least remaining silent, on naval ranges long after the full duration of a noise exposure, the avoidance durations listed in Table 5 should be interpreted conservatively as minimum avoidance durations. Table 5 shows the avoidance factors that are used in the avoidance algorithm.

Table 5. Avoidance factors by behavioral and hearing groups

Hearing Group	Avoidance Group	BRF p(response) = 0.5 (dB rms)	Avoidance Speed (m/s)	Avoidance Duration (min)
Sensitive				
HF	Beaked whales	133	3	Full duration of event
VHF	Harbor porpoises	133	3	Full duration of event
Odontocete				
HF	Other odontocetes	168	2.5	15
VHF	Other odontocetes	168	2.5	15
Mysticete				
LF/VLF	Other mysticetes	185	2	15
LF	Minke whales	185	2	Full duration of event
Pinniped				
PCW	Pinnipeds	156	2	10
OCW	Pinnipeds	156	2	10

Note: HF = high-frequency cetaceans, VHF = very-high-frequency cetaceans, LF = low-frequency cetaceans, VLF = very-low-frequency cetaceans, PCW = phocids and carnivores in water, and OCW = otariids and other non-phocid marine carnivores in water.

4.4.2.2.8 Avoidance at Pierside Locations

The avoidance method does not consider geographic features when approximating an avoidance response. An animat moving away from a platform does so as if it is in open ocean, regardless of its proximity to shore. Stationary sources modeled at pierside locations in NAEMO, however, are situated very close to the coastline and often surrounded by complex coastal features. Animals avoiding platforms at these locations would eventually move to a position where there was a land feature between itself and the platform, creating a shadow zone for sound propagation.

Because this dynamic is not captured by the standard avoidance method, NAEMO includes the capability to account for it by instituting an avoidance distance maximum for modeling stationary sources at pierside locations. The avoidance method operates the same until an animat has avoided for a distance equaling the maximum. After this distance is reached, exposures from the platform are set to 0 dB to reflect the shadow zone into which the animat is assumed to have moved.

The avoidance distance maximum represents the farthest possible distance an animat in the modeling area would have to swim to reach a position in a shadow zone. These maxima are unique to a pierside location and assigned conservatively by MSMT and BAART to approximate the specific characteristics of the area. NAEMO does not use this capability by default, but it can be turned on by the user when appropriate.

4.4.2.2.9 Impact on Effects Estimates

The avoidance process is completed for every combination of eligible animat and platform until all appropriate received levels are reduced accordingly.

4.4.2.2.9.1 Auditory Injury and Temporary Threshold Shift

All updated received sound pressure levels (SPLs) are input to the remaining steps of the Animat Processor for final temporary threshold shift (TTS) and auditory injury (AINJ) effect estimation. TTS and AINJ are determined based on a sound exposure level (SEL) calculation that uses the collection of SPLs as an input.

Reductions of received SPLs will thus propagate through the Animat Processor and reduce the SEL of an avoiding animat. The SEL reduction could lower an animat’s calculated SEL value below the TTS or AINJ species-specific threshold, thereby reducing the total number of auditory effects estimated for each iteration.

4.4.2.2.9.2 Behavioral Effects

The avoidance-adjusted received levels are not used to calculate behavioral effects estimates. Because avoidance is a type of a behavioral response, it would be inappropriate to apply any reductions to the calculation of those effects. The original set of received levels are retained in the Animat Processor and the maximum SPL that an animat receives from the original simulation data is used to calculate the probability of the behavioral response.

4.4.2.3 **Sound Exposure Level (SEL) Effects Calculation**

Accumulated SEL is used to determine AINJ and TTS, and it 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 3.2.4) are applied to adjust the received levels for the frequency of each non-impulsive source. The weighted SPL is given by Equation (20).

$$\mathrm{SPL}_{\mathrm{weighted},\,t} = \mathrm{SPL}_s + W_{\mathrm{species}} + 10\log_{10}\mathrm{PL}_s \tag{20}$$

where s is source, t is time, $\mathrm{SPL}_{\mathrm{weighted},\,t}$ is the received level adjusted by the species auditory weighting function (W_{species}) 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, as given by Equation (21).

$$\mathrm{cSEL} = 10\log_{10}\sum_{i=1}^{n}10^{\frac{\mathrm{SPL}_{\mathrm{weighted},t,n}}{10}} \tag{21}$$

where n is the number of exposures at each time step. The cSEL is compared to the species-specific AINJ and TTS thresholds to determine whether an animat has either AINJ or TTS, respectively. Each animat can be reported only under a single criterion (e.g., once an animat is reported for AINJ, it cannot additionally be reported for the TTS or behavioral effects criteria).

4.4.2.4 Sound Pressure Level (SPL) Effects Calculation

Animats that do not receive AINJ or TTS based on the SEL accumulation are considered for behavioral effects calculation. The maximum SPL is used to determine the probability of behavioral response, based simply on the maximum received level reported in the Simulator. For broadband sources, the maximum received level after sub-bin recombination is used.

