Application for Letter of Authorization
for the Non-Lethal Taking of Marine Mammals:

bp Sustainable Seismic Field Trial
Outer Continental Shelf, Gulf of Mexico

Prepared by:

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Prepared for:
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Application for Letter of Authorization for the Non-Lethal Taking of Marine Mammals: bp Sustainable Seismic Field Trial Outer Continental Shelf, Gulf of Mexico

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INT-02					

Client deliverable

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List of Acronyms and Abbreviations

μPa	micropascal
BOEM	Bureau of Ocean Energy Management
bp	BP Exploration & Production Inc.
CFR	Code of Federal Regulations
dB	decibel
EWG	expert working group
FR	*Federal Register*
GOMx	Gulf of Mexico
HFC	high-frequency cetacean
ITR	Incidental Take Regulation
LOA	Letter of Authorization
LFC	low-frequency cetacean
MFC	mid-frequency cetacean
MMPA	Marine Mammal Protection Act
NMFS	National Marine Fisheries Service
PTS	permanent threshold shift
re	referenced to
SEL_{24h}	sound exposure level over 24 hours
SL	source level

1.0 Description of Proposed Activities

In accordance with the final incidental take regulation (ITR) published 24 April 2024 (89 *Federal Register* [FR] 31488), which went into effect 24 May 2024 during which survey coverage is being requested, BP Exploration & Production Inc. (bp), hereinafter referred to as the "Applicant", submits this request for a Letter of Authorization (LOA) for the non-lethal, unintentional taking of small numbers of marine mammals resulting during operations of a marine vibrator source array in the Gulf of Mexico (GOMx). The information provided in this document is submitted in accordance with the final ITR published 24 April 2024 (89 FR 31488) and the requirements of 50 Code of Federal Regulations (CFR) § 216.104 to allow for take by incidental harassment of small numbers of marine mammals resulting from geophysical surveys for oil and gas exploration activities.

1.1 PROJECT DESCRIPTION

bp proposes to conduct the Sustainable Seismic Field Trial in the Atlantis prospect area centered around Green Canyon (GC) block 743 for a duration of 10 to 14 days. The survey is expected to begin no earlier than November 2024. The marine vibrator source array will be deployed from the robotic survey vessel as described in the follow subsections.

The prospect area under consideration is located in the Green Canyon lease area. In 2024, the Applicant anticipates a single Field Trial within this prospect area. **Table 1** provides the protraction blocks for the primary boundaries of this prospect. Surrounding blocks may be included in some surveys; however, all blocks involved in the survey will remain in either zone 5 or zone 7.

Table 1. Primary Gulf of Mexico protraction blocks for the Sustainable Seismic Field Trial in which survey will occur.

Atlantis
GC: 566, 609, 610, 611, 654, 655, 698, 699, 700, 743, 744, 787, 789, 832, 833, 876, 877, 878, 920, 921
Sustainable Seismic Field Trial
GC: 566, 609, 610, 611, 654, 655, 698, 699, 700, 743, 744, 787, 789, 832, 833, 876, 877, 878, 920, 921

GC = Green Canyon.

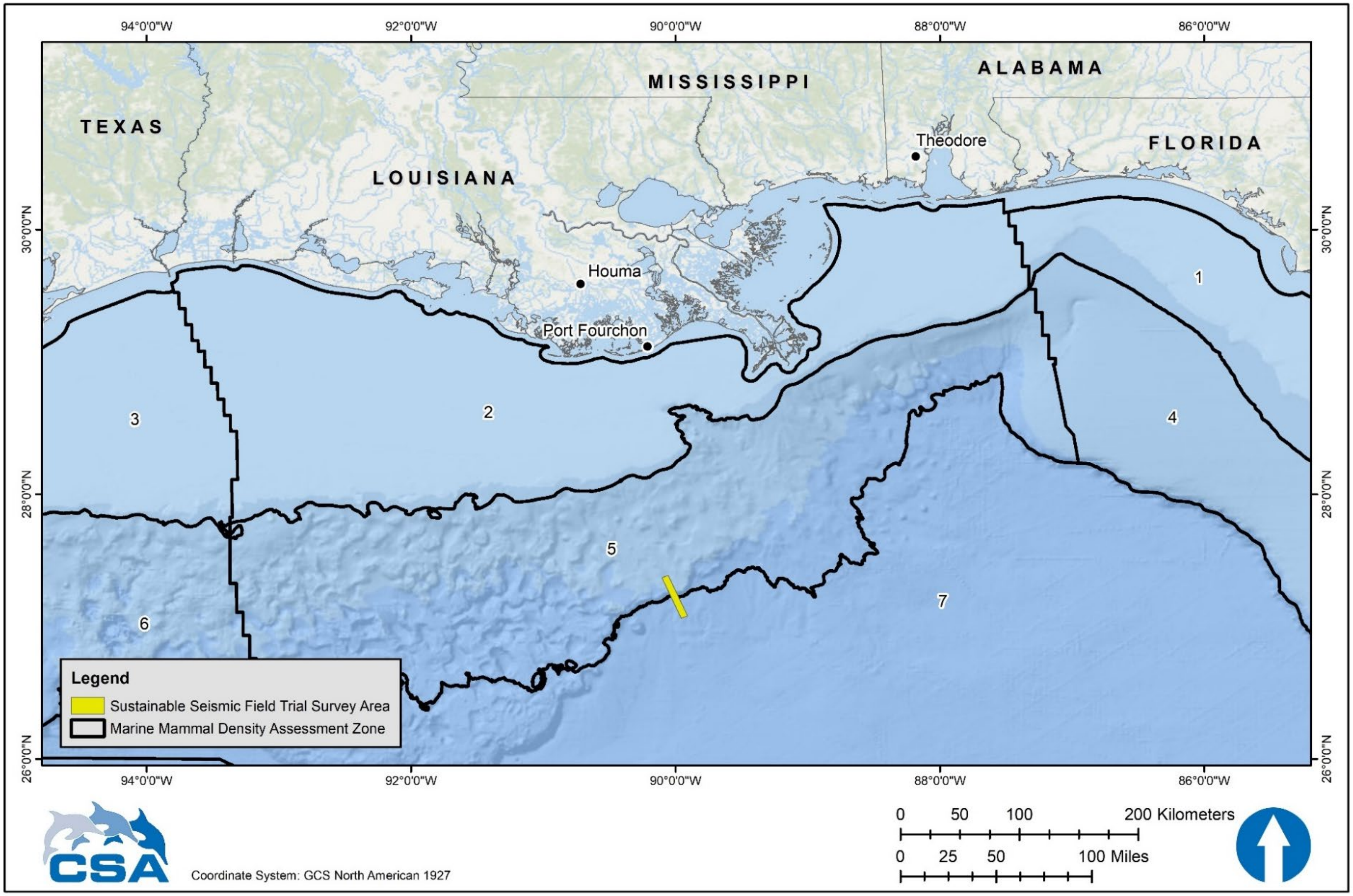

Figure 1. Location of the proposed marine vibrator source array Field Trial in bp Exploration & Production Inc. Atlantis prospect area located within the Bureau of Ocean Energy Management's (BOEM's) Gulf of Mexico Central Planning Area in relation to the assessment zones identified in the Incidental Take Regulation (ITR) (89 Federal Register [FR] 31488).