Further, the received levels used to determine the maximum are also not affected by the avoidance process. Avoidance is a type of behavioral response; thus, the reduction in received levels from that process should not subsequently reduce the probability of a behavioral response.

On an animat level, behavioral effects are reported as fractional effects based on the probability of response. That probability is determined by sampling the maximum SPL along the species' behavioral response function. The corresponding value from that curve (0–1) is the resulting behavioral effect for a given animat.

4.4.2.4.1 Behavioral Cutoff Criteria

Behavioral effects calculations within NAEMO are based on the maximum SPL to which an animat is exposed. NAEMO retains exposures exceeding 100 dB and inside the 100-km modeling extent within the simulation data. When no cutoffs are applied, all exposures are considered when determining the maximum SPL for each animat, which is converted into a probability of response based on the BRF.

There is empirical evidence to suggest that animals are not likely to exhibit behavioral responses when exposed to low levels of sound from a source that is far away. To account for this in Phase IV, NAEMO has implemented behavioral cutoffs that consider both received sound level and distance from the source. These cutoffs are unique to each behavioral hearing group, and the criteria was provided by BAART for Phase IV at-sea modeling efforts. The behavioral cutoff criteria are programmed into the NAEMO database as outlined in Table 6.

Table 6. Behavioral cutoff conditions by behavioral hearing group

Behavioral Hearing Group	Received Level Cutoff Condition: p(response) = 0.5 (dB rms)	Distance Cutoff Condition (km)
Mysticetes	185	10
Odontocetes	168	15
Pinnipeds	156	5
Sensitive species	133	40

As NAEMO interrogates the simulation data in the Animat Processor, exposures that are **both outside** the distance cutoff **and below** the received level cutoff are omitted when determining the maximum SPL for each animat. This differs from Phase III, in which only distance cutoffs were applied, meaning that all exposures **outside** the distance cutoffs were omitted, with no consideration of received level.

The presence of the two cutoff criteria in Phase IV provides a more accurate and conservative estimation of behavioral effects because louder exposures that would have been omitted previously, when only a distance cutoff was applied, are considered in Phase IV, while the estimation of behavioral effects still omits exposures at distances and received levels that would be unlikely to produce a behavioral response. NAEMO retains the capability of calculating behavioral effects without the cutoffs applied, depending on user preference.

The impulsive behavioral criteria are not based on the probability of a behavioral response but rather on a single SEL metric. For consideration of impulsive behavioral effects, the cutoff conditions in Table 6 are not applied. Instead a consistent cutoff of 100 km is used.

4.4.2.5 Extended Effects

The NAEMO Animat Processor produces a secondary data output known as “extended effects.” The extended effects data provides an additional layer of specificity to the results and allows analysis of the distribution of sound exposure within a simulation.

The extended effects function groups the simulation data in the Animat Processor in three ways, based on the maximum SPL each animat is exposed to. The first grouping allocates each animat into bins based on the dB at this maximum SPL. The default bin boundaries start at 100 dB and increase incrementally by 6 dB up to 220 dB. For example, the default 6-dB bin resolution starting at 100 dB would result in the first bin spanning 100–106 dB, the second spanning 106–112 dB, the third spanning 112–118 dB, and so on. The total number of animats within each dB bin for a given iteration is output by NAEMO.

The second grouping converts the maximum SPL to a probability of response based on the species BRF. The probabilities of response are then allocated into bins based on the dB at the maximum. The same bin boundaries are used for both the first and second groupings. The summation of the probabilities of response within each dB bin for a given iteration is output by NAEMO.

The third grouping also uses the converted probability of response but allocates it into bins based on the distance from the platform to the animat when the maximum SPL occurred. The default distance bin boundaries start at 0 km and increment by 5 km up to 100 km. For example, the default 5-km bin resolution starting at 0 km would result in the first bin spanning 0–5 km, the second spanning 5–10 km, the third spanning 10–15 km, and so on. The summation of the probabilities of response within each distance bin for a given iteration is output by NAEMO. The groupings that use the probabilities of behavioral response can be run with either the behavioral cutoff criteria (Section 4.4.2.4.1) applied or omitted.

4.4.2.6 Mitigation

The Action Proponents implement mitigation to avoid or reduce potential impacts from training and testing on marine species. The term "mitigation" in this technical report refers specifically to measures based on visual observations. Mitigation measures applicable to the discussions here are those that involve the use of personnel trained as lookouts to observe the presence of marine mammals and sea turtles within designated mitigation zones around active sonar sources, airguns, pile driving, and explosives. The mitigation zone is based on source control capabilities and visual observation mitigation requirements by frequency and sound level. Mitigation zones are measured as the radius from a stressor. In response to a marine mammal or sea turtle observed within a mitigation zone, the Action Proponents would delay the initial start of an event, power down or shut down active sonar, or cease the use of airguns or explosives.