1.1.1 Activities Considered in Application

The marine vibrator source array proposed for the Sustainable Seismic Field Trial is the C-BASS. The C-BASS source array was designed by bp based on the GeoSpectrum C-BASS series of sound sources for the purposes of the Sustainable Seismic Field Trial. A single 10- to 14-day Field Trial using the C-BASS source array is expected to begin no earlier than November 2024 in the Atlantis prospect area. The total duration of the Field Trial is estimated to be a maximum of 14 days. The survey is expected to occur in the Fall.

1.1.2 Acoustic Sources

The marine vibrator source array proposed for the Sustainable Seismic Field Trial an array of six M72-15 C-BASS units and two M72-30 C-BASS units. The C-BASS source array was designed by bp based on the GeoSpectrum C-BASS series of sound sources for the purposes of the Sustainable Seismic Field Trial. The eight total source units (six M72-15 and two M72-30 C-BASS units) will be mounted on a tow body as shown in **Figure 2**. Both sets of units have an 8.25 s overlapping sweep, with a small amount of dither, followed by a 7.5 s rest period after the sweep, corresponding to a signal duty cycle of approximately 50%. The M72-30 C-BASS unit signal will lag the M72-15 C-BASS unit signal by 0.5 s. The duty cycle can be defined as the duration of a signal divided by the sum of signal duration and the interval between signals (Hartmann 1997). The dominant frequencies of the C-BASS sweep are between 10 to 50 Hz, with minimal signal energy occurring above 100 Hz (**Table 2**). The C-BASS Field Trial will be conducted using a single source vessel (the Armada 78 02 described in **Section 2.2**) sailing at 3 knots along the same racetrack pattern, parallel to the 153°to 333° azimuths. The C-BASS source array lines will be spaced 93 m apart, with the source array towed at an average depth of 12 m. Three nodes will be deployed using the Seaeye Leopard remotely operated vehicle (ROV) during the Field Trial to record the source characteristics of the C-BASS and will be placed in the following coordinates:

- Node #1 – E: 792925.4, N:3021462.0
- Node #2 – E: 791582.3, N: 3020849.9
- Node #3 – E: 787553.0, N: 3019013.6

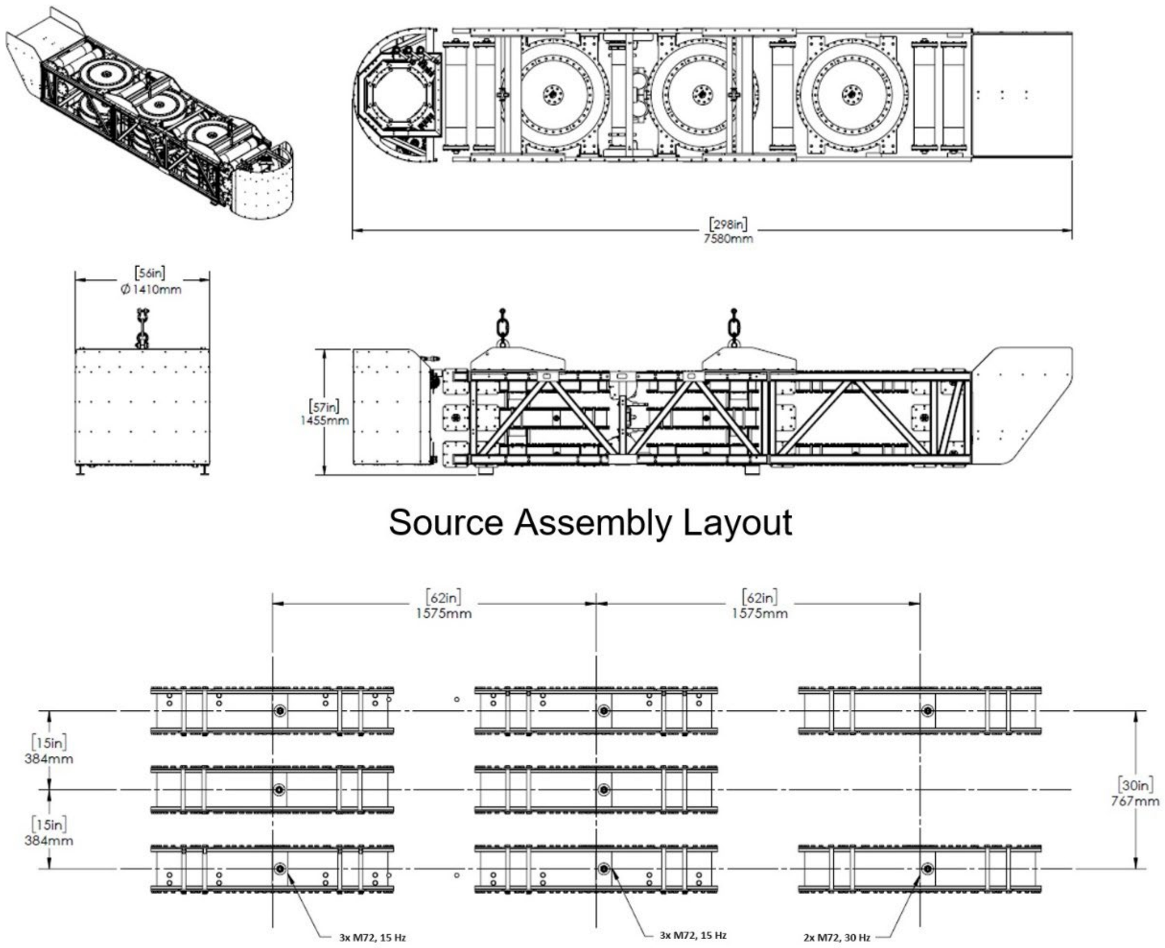

Figure 2. Overview of the individual C-BASS system units (top) and eight-unit array (bottom).

Table 2. Survey specifications for the C-BASS source array proposed for the Sustainable Seismic Field Trial.

Source Information	Sustainable Seismic Field Trial
Mean vessel survey speed (knots)	3
Approximate total survey area (km^2)	185.7
Average tow depth (m)	12
SL (SEL) in dB re 1 μPa^2 m^2 s	212[1]
SL (SPL) in dB re 1 μPa m	199.6[2]
Frequency range (Hz) for full array	10-50
Sweep duration (s) (all units)	8.25

μPa = micropascal; dB = decibel; re = referenced to; SL = source level; SEL = sound exposure level; SPL = root-mean-square sound pressure level.

[1] The source level provided in this table represents the horizontal source level modeled by JASCO (**Appendix**) for the full C-BASS source array (i.e., all eight units) towed at approximately 12 m for the full frequency range produced by the entire source array.

[2] This source level represents the highest source level produced by the either of the two C-BASS unit types proposed for this source array, as provided in the accompanying Geological and Geophysical (G&G) permit application submitted to the Bureau of Ocean Energy Management (BOEM).

2.0 Survey Dates, Duration, and Specific Geographic Region

2.1 SURVEY ACTIVITY DATES AND DURATION

Survey activities considered under this Application will occur no earlier than November 2024. The field trial will take up to 14 days (**Section 1.0**).

2.2 SPECIFIC GEOGRAPHIC REGION

The Applicant's survey activities will occur within the Atlantis prospect area within the Bureau of Ocean Energy Management's (BOEM's) Central Planning Area of the GOMx (**Figure 1**). The proposed prospect area falls within ITR assessment zones 5 and 7.

3.0 Species and Numbers of Marine Mammals

Marine mammal species occurring in the U.S. GOMx were identified and provided in the 2021 ITR (86 FR 5322) and updated with new information in the 2024 final rule (89 FR 31488). Information about each species distribution, abundance, and status can be found in that document. A summary of the GOMx species with predicted abundance estimates from the ITR (89 FR 31488) is provided in **Table 3**.

Table 3. Summary of marine mammals of the northern Gulf of Mexico.

Common Name	Scientific Name	Stock	ESA/MMPA Stock Status	Predicted Abundance Estimates[1]
Rice's whale	*Balaenoptera ricei*	Northern Gulf of Mexico	E/S	37
Sperm whale	*Physeter macrocephalus*	Northern Gulf of Mexico	E/S	3,007
Atlantic spotted dolphin	*Stenella frontalis*	Northern Gulf of Mexico	NS	1,782[2]
Beaked whale	*Ziphius cavirostris* and *Mesoplodon* spp.	Northern Gulf of Mexico	NS	803[3]
Common bottlenose dolphin	*Tursiops truncatus*	Northern Gulf of Mexico	NS	9,672[4]
Clymene dolphin	*Stenella clymene*	Northern Gulf of Mexico	NS	4,619
False killer whale	*Pseudorca crassidens*	Northern Gulf of Mexico	NS	6,113[5]
Pygmy killer whale	*Feresa attenuata*	Northern Gulf of Mexico	NS	
Killer whale	*Orcinus orca*	Northern Gulf of Mexico	NS	
Melon-headed whale	*Peponocephala electra*	Northern Gulf of Mexico	NS	
Fraser's dolphin	*Lagenodelphis hosei*	Northern Gulf of Mexico	NS	1,665
Pantropical spotted dolphin	*Stenella attenuata*	Northern Gulf of Mexico	NS	67,225
Risso's dolphin	*Grampus griseus*	Northern Gulf of Mexico	NS	1,501
Rough-toothed dolphin	*Steno bredanensis*	Northern Gulf of Mexico	NS	4,853
Short-finned pilot whale	*Globicephala macrorhynchus*	Northern Gulf of Mexico	NS	2,741
Spinner dolphin	*Stenella longirostris*	Northern Gulf of Mexico	NS	5,548
Striped dolphin	*Stenella coeruleoalba*	Northern Gulf of Mexico	NS	5,634
Kogia spp.	*Kogia breviceps* and *Kogia sima*	Northern Gulf of Mexico	NS	980[4]

[1] Abundance estimates from the final incidental take regulation (ITR) published 24 April 2024 (89 FR 31488).

[2] The mean abundance for Atlantic spotted dolphins is based on the oceanic population in the final 2024 ITR (89 FR 31488).

[3] Due to difficulty in identifying to species level during visual surveys, *Kogia* spp. and beaked whale species are grouped into guilds and abundance estimates are provided for these guilds rather than each species.

[4] The mean abundance for common bottlenose dolphins is based on the oceanic population in the final 2024 ITR (89 FR 31488).

[5] The mean abundance for these four species is based on the estimated for an undifferentiated blackfish guild provided in the final 2024 ITR (89 FR 31488).

ESA = Endangered Species Act; E = endangered; MMPA = Marine Mammal Protection Act; NS = non-strategic stock; S = strategic stock.

4.0 Affected Species Status and Distribution

Affected species status and distribution were examined by the National Marine Fisheries Service (NMFS) within the scope of the proposed regulation, and more information can be found in the published 2024 ITR (89 FR 31488).

5.0 Type of Incidental Taking Authorization Requested

The Applicant requests an LOA pursuant to Section 101 (a)(5)(D) of the Marine Mammal Protection Act (MMPA) for incidental take by behavioral harassment of small numbers of marine mammals during geophysical surveys conducted as part of oil and gas exploration and production activities within the U.S. GOMx. Proposed activities, as outlined in **Section 1.0**, have the potential to impact marine mammals from sounds generated by the vessel and survey equipment.

The C-BASS source array described in **Section 1.0** has an estimated source level (SL), expressed as SEL, of 212 dB re 1 µPa m, and an estimated SL expressed as SPL of 199.6 dB re 1 µPa m (**Table 2**) that would propagate sound levels that may exceed established acoustic thresholds for marine mammals (Wood et al., 2012; NMFS 2023). Acoustic thresholds are received sound levels that meet current scientific criteria as sufficient for eliciting the onset of a permanent threshold shift (PTS), termed Level A harassment, or a behavioral response, termed Level B harassment.

The C-BASS source array was not specifically modeled as part of the 2024 ITR (89 FR 41533); however, acoustic propagation modeling, using the same methodologies applied in the 2024 ITR, was conducted for the C-BASS source array to estimate ranges to the acoustic thresholds for marine mammals (**Appendix**) and are summarized in **Table 4**. The source array characteristics described in **Section 1.0** are consistent with those modeled and assessed in the final 2024 ITR (89 FR 31488) under which authorization for the proposed Field Trial is being requested, so all potential effects would fall within the range of those expected in that assessment.

Table 4. Maximum modeled acoustic threshold ranges for low frequency cetaceans and during operations of the C-BASS marine vibrator source array based on acoustic propagation modeling (**Appendix**).

Faunal Group	PTS Threshold Range[1] (m)	Behavioral Disturbance Threshold Range[2] (m)
LFC	<20	190
MFC	-	190
HFC	-	190

- = indicates the threshold was not reached; HFC = high-frequency cetacean; LFC = low-frequency cetacean; MFC = mid-frequency cetacean; PTS = permanent threshold shift.

[1] The modeling report in Appendix modeled threshold ranges for the National Marine Fisheries Service (NMFS; 2018) PTS thresholds for impulsive sources for the C-BASS to be directly comparable to seismic array sources.

[2] The behavioral threshold modeling in **Appendix** modeled ranges to the threshold for a non-impulsive, intermittent source for the C-BASS source array, which follows the modeling used for high-resolution geophysical (HRG) sources in the 2024 Incidental Take Regulation (ITR).

Based on the frequency range of the source (<100 Hz) low-frequency cetaceans (LFC) are the only species for which the operational frequency of the C-BASS source array overlaps with the hearing range enough that acoustic effects could potentially occur. The source is not expected to overlap with the hearing range of high-frequency cetacean (HFC) species and would only overlap with the lower end of mid-frequency cetacean (MFC) hearing where their sensitivity to underwater sound is lower and therefore responses are less likely. This is further validated by the modeling results in **Table 4** which indicate the frequency-weighted sound exposure level over 24 hours (SEL_{24h}) PTS threshold was only exceeded for low-frequency cetaceans. However, the range to the PTS threshold was estimated to be <20 m for low-frequency cetaceans, so the likelihood of PTS occurring for these species is extremely low. Similarly, the range to the behavioral disturbance threshold for marine mammals (which is not frequency weighted) was only estimated to extend to 190 m.

The Applicant expects that the potential for effects from this proposed survey would be less than that described for all of zones 5 and 7 in the 2024 ITR as the survey area is only a small portion of the larger zones (**Figure 1**). Therefore, the survey would only occur over 10 operational days instead of the annual scale over which exposures were calculated and assessed in the 2024 ITR. The Applicant is requesting authorization for incidental take by behavioral harassment of small numbers of marine mammals during the proposed sustainable seismic survey activities which is expected to remain under the small numbers standard and negligible impact determination provided in the 2024 ITR (89 FR 31488).