For Phase IV, NAEMO added new functionality to keep track of how many animats could be located within an acoustic or impulsive mitigation zone. As the Animat Processor interrogates the simulation data, a record is maintained of which animats are located within the maximum mitigation zone size of all sources modeled in a given event. This record includes platform location, animat location, and distance from the platform to the animat. Mitigation data are recorded for both acoustic and impulsive modeling, though the maximum mitigation zone differs for each method. The maximum mitigation zone for acoustic sources is 2,000 yards, while the maximum mitigation zone for impulsive sources is 3 NM. Mitigation calculations are completed only for sources required to implement mitigation as described in each Phase IV EIS/OEIS document (U.S. Department of the Navy, n.d.-a, n.d.-b) in Chapter 5 on mitigation (e.g., active acoustic sources under positive control).

Because the simulation data only records platform and animat locations when an animat is exposed to sound, mitigation data are only available when the source is active (i.e., not between pings or detonations as a platform moves through the modeling area). For every iteration of a modeled event, if the shortest distance from the platform to the animat falls within the maximum mitigation zone, NAEMO records it. Since NAEMO has implemented an animal avoidance methodology for Phase IV (Section 4.4.2.2), mitigation calculations use avoidance-adjusted ranges to prevent duplicating credit for both avoidance and mitigation.

NAEMO logs the specific source that is active when an animat is in the maximum mitigation zone. This information is used during the reporting process to determine whether the distance from the platform to the animat is within the maximum mitigation zone of that particular source. Chapter 5 ("Mitigation") of each Phase IV EIS/OEIS (U.S. Department of the Navy, n.d.-a, n.d.-b) document outlines the various mitigation zones that are programmed into NAEMO.

The MSMT filters, compiles, and summarizes the mitigation data recorded by NAEMO for delivery to BAART for further processing. The primary report delivered to BAART contains the overall number of animats calculated to receive AINJ (for acoustic sources) or mortality (for impulsive sources) exposures along with their closest point of approach within a mitigation zone. This data is incorporated by BAART into the acoustic effects analysis.

4.5 NAEMO OUTPUT

All scenarios analyzed in NAEMO are evaluated as single events occurring within a given season and location. Scenarios that occur over multiple seasons and locations are modeled for each combination of season and location. To create the effects delivery, each scenario is averaged based on the number of iterations modeled within each combination of season and location. The NAEMO output is the single-day average per event, location, and season without factoring in the day multiplier (e.g., the number of days typically comprising each event) or the annual multiplier (e.g., the number of times per year the event occurs). These day and annual multipliers are included in the NAEMO output for further postprocessing. 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.

5. RANGE-TO-EFFECT

5.1 DEFINITION OF RANGE-TO-EFFECT

A range-to-effect is the distance from the location where a source is used to the farthest distance at which an effect would be expected to occur (i.e., the distance at which the probability of a given species experiencing a given adverse acoustic effect drops below a given threshold). The value of the range-to-effect depends on the following parameters:

1. Source bin parameters: frequency, sound level, pulse length, pulse interval
2. Source exposure parameters: duration of active sonar, cluster size for explosives
3. Source origin: latitude, longitude, depth, time of year
4. Source directionality: bearing
5. Species’ dive profile
6. Species-effect criteria

The “ranges-to-effects” are the collection of range-to-effect values for sources simulated during Phase IV acting upon the species that are within the range of each source’s origin for all of the possible acoustic effects that each species could experience. For a given acoustic propagation, species, and acoustic effect, the range-to-effect is computed as follows:

1. Start with the acoustic propagation received sound level versus range and depth for a given source bin, origin, and bearing.

2. For the given acoustic effect, calculate the “binary” map signifying whether the sound level exceeds the acoustic effect criterion for this species at each range and depth.

3. At each range, multiply the binary map by the species' dive profile. If the bathymetric depth at a range is shallower than the maximum depth of the dive profile, the dive profile is truncated and normalized such that the total probability of the dive profile remains at 100%.

4. At each range, sum the probability from step 3 over all depths. This yields the total probability of the species experiencing the given acoustic effect at that range.

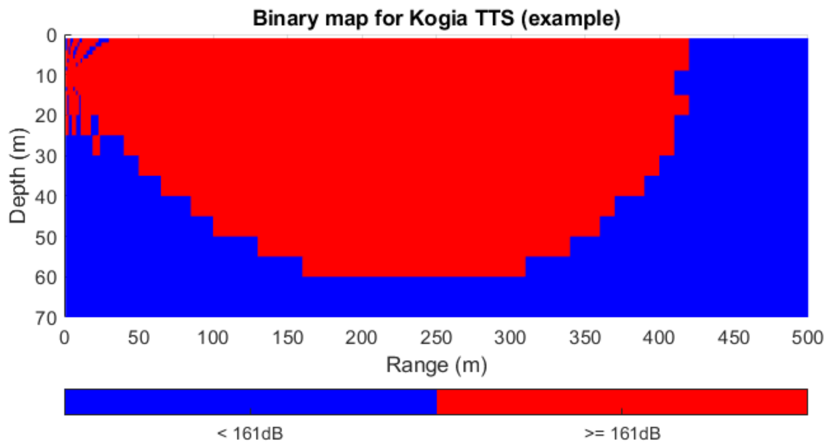
5. The range-to-effect is defined as the range where the probability decreases below the chosen threshold level of 5% for the last time.