6.0 Effects on Marine Mammal Species or Stocks

Anticipated impacts on marine mammal habitat were examined by NMFS within the scope of the proposed regulation, and more information can be found in the 2024 published ITR (89 FR 31488).

Effects of proposed seismic survey activities for a period of up to 10 years throughout the U.S. GOMx were assessed in the ITR, following the expert working group (EWG) framework developed by Southall et al. (2014). This framework considers the context within which acoustic exposures will occur, along with the vulnerability of individual marine mammal stocks, to determine the likelihood of stock-related population-level impacts. The results of this analysis found that the total take from proposed activities will have only negligible impacts on all affected GOMx marine mammal stocks. A more detailed explanation can be found in the published 2024 ITR (89 FR 31488).

Given that the scope of activities proposed in this Application are less than that of the ITR, both in terms of spatial and temporal extent, the activities in this Application are expected to remain within this finding of only negligible impacts. The densities and take estimates assessed in the final 2024 ITR represent estimates for the entirety of zones 5 and 7, when in actuality the proposed activities would only cover up to 185.7 km^2 for the survey (**Table 2**), reducing the spatial extent of potential marine mammal encounters. Additionally, the take estimates do not account for mitigation which would be expected to negate any potential for Level A takes and reduce the risk of marine mammals experiencing biologically significant Level B harassment. Therefore, it is reasonable to assume that the project activities would not negatively affect stocks.

7.0 Minimization of Adverse Effects to Subsistence Uses

This section addresses NMFS' requirement to identify methods to minimize adverse effects of the proposed activity on subsistence uses.

There are no current subsistence hunting areas in the vicinity of any of the proposed lease blocks and there are no activities related to the proposed surveys that may affect the availability of a species or stock of marine mammal for subsistence uses. Consequently, there are no available methods to minimize potentially adverse effects to subsistence uses.

8.0 Anticipated Impacts on Habitat

Anticipated impacts on marine mammal habitat were examined by NMFS within the scope of the proposed regulation, and more information can be found in the 2024 published ITR (89 FR 31488).

9.0 Anticipated Effects of Habitat Impacts on Marine Mammals

Anticipated effects of habitat impacts on marine mammals were examined by NMFS within the scope of the proposed regulation, and more information can be found in the 2024 published ITR (89 FR 31488).

10.0 Mitigation Measures

This section addresses NMFS' LOA requirement to assess the availability and feasibility (economic and technological) of methods and manner of conducting these proposed survey activities that have the least practicable impact upon affected species or stock, their habitat, and their availability for subsistence uses, paying particular attention to rookeries, mating grounds, and areas of similar significance.

The Applicant has demonstrated a strong commitment to minimizing impacts to marine mammal species through a comprehensive and progressive mitigation and monitoring program. The Applicant will follow all monitoring and mitigation measures set forth in the ITR (89 FR 31488) that are applicable to air gun surveys with total source volumes below 1,500 in^3.

The mitigation measures will meet those currently required under existing regulations (e.g., BOEM Notice to Lessees and Operators 2016-G02, revised 19 June 2020) as well as additional mitigation outline in the published ITR (89 FR 31488) and the NMFS 2020 Biological Opinion and its appendices (NMFS, 2020), as they apply to the proposed survey activities, and may exceed these measures in certain cases where bp voluntary mitigation measures for protected species are more conservative than the existing regulations.

11.0 Arctic Plan of Cooperation

This requirement is applicable only for activities that occur in Alaskan waters north of 60° N latitude. The proposed survey activities will not take place within the designated region and, therefore, will not have an adverse effect on the availability of marine mammals for subsistence uses. As such, there is no need to form such a plan.

12.0 Monitoring and Reporting

The Applicant will comply with all monitoring and reporting guidelines provided in the 2024 published ITR (89 FR 31488) as they pertain to Protected Species Observer and passive acoustic monitoring data, and reporting injured or dead marine mammal species.

13.0 Suggested Means of Coordinated Research

Relevant research efforts which may effectively supplement the monitoring and reporting requirements pursuant to issued LOAs are described in detail by NMFS in the published ITR (89 FR 31488).

14.0 List of Preparers

CSA Ocean Sciences Inc.

- Mary Jo Barkaszi, Marine Mammal Programs Manager
- Kayla Hartigan, Project Scientist

bp

- David Duke, Senior Environment & Social Advisor
- Angie Batchelor, GOMx Seismic and Regulatory Compliance Advisor

15.0 References

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BP GoM Sustainable Seismic Animal Exposure Modeling Report

Underwater Acoustic Modeling

JASCO Applied Sciences (USA) Ltd

14 January 2025

Submitted to:
bp America

Authors:

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Project: P001859-001
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Version 2.0

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Report approved by:

Version	*Role*	*Name*	*Date*
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1.0	Senior Review	David Zeddies	18 Jul 2024
2.0	Project Manager	Mark Cotter	05 Aug 2024
2.0	Senior Review	David Zeddies	02 Aug 2024

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Executive Summary

BP Exploration & Production Inc. (bp) has requested a comparison of the predicted numbers of animals exposed to underwater sound generated by a novel vibrosource array and traditional airgun arrays. The acoustic propagation, animal movement and exposure modelling have been modeled for the Atlantis production field in the Central Planning Area of the Gulf of Mexico (GoM) (Figure 1). This modelling location is approximately 210 km south of the coast of Louisiana.

The vibrosource modeling included an array of eight C-BASS very-low-frequency seismic source units. The representative sweep cycle of the C-BASS is an intermittent signal, which includes quiet period during approximately half of the cycle. The C-BASS source array was designed by bp based on the GeoSpectrum C-BASS low frequency sound projector unit. Three different conventional airgun arrays, have been used for the comparison, defined by the specifications provided in Section 1.2.2. The four array types have been modeled over a period of three days using source effort sail lines designed for the field trial. The number of lines will be adjusted between the C-BASS array and conventional airgun array models to account for the different tow speeds for those array types.

This modelling effort evaluates potential acoustic effects to marine species present in the GoM and how that differs between source types. For all species the C-BASS source had a markedly lower number of exposures than the largest (5,110 in3) airgun array (This volume is representative of conventional airgun source arrays commonly used for deep penetration marine seismic surveys in the GoM region and elsewhere). Behavioral exposures for marine mammals were approximately 1% of the airgun array values while sea turtle behavioral exposures were about 6%. Physiological (TTS and PTS) exposures for the C-BASS array were mostly zero. However, when exposure to sound level above threshold values did occur with C-BASS, it was < 8% of the numbers predicted for the largest airgun array. These model results indicate that use of the C-BASS array could greatly reduce environmental impact of seismic surveys.

1. Introduction

BP Exploration & Production Inc. (bp) has requested a comparison of the predicted numbers of animals exposed to underwater sound by a novel vibrosource array and traditional airgun arrays. The acoustic propagation, animal movement and exposure modelling have been modeled for the Atlantis production field in the Central Planning Area of the Gulf of Mexico (GoM) (Figure 1). This modelling location is approximately 210 km south of the coast of Louisiana.