The probability threshold level of 5% was chosen to align with the threshold level used in the outlier detection method utilized in Phase III. Figure 4 shows an example from a range-to-effect calculation for a Kogia whale that is visualized with the binary map (top) and the probability versus range curve (bottom). Observe that the calculated range-to-effect is where the probability versus range curve decreases below 5% for the final time, which is 430 meters in this case.

5.2 DIFFERENCES FROM PHASE III

In Phase III, species' dive profiles were not used when computing ranges-to-effects. Instead, the maximum dive depth of the species was used, and an even dive profile (constant for all depths) was assumed. Outliers in the binary map were removed when the data exceeding the threshold was noncontiguous in range. No more than 5% of the water column was disregarded in the outlier method when applicable.

In Phase IV, the use of the species' dive profile removes the need for a separate outlier detection method. The same ranges-to-effect are returned for both Phase III and Phase IV methods if (1) the Phase III method is used with no outlier detection and (2) the Phase IV method is used with a probability threshold level of 0%, which is the farthest range at which the sound level is above the given acoustic effect criteria at any depth within the species' dive profile.



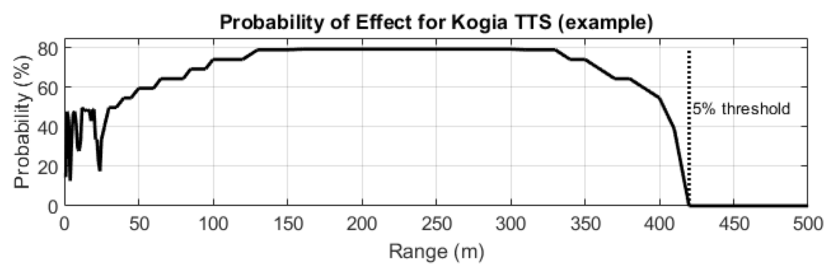


Figure 4. Visualization of a binary map and probability (top) range curve (bottom) for a Kogia whale given its dive profile and TTS threshold criteria of 161 dB. The calculated range-to-effect is where the probability versus range curve decreases below 5% for the final time, which in this case is 430 meters.

Figure 5 displays the results from a hypothetical example of calculation of the ranges-to-effects along one radial from a sonar source for AINJ (green), TTS (cyan), behavioral response (purple), and no effects (blue). In this example, the maximum dive depth considered for species A (white dashed line) was 300 meters. The ranges-to-effect calculations are bound by a species' maximum dive depth, and only the data for effects at less than or equal to the maximum dive depth of the species is used to estimate impact ranges.

For example, only data at less than or equal to a depth of 300 meters is considered for impact ranges for species A displayed in Figure 5. The point at which the maximum dive depth line intersects with the edge of a colored impact region depicts the range to the effects. Note the green star marking the 688-meter range for AINJ, the cyan star marking the 1,406-meter range for TTS, and the purple star marking the 1,594-meter range for behavioral response.

Since these ranges do not represent a cylinder of effect in the water column, there are portions of the water column within these ranges that would not exceed the threshold. For example, from 0 to 300 meters in depth and from 0 to 688 meters in range, exposure thresholds for AINJ would not be exceeded in regions that are colored cyan, purple, or blue. In some instances, a significant portion of the water column within an impact range may not exceed the threshold.

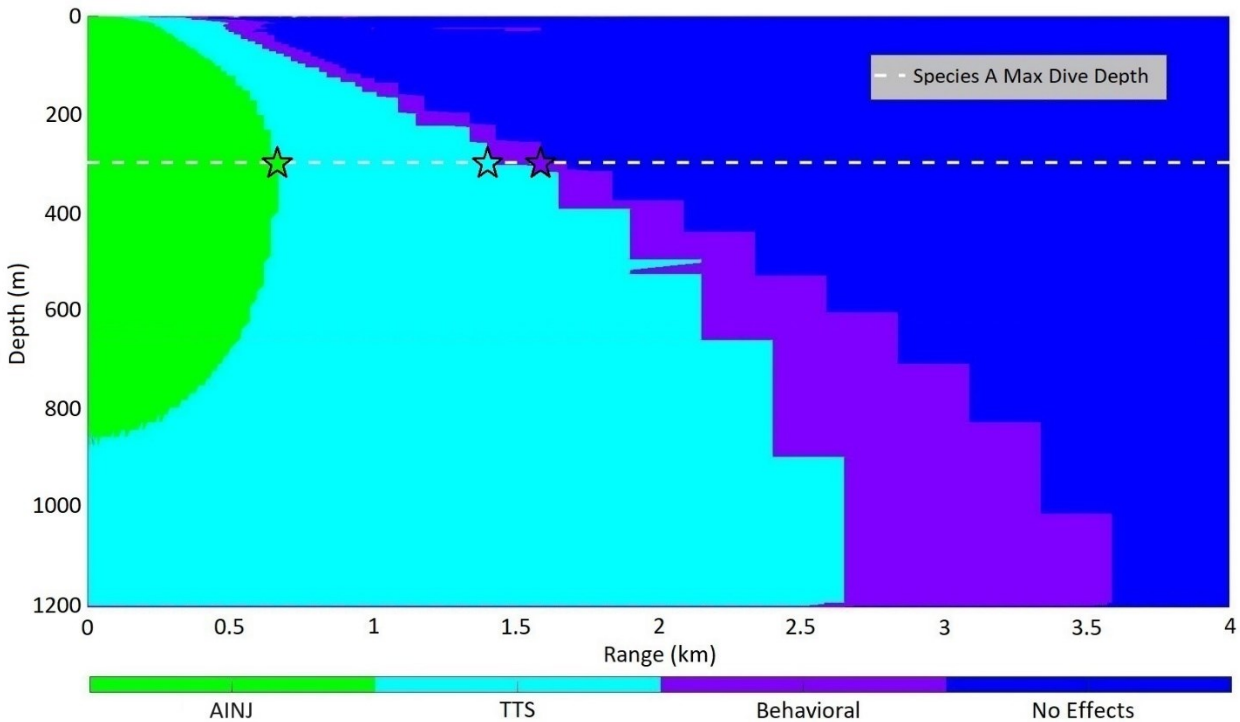


Figure 5. Hypothetical ranges-to-effects calculations along one radial from a sonar source: AINJ (green), TTS (cyan), behavioral response (purple), and no effects (blue). The maximum dive depth considered is 300 meters for species A (white dashed line).

6. PILE DRIVING ACOUSTIC EFFECTS ANALYSIS

The Navy performed a quantitative analysis without NAEMO to estimate the number of times that marine mammals and sea turtles could be affected by pile driving and extraction used during proposed training activities. A similar method was used to determine the ranges to specific effects for fishes.

The analysis considered details of the activity, sound exposure criteria, and the number and distribution of marine mammals and sea turtles (density data are not available for fishes). This information was then used in an "area∗density" model in which the areas within each footprint (i.e., zone of influence (ZOI)) that encompassed a potential effect were calculated for a given day's activities. The effects analyzed included behavioral response, TTS, and AINJ for marine mammals and sea turtles and TTS, injury, and mortality for fishes.

Then, for marine mammals and sea turtles, these areas were multiplied by the density of each marine species within the nearshore environment to estimate the number of effects. Uniform density values for species expected to be present in the nearshore areas where pile driving could occur were estimated using the NMSDD or available survey data specific to the activity location. More detail is provided in the draft supplemental EIS/OEIS for Atlantic Fleet Training and

Testing (AFTT) (U.S. Department of the Navy, n.d.-b) and the draft Hawaii-California Training and Testing (HCTT) EIS/OEIS (U.S. Department of the Navy, n.d.-a). 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, which was then multiplied by the maximum number of times per year this activity could happen. The result was the estimated effects per species and stock in a year.

6.1 PROPOSED ACTIVITY

Port damage repair training activities are conducted by naval construction groups and involve intermittent impact and vibratory pile driving over multiple days per event and several events per year. Crews could work 24 hours a day for each event. Activity parameters (e.g., total number of piles per day, events per year) may vary between the AFTT and the HCTT and are described in greater detail in the AFTT (U.S. Department of the Navy, n.d.-b) and HCTT (U.S. Department of the Navy, n.d.-a).

6.2 CRITERIA AND THRESHOLDS

A comprehensive discussion on how the criteria and thresholds for AINJ and TTS in marine mammals and sea turtles were derived is available in the criteria and thresholds TR (U.S. Department of the Navy 2024a). 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 AINJ for these sources. Vibratory pile driving and removal produces continuous, non-impulsive noise. Therefore, the non-impulsive criteria were used to assess the onset of TTS and AINJ.

Table 7 shows the weighting factors that were used in this analysis for both impact and vibratory pile driving. Weighting factors were derived from the marine mammal and sea turtle weighting functions by using the National Marine Fisheries Service (NMFS) default frequencies based on the type of pile driving (see the NOAA "Fisheries Section 7 Consultation Guidance" in (National Oceanic and Atmospheric Administration, n.d.). These standard values are as follows:

- 2 kHz for marine mammals exposed to impact pile driving
- 2.5 kHz for marine mammals exposed to vibratory pile driving
- 0.16 kHz for sea turtles exposed to impact or vibratory pile driving

The NMFS risk criteria were applied to estimate behavioral effects from impact and vibratory pile driving. Frequency weighting was not used for behavioral response criteria for impact or vibratory pile driving and extraction.

The criteria and thresholds for the effects of pile driving acoustics on fishes are described in the AFTT and HCTT EIS/OEISs and are largely consistent with the ANSI sound exposure guideline technical report (Popper et al. 2014). Sound pressure level and cumulative sound exposure criteria are used to estimate ranges to mortality and non-auditory injury. Cumulative sound exposure criteria are used to estimate ranges to TTS.