The C-BASS source was designed by bp based on GeoSpectrum C-BASS sound source elements. The source consists of two types of sweep units: six M72-15 and two M72-30, comprising eight total source units mounted on the tow body (Section 1.2.1). Both sets of units (M72-15 and M72-30) will sweep for 8 s, with the two signals overlapping. The M72-30 signal will lag the M72-15 by 0.5 s. The total sweep cycle will be repeated every 16 s with a 7.5 s quiet period in between sweeps. The dominant frequencies of the C-BASS sweep are between 10–50 Hz, with minimal signal energy occurring above 100 Hz.

The National Marine Fisheries Service (NMFS) characterizes sound sources as impulsive or non-impulsive for the purposes of selecting physiological effects criteria as well as intermittent or continuous for behavioral effects criteria ([NMFS] National Marine Fisheries Service (US) 2023a). The C-BASS sweep will emit sound for approximatley half of the total cycle and is therefore considered to be an intermittent signal with respect to behaivoral effects criteria. The C-BASS signal is also non-impulsive, so those non-impulsive physiological effects criteria will be used. Conventional seismic airgun arrays have been well-characterized and are classified as intermittent and impulsive sources.

bp provided the specifications of 680 in^3, 1000 in^3, and 5110 in^3 airgun arrays (see Section 1.2.2) that were modeled as a comparison to the Field Trial source. The acoustic characteristics of the airgun arrays were modeled with JASCO's Airgun Array Source Model that accounts for individual airgun volumes and the array geometry. Acoustic modeling was conducted using JASCO's Marine Operations Noise Model and full waveform modeling apprach (FWRAM). For a single pulse, sound propagation was modeled at distances up to 40 km from the sound sources at one location (Figure 1) with a single sound speed profile for the water column (September). Cumulative sound levels for each source throughout the Field Trial were computed by accumulating the individual pulses across their expected tow tracks.

Animal movement exposure modeling was conducted to further investigate the difference in the number of animals exposed to sound levels above recognised threshold values between the two array types. All marine mammals and sea turtles that could be expected in the area were modeled.

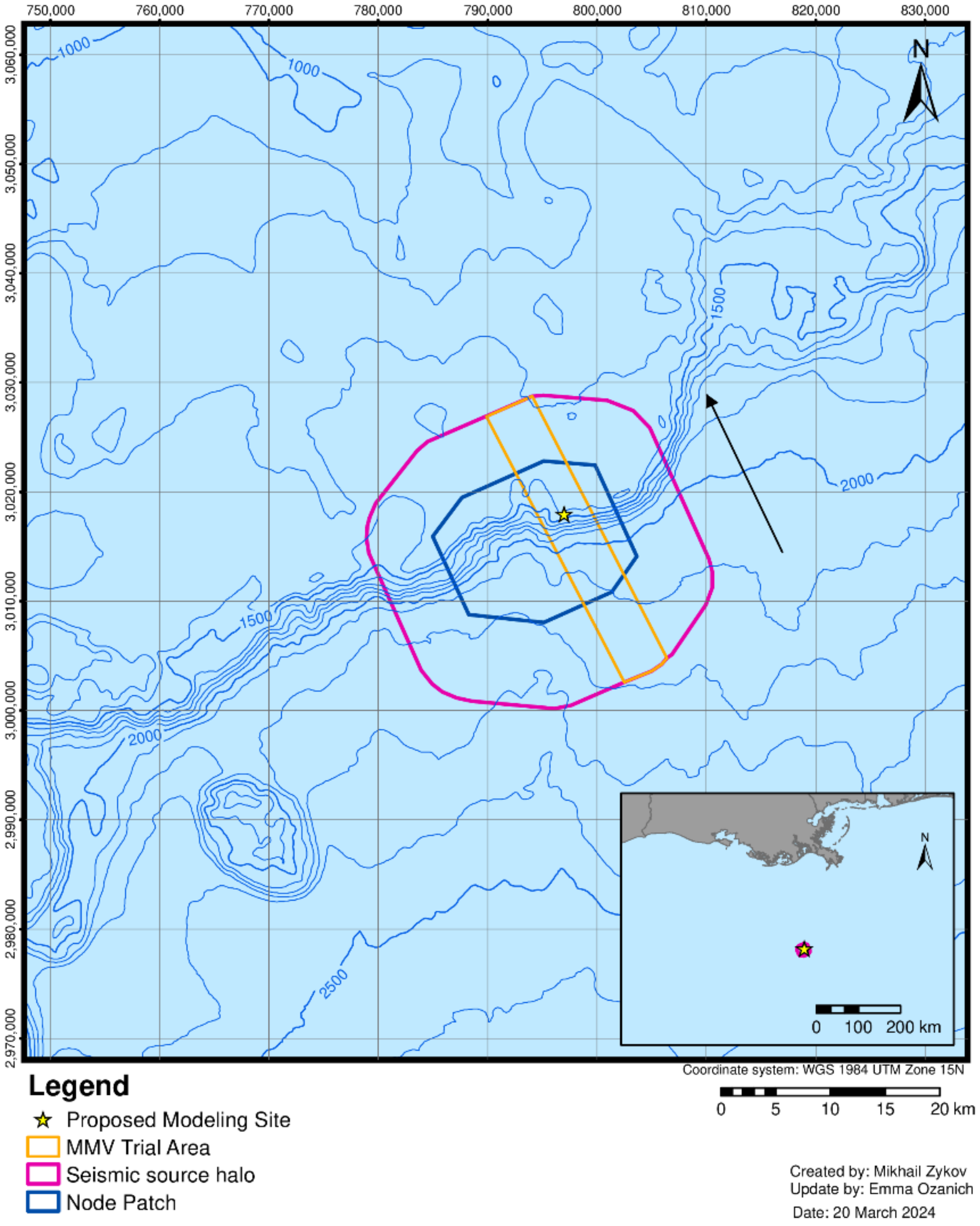

Figure 1. Example of the modeling area, showing proposed survey lines.

1.1. Animal Exposure Prediction Modelling Location

The 2024 Sustainable Seismic Source Field Trial is planned to begin in September 2024 at the Atlantis site, located 210 km south of coastal Louisiana, in a Field Trial area approximately 4.5 km x 27 km. Ocean depths within the trial site vary from 1300 m to 2200 m. The animal exposure modeling will be conducted using these site parameters and acoustic propagation modeling results.

The conventional airgun source arrays have been modeled using one source vessel sailing at 4.5 knots along parallel lines spaced approximately 305 ft (93 m) apart. The source vessel will tow two seismic source arrays, with the arrays alternately releasing an acoustic impulse every 176 ft (54 m) or one impulse every ~12 seconds, corresponding to a source point separation of 87 ft (26.5 m). For each of the airgun source scenarios, the vessel will tow the 680 in^3 and the 1000 in^3 arrays at 12 m depth, and the 5110 in^3 array at 15 m depth. The source effort sail lines move from west to east in a racetrack pattern along the 153°–333° azimuths (Figure 2). A total of 23 lines will be modeled to provide for three days of animal exposure modeling for each airgun array.

C-BASS modeling represents a single source vessel sailing at 3 knots along the same racetrack pattern, parallel to the 153°–333° azimuths. The C-BASS source lines are spaced 305 ft (93 m) apart. The C-BASS sweep cycle will occur every 16 s (Section 1.2.1), corresponding to a pulse step of 82 ft (25 m). A total of 15 lines will be modeled to provide for three days of animal exposure modeling for the C-BASS array.