Table 7. Weighting factors applied to each hearing group for impact and vibratory pile driving: applies to TTS and INJ effects only

Marine Species Hearing Groups	Weighting Factor for Vibratory Pile Driving (cSEL)	Weighting Factor for Impact Pile Driving (cSEL)
Very-low-frequency cetaceans	−0.09	−0.03
Low-frequency cetaceans	−0.01	−0.05
High-frequency cetaceans	−2.32	−3.45
Very-high-frequency cetaceans	−17.41	−21.19
Otariids (in-water)	−3.54	−5.23
Phocids (in-water)	−0.45	−0.80
Sirenians	−10.08	−12.86
Sea turtles	−5.86	−5.86

Note: cSEL is the cumulative sound exposure level.

6.3 ACOUSTIC PARAMETERS

Measured sound levels specific to port damage repair exercises are available only for one pile size and type (24-inch steel sheet piles using a vibratory hammer). All other sound levels used in this analysis were derived from surrogate measurements that utilize similar pile sizes, types, and methods. A summary of the sound levels for each pile size and type to be used during port damage repair activities is provided in the AFTT and HCTT EIS/OEISs.

Consistent with recommendations from NMFS, the transmission loss (TL) was assumed to be equal to $15 * \log 10\,(\text{range})$. As this standard value does not account for absorption or attenuation, predicted ranges to effects and resulting ZOIs may overestimate the actual footprint of the ensonified area and therefore may overestimate the number of potential effects.

6.4 RANGE-TO-EFFECT

6.4.1 Marine Mammals and Sea Turtles

Ranges to potential effects (e.g., behavioral response, TTS, and AINJ) were calculated using the equation for TL reported in Section 6.3. The functional threshold for a given effect was subtracted from the source level of a given pile (specific to the size, type, and method) to find the TL needed to reach that threshold. For TTS and AINJ, the functional threshold was found by adding the weighting factor (see Table 7) to the species-specific hearing group TTS or AINJ weighted threshold. The thresholds that were used for the behavioral response criteria were not weighted. The metric used to estimate TTS and AINJ effects was the cumulative sound exposure level (cSEL), which increases with the signal duration, based on the number of strikes for impact pile driving, given by Equation (22), or the number of seconds for vibratory pile driving or extraction, given by Equation 23.

$$\text{cSEL} = \text{single strike SEL} + 10 * \log_{10}(\text{nbr of strikes})\,. \qquad (22)$$

$$\text{cSEL} = 1\ \text{second SEL} + 10 * \log_{10}(\text{nbr of seconds})\ . \tag{23}$$

Based on the best available science regarding animal reactions to sound, selecting a reasonable accumulation period is necessary to accurately reflect the period that an animal is likely to be exposed to the sound. A representative duration of 5 minutes (300 seconds) was used for this accumulation period, with approximately 35 to 60 strikes per minute per pile for piles driven using the impact method (see details in the AFTT EIS/OEIS (U.S. Department of the Navy, n.d.-b) and HCTT EIS/OEIS (U.S. Department of the Navy, n.d.-a)). The 5-minute duration was chosen because most marine mammals and sea turtles should be able to easily move away from the expanding ZOI of TTS/AINJ within this timeframe, especially considering the soft start procedures of the Action Proponents which may "warn" marine species and cause them to move away from the sound source before impact pile driving increases to full operating capacity. Alternatively, animals could avoid the zone altogether if they are outside the immediate area upon startup. This should reduce their exposure to higher levels of individual pile strikes, thereby reducing their cumulative SEL.

Once the difference between the source level and the appropriate criteria was found, the range to this TL was solved for AINJ and TTS effects by using Equation (24) and for behavioral effects by using Equation (25).

$$10 * 10^{\left(\frac{\text{Source Level [cSEL]} - \text{Functional Threshold}}{\text{spreading coefficient}}\right)}. \tag{24}$$

$$10 * 10^{\left(\frac{\text{Source Level [dB rms]} - \text{Functional Threshold}}{\text{spreading coefficient}}\right)}. \tag{25}$$

These solutions provided the single-pile range-to-effect for each effect category and each marine species hearing group. The range-to-effects values are shown in the AFTT and HCTT EIS/OEIS.

6.4.2 Fishes

Ranges-to-effects were also calculated for fishes. As in the methods described above, thresholds to TTS, injury, and mortality were subtracted from the source level of a given pile to find the TL needed to reach that specific threshold. Because weighting functions do not exist for fishes, this part of the calculation was not performed. Additionally, two separate exposure durations were selected to allow estimates of potential ZOIs for passing or migratory species versus ZOIs for species that may remain near the activity for longer durations (e.g., resident species). Brief exposures were defined as 5 minutes of impact pile driving (175 strikes), and long exposures were defined as 1 day (e.g., 4 piles per day $*$ 175 strikes = 700 strikes per day). The ranges-to-effects are shown in the AFTT EIS/OEIS (U.S. Department of the Navy, n.d.-b) and HCTT EIS/OEIS (U.S. Department of the Navy, n.d.-a).