A representative modeling site near the middle of the modelling area was selected at 27.25° N, 90.00° W (Figure 1; Table 1). The sound pressure level and propagation loss were modeled with an Nx2D approach using 36 radials (10° spacing) to simulate the acoustic sound field over a spatial area.

Table 1. Location and description of modeling scenarios considered.

Scenario	Site ID	Source type	Time of Year	Source depth (m)	Latitude	Longitude	UTM Zone 15N		Water depth (m)
							X (m)	Y (m)	
PP-1	S1	Marine Vibrosource	September	12	27.25°N	90.00°W	797000	3018000	1400.0
PP-2		Airgun array		15					
PP-3		Airgun array		12					
PP-4		Airgun array		12					

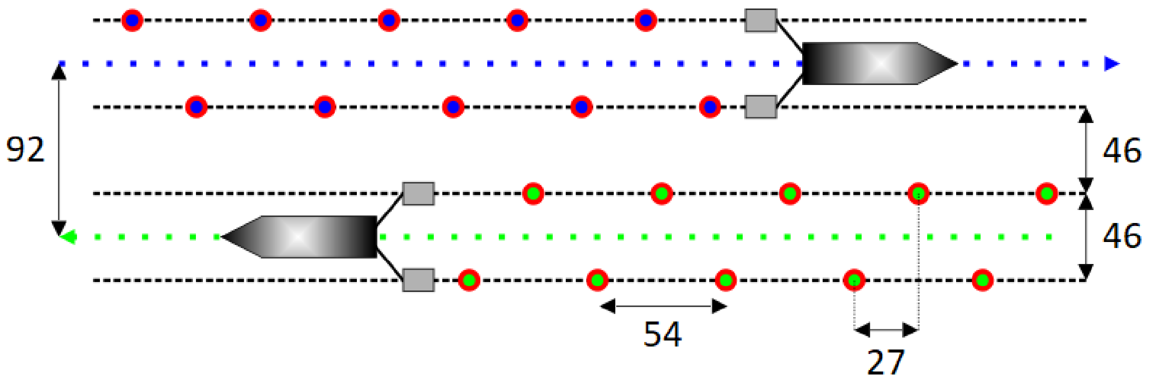

Figure 2. Example of the spacing for the racetrack tow pattern used for all source types. The track field was computed oriented N-S and then corrected for a true rotation angle of -27° E of N.

1.2. Acoustic Sources

Individual source types and scenarios proposed for the modelling comparison are summarized in Table 2. The sources include the C-BASS very-low-frequency marine vibrosource and three airgun arrays of varying displacement volume. Details of each source type and its operation are discussed in the sections following.

Table 2. Description of sources modeled for the Field Trial.

Scenario	Site ID	Source type	Model	Source depth (m)
PP-1	S1	C-BASS Marine Vibrosource	6×M72-15 + 2×M72-30	12
PP-2		Airgun array	Bp 5110 in^3	15
PP-3		Airgun array	Bp 680 in^3	12
PP-4		Airgun array	1000 in^3	12

1.2.1. Marine Vibrosource

The C-BASS source was designed by bp based on the GeoSpectrum C-BASS series of sound sources. The source consists of two types of sweep units: six M72-15 and two M72-30, with eight total source units mounted on a tow body (Figure 3). Both sets of units (M72-15 or M72-30) have an 8 s overlapping sweep, with the M72-30 signal lagging the M72-15 signal by 0.5 s for a total duration of 8.5 s. The sweep cycle is 16 s including a 7.5 s rest period after the sweep, corresponding to a signal duty cycle of 53%. The duty cycle can be defined as the duration of a signal divided by the sum of signal duration and the interval between signals (Hartmann 1997). The dominant frequencies of the C-BASS sweep are between 10–50 Hz, with minimal signal energy occurring above 100 Hz.

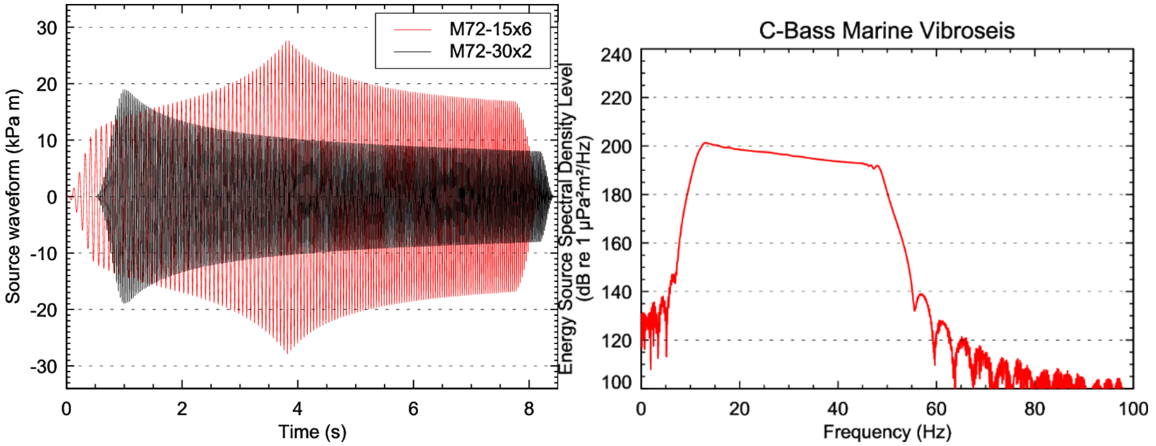

Figure 3. Plots of the C-BASS sweep timeseries (left) and spectral response (right) used as input for the acoustic models.

Table 3. Assumed source parameters for the marine vibrator source.

Parameter	Combined sources
Sweep	
Start frequency	
End frequency	
Sweep duration	8 s
Tapering function	
Tapering duration	
Peak pressure	208.8 dB re µPa^2
Description of harmonics	

1.2.2. Airgun arrays

bp provided the specifications of 680 in^3, 1000 in^3, and 5110 in^3 airgun arrays. The source engagement pattern and sail line sequence specific to an OBN seismic survey type was considered. The acoustic characteristics of the airgun array were modeled with JASCO's Airgun Array Source Model that accounts for individual airgun volumes and the array geometry. Acoustic modeling was conducted using JASCO's Marine Operations Noise Model and full waveform modeling apprach (FWRAM). For a single pulse, sound propagation was modeled at distances up to 40 km from the sound sources at one location (Figure 1) with a single sound speed profile for the water column (September). Cumulative sound levels for each source throughout the modelling scenario were computed by accumulating the individual pulses across their expected tow tracks.

Geometry and airgun volume for three arrays is shown in Tables and Figures 4, 5 and 6.The *x*-direction is positive with respect to the array tow direction and the *y*-direction is positive with respect to port side of the towing vessel.

Table 4. Coordinates of the elements within the 680 in^3 G-Gun array.