6.5 CALCULATING THE NUMBER OF EFFECTS PER SPECIES AND STOCK

The ZOI for an effect is the area that encompasses the sound levels at or above a threshold for that given effect up 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 AINJ threshold. The number of times marine mammals or sea turtles could be affected was found by multiplying these ZOIs by the density of marine species in the area.

To calculate the total ZOI, one of two methods were used depending on the study area. For the AFTT, the single-pile ZOI was needed first. Since pile driving activities for port damage repair occur in the nearshore environment and animals would generally be seaward of the area, the area of a circle (for ZOIs that do not overlap major land features) or a half-circle (for ZOIs that overlap land features) was calculated with a range (i.e., radius) to each effect category for impact and vibratory pile driving. The single-pile "ring-shaped" or "c-shaped" ZOI for each effect was then found by subtracting the next smaller effect area (i.e., the higher-order effect): $\text{TTS ZOI} = \text{TTS Area} - \text{AINJ Area}$). For the HCTT, a multi-ring buffer analysis tool in Geographic Information System (GIS) was used to estimate the ZOI as it expanded by 1-meter increments limited to the boundaries of the harbor where the port damage repair activities would occur. This tool created a lookup table that was used to pull the appropriate ZOI based on the available ranges-to-effects values.

As mentioned above, marine mammals and sea turtles are likely to leave the immediate area of pile driving and extraction activities and are 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 animat "refresh rate" of 10% was selected. This means that 10% of the single-pile ZOI is added for each consecutive pile within a given 24-hour period to generate the daily ZOI per effect category. These daily ZOI values are then multiplied by the number of days of pile driving and pile extraction, and the result is summed to generate a total ZOI per effect category (i.e., behavioral response, TTS, AINJ). These total ZOI values are then multiplied by the density of marine species to produce estimates of the number of times that animals of each species could be affected.

APPENDIX — MARINE MAMMAL SWIM SPEED AND DURATION DATA

Table 8. Summaries of studies with baseline and avoidance swim speed and duration data for marine mammals

Hearing Group	Species	Condition (Baseline or Type of Stressor)	Swim Speed (m/s)	Avoidance Duration (min)	Notes and Caveats	References
Sensitive Species Behavioral Group						
High-frequency cetaceans	Baird's beaked whale	Sonar	2.4–3.0	120	Avoided for the duration of exposure	Stimpert et al. (2014)
		Baseline	1.4–1.5	--		Stimpert et al. (2014)
	Blainville's beaked whale	Sonar	3.0	NA	Maximum swim speed	Tyack et al. (2011)
		Baseline	1.5	--		Baird et al. (2006); Baird et al. (2008); Madsen et al. (2005); Tyack et al. (2006); Waring et al. (2001)
	Cuvier's beaked whale	Sonar	2.6–3.1	99		DeRuiter et al. (2013)
		Baseline	1.5	--		Baird et al. (2006); Baird et al. (2008); Madsen et al. (2005); Tyack et al. (2006); Waring et al. (2001)
	Northern bottlenose whale	Sonar	1.0–5.0	390–480	Minimum avoidance duration (tag limitations)	Lam et al. (2016); Miller et al. (2015); Sivle et al. (2015); Wensveen et al. (2019)
		Baseline	0.5–4.0	--		Wensveen et al. 2019)
Very-high-frequency cetaceans	Harbor porpoise	Vessel	5.8–6.2	NA	Avoidance swim speed when chased by a boat	Gaskin, Arnold, and Blair. (1974); Johnston (2002)
		Pile driving	NA	43–8468		Dähne et al. (2013); Kastelein et al. (2018); Haelters et al. (2014)
		Acoustic harassment device	1.4–4	16–42	Most ($N = 5$) avoided, sometimes more than doubling swim speed within 30 seconds. One froze near seafloor in response.	Elmegaard et al. (2023)
		Baseline	0.7–4.6	--	Most baseline swim speed records < 1.5 m/s. Brandt et al. (2011) used high baseline swim speed (4.3 m/s) in seismic avoidance paper.	Brandt et al. (2011); Carstensen, Henriksen, and Teilmann (2006); Elmegaard et al. (2023); Osmek et al. (1996); Westgate et al. (1995); Otani et al. (2000); Otani et al. (1998)

Hearing Group	Species	Condition (Baseline or Type of Stressor)	Swim Speed (m/s)	Avoidance Duration (min)	Notes and Caveats	References
Odontocete Behavioral Group						
High-frequency cetaceans	Killer whale	Sonar	1.0–4.0	240		Lam et al. (2016); Miller (2012); Miller et al. (2011); Miller et al. (2014); Sivle et al. (2012)
		Vessel (tour boat)	1.0–4.0	240	BRS data of individual whale swim speed provided	Evans (1996); Kruse (1991)
		Baseline	0.5–4.0	--		Miller (2012); Miller et al. (2014)
	Sperm whale	Sonar	0.5–3.0	42	BRS data of individual whale swim speed provided. This is vertical avoidance swim speed (*N* = 16).	Isojunno et al. (2021); Isojunno et al. (2020); Miller (2012); Lam et al. (2016); Miller et al. (2011); Sivle et al. (2012)
		Baseline	0.25–3.0	--	Data of individual whale swim speeds provided (*N* = 18).	Amano and Yoshioka (2003); Aoki et al. (2007); Miller et al. (2008); Miller et al. (2004); Miller (2012); Watwood et al. (2006)
	Long beaked common dolphin	Sonar	2.8	NA	Did not increase swim speed in response to sonar	Durban et al. (2022)
		Baseline	3.5	--		Durban et al. (2022)
	Pilot whale	Sonar	1.0–5.0	13	Typically 1–3 m/s “except for occasional sprints”. Whales increased or decreased speed in response to sonar (Antunes et al 2014).	Antunes et al. (2014); Lam et al. (2016); Miller et al. (2011); Miller (2012); Sivle et al. (2012)
		Baseline	0.5–3.0	--		Antunes et al. (2014); Miller (2012)
	White-beaked dolphin	Baseline	1.7–8.3	--	Typical range is 1.7–3.3 m/s but speeds up to 8.3 m/s have been recorded.	Kinze (2009); Evans and Smeenk (2008)

Hearing Group	Species	Condition (Baseline or Type of Stressor)	Swim Speed (m/s)	Avoidance Duration (min)	Notes and Caveats	References
Mysticete Behavioral Group						
Very-low-frequency cetaceans	Blue whale	Sonar	0.5–8.0	NA		Southall et al. (2019); Goldbogen et al. (2013)
		Seismic	1.6–1.9	NA		Dunn and Hernandez (2009)
		Baseline	1.6	--		Calderan et al. (2023)
	Fin whale	Baseline	1.6	--		Acevedo-Gutiérrez et al. (2002); Croll et al. (2001); Goldbogen et al. (2006)
Low-frequency cetaceans	Gray whale	Sonar	1.7	NA	Slowed in response to sonar.	Frankel and Stein (2020)
		Seismic	1.4–2.5	NA	$N = 1$.	Gailey et al. (2016)
		Drilling playback	1.7–2.7	NA		Malme et al. (1984)
		Baseline	0.6	--	$N = 1$.	Gailey et al. (2016)
	Humpback whale	Sonar	0.25–3.8	14	BRS data of individual whale swim speeds provided.	Henderson et al. (2019); Kvadsheim et al. (2011); Kvadsheim et al. (2012); Lam et al. (2016); Wensveen et al. (2017); Sivle et al. (2015)
		Seismic	5.0	NA		Dunlop et al. (2015)
		Killer whale playback	1.5–3.3	NA		Kvadsheim et al. (2012)
		Baseline	0.25–4.3	--	Data of individual whale swim speeds provided ($N = 9$). Most typical range = 0.44–1.11 m/s.	Dunlop et al. (2015); Henderson et al. (2019); Kavanagh (2014); Noad and Cato (2007)
	Minke whale	Sonar	0.3–4.4	180	BRS data of individual whale swim speeds provided.	Kvadsheim et al. (2011); Lam et al. (2016); Sivle et al. (2015)
		Baseline	0.25–2.0	--	Data of individual whale swim speeds provided; minimum avoidance duration (tag limitations).	Lam et al. (2016); Sivle et al. (2015)

Hearing Group	Species	Condition (Baseline or Type of Stressor)	Swim Speed (m/s)	Avoidance Duration (min)	Notes and Caveats	References
Pinniped Behavioral Group						
Otariid and other non-phocid marine carnivores in water	California sea lion	Baseline	0.8	--		Feldkamp et al. (1989); Kuhn (2006); Weise, Coasta, and Kudela (2006)
Phocid carnivores in water	Harbor seal	Baseline	0.4	--		Baechler, Beck, and Bowen (2002); Coltman et al. (1997); Eguchi and Harvey (2005); Frost, Simpkins, and Lowry (2001); Gjertz, Lydersen, and Wiig (2001); Hastings et al. (2004); Lander et al. (2002); Lesage, Hammill, and Kovacs (1999); Lowry et al. (2001); Tollit et al. (1998)
	Northern elephant seal	Baseline	1.5–1.7	--		DeLong and Stewart (1991); Hassrick et al. (2007); Le Boeuf et al. (2000); Le Boeuf and Laws (1994); Le Boeuf et al. (1996); Le Boeuf et al. (1989)
	Ringed seal	Seismic	NA	NA	No swim speeds recorded, just behavior. 39% of population swam away, 36% dove. No mention of swim speed, but seals swam away/avoided closest zone to seismic (150 meters) and did not displace much past 250 meters.	Harris, Miller, and Richardson (2001)
	Bearded seal	Seismic	NA	NA		

NA = not available. Avoidance durations could be longer than those specified owing to limitations in field data collection and, as a conservative measure, should be interpreted as minimum avoidance durations, especially when noted.

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