Gun	*x* (m)	*y* (m)	Volume (in^3)	Depth (m)
1	0.0	2.0	100.0	12
2	0.0	-2.0	40.0	12
3	2.0	2.0	150.0	12
4	2.0	-2.0	250.0	12
5	4.0	2.0	70.0	12
6	4.0	2.0	70.0	12

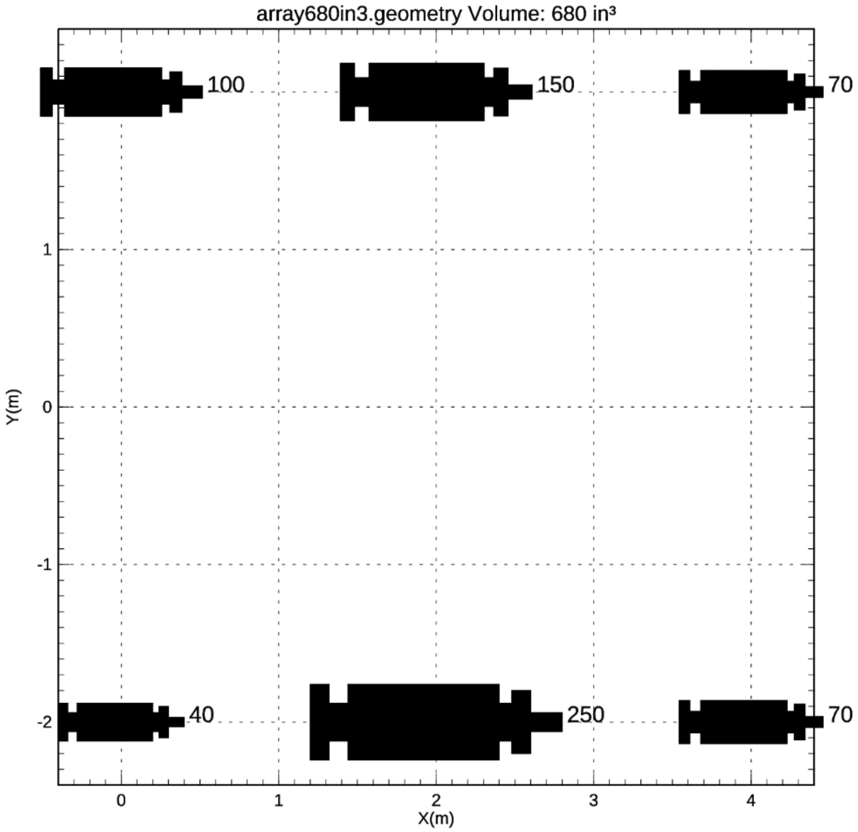

Figure 4. Map showing the elements within the 680 in³ G-Gun array.

Table 5. Coordinates of the elements within the 1000 in³ G-Gun array.

Gun	*x* (m)	*y* (m)	Volume (in^3)	Depth (m)
1	0	0.8	50.0	12
2	0	0.0	50.0	12
3	0	-3.8	50.0	12
4	0	-4.6	50.0	12
5	2	0.8	120.0	12
6	2	0.0	150.0	12
7	2	-3.8	150.0	12
8	2	-4.6	120.0	12
9	4	0.8	50.0	12
10	4	0.0	80.0	12
11	4	-3.8	80.0	12
12	4	-4.6	50.0	12

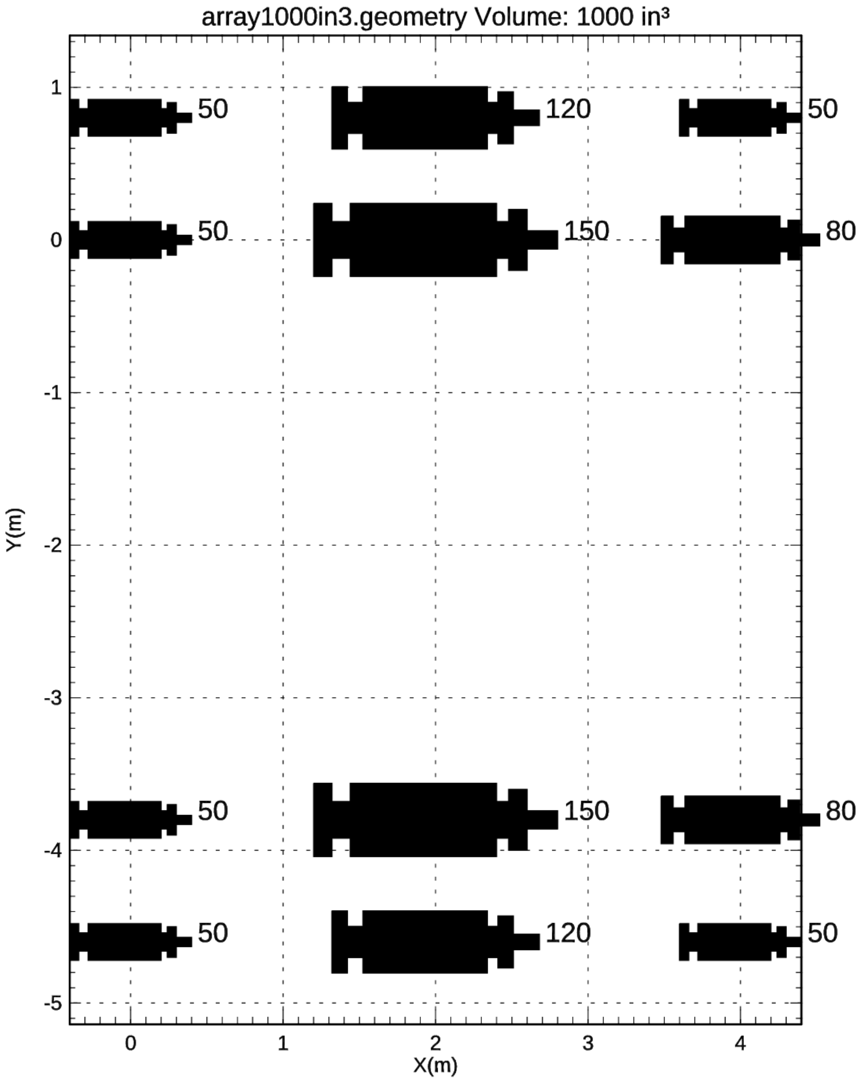

Figure 5. Map showing the elements within the 1000 in³ G-Gun array.

Table 6. Coordinates of the elements within the 5110 in³ T-Gun array.

Gun	*x* (m)	*y* (m)	Volume (in^3)	Depth (m)
1	0.0	-0.5	90.0	15
2	0.0	0.5	90.0	15
3	0.0	-6.0	140.0	15
4	0.0	6.0	90.0	15
5	2.5	-0.5	120.0	15
6	2.5	0.5	120.0	15
7	2.5	-5.5	155.0	15
8	2.5	5.5	155.0	15
9	2.5	-6.5	155.0	15
10	2.5	6.5	155.0	15
11	5.0	-0.5	250.0	15
12	5.0	0.5	250.0	15
13	5.0	-5.5	200.0	15
14	5.0	5.5	230.0	15
15	5.0	-6.5	200.0	15
16	5.0	6.5	230.0	15
17	7.5	-0.5	175.0	15
18	7.5	0.5	175.0	15
19	7.5	-5.5	230.0	15
20	7.5	5.5	200.0	15
21	7.5	-6.5	230.0	15
22	7.5	6.5	200.0	15
23	10.0	-0.5	120.0	15
24	10.0	0.5	120.0	15
25	10.0	-5.5	155.0	15
26	10.0	5.5	155.0	15
27	10.0	-6.5	155.0	15
28	10.0	6.5	155.0	15
29	12.5	-0.5	90.0	15
30	12.5	0.5	90.0	15
31	12.5	-6.0	90.0	15
32	12.5	6.0	140.0	15

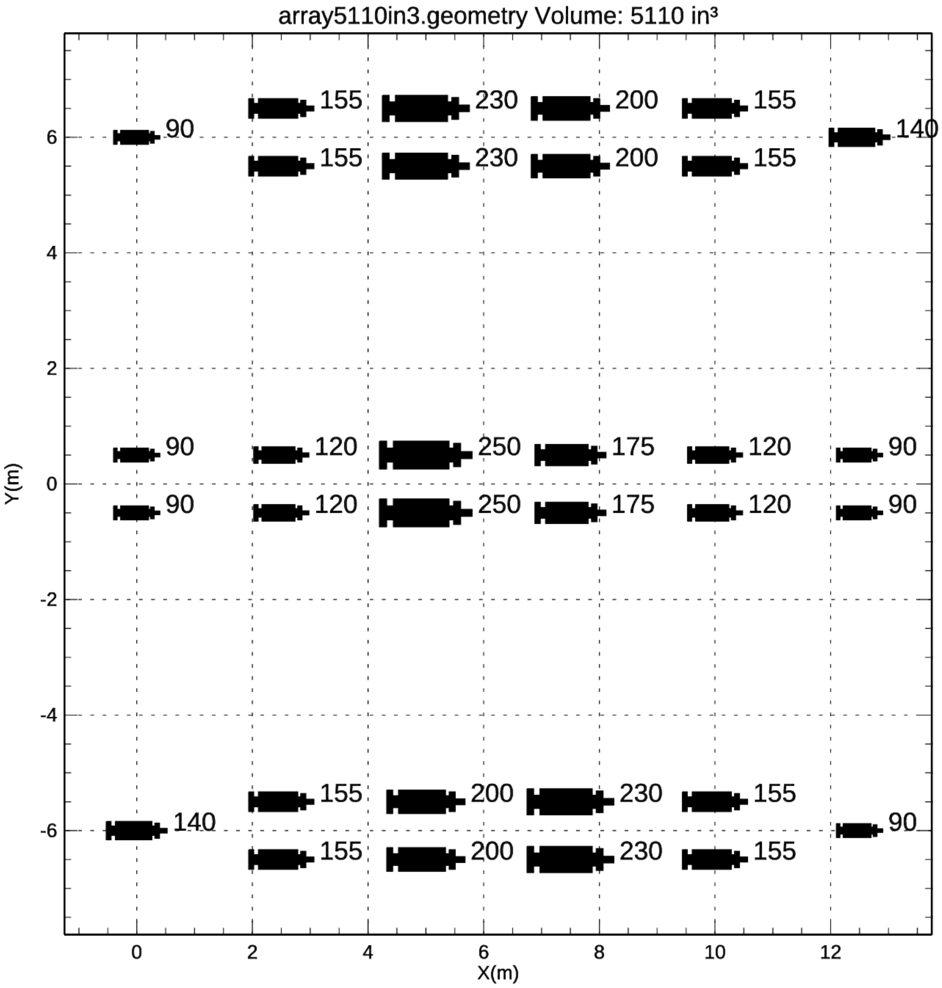

Figure 6. Map showing the elements within the 5110 in³ G-Gun array.

2. Methods

2.1. Acoustic Environment

The Atlantis 2024 Field Trial site is in deep water approximately 210 km south of coastal Louisiana. Ocean depths within the trial site vary from 1300 m to 2200 m, and the bathymetry slopes downward towards the southeast. The sediment composition in in the Field Trial site is primarily coarse clay to silt. Near the middle of the test site there is a steeper bathymetric gradient which drops 600 m over the length of less than 1 km, and an acoustic modeling site was selected adjacent to this increased gradient. The sound speed profile is primarily depth-dominated below 100 m and displays minimal seasonal variability, with a near-surface duct appearing within 50 m of the sea surface during winter months.

2.2. Acoustic Modeling

Three complementary acoustic models were used to predict the underwater acoustic field for the studied seismic source. The pressure signatures and directional energy source levels of the airgun array were predicted with JASCO's Airgun Array Source Model (AASM). Propagation losses around the airgun arrays and C-BASS seismic sweep were modeled with JASCO's Marine Operations Noise Model (MONM) from 10 Hz to 25 kHz based on computed signatures and energy source levels. The peak sound pressure level field from the airgun arrays were modeled using the full waveform modeling apprach (FWRAM) from 10 Hz to 2 kHz that produces synthetic pressure waveforms (seismograms). All models incorporated parameters specific to the sources and the environments.

2.3. Acoustic Effects Criteria

The process of determing the appropriate effects criteria used to evaluate effects is a function of both the source characteristics and the animal group. The first step is to determine the characteristics of the sound produced by the source(s). Next the species that are likely to be present need to be determined. Different species are represented with different hearing groups for which there are group-specific criteria. These criteria include group-specifc weighting functions for the physiological criteria that consider integrated SEL metrics. Behavioral criteria are based on sound pressure levels. The current NMFS criteria are appllied to unweighted SPLs while the (Wood et al. 2012) behavioral criteria are based on M-weighted SPLs (defined in Southall et al. 2007).

2.3.1. Source Signal Categorization

NMFS (2023a) characterizes sound sources as impulsive or non-impulsive for the purposes of selecting physiological effects criteria as well as intermittent or continuous for behavioral effects criteria. Those definitons are reproduced below.

> **Impulsive sound sources**: produce sounds that are typically transient, brief (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay. Impulsive sounds can occur in repetition (e.g., seismic airguns, impact pile driving) or as a single event (e.g., explosives).
>
> **Non-impulsive sound sources**: can be continuous or intermittent, and produce sounds that can be broadband, narrowband or tonal, and brief or prolonged. Non-impulsive sources do not have the high peak sound pressure with rapid rise time typical of

impulsive sounds. Examples of non-impulsive sources include drilling, vibratory pile driving, and certain active sonars.

Continuous sound sources: emit sound with a sound pressure level that remains above ambient sound during the entire observation period. Examples of continuous sound sources include drilling and vibratory pile driving.

Intermittent sound sources: have interrupted levels of low or no sound or bursts of sound separated by silent periods. Typically, intermittent sounds have a more regular (predictable) pattern of bursts of sounds and silent periods (i.e., duty cycle). Examples of intermittent sound sources include scientific sonar, high-resolution geophysical survey equipment (i.e., sub-bottom profilers), and impact pile driving.

Humans exposed to continuous (100%) and intermittent (50% duty cycle) signals found that the level necessary for annoyance from a continuous sound was 6–7 dB lower than that for intermittent sound (Dornic and Laaksonen 1989). When harbor porpoises were exposed to 6–7 kHz simulated sonar signals at duty cycles of 10% and 100% at the same cumulative SEL level, the porpoises experienced greater temporary threshold shift (TT 1–4 min) after the continuous sound than after the intermittent signals, even though the cumulative SELs were identical (Kastelein et al. 2015).

The signals from mid-frequency active sonars (MFAS) operating in the western Pacific Ocean had duty cycles of < 10% (Simonis et al. 2020), while the low-frequency active sonar system (LFAS) operated by the US Navy produces a wide variety of signals. Signal wavetrains are composed of multiple signals that have an average duration of 60 seconds, with no individual signal lasting longer than 10 seconds. The system has a maximum duty cycle of less than 20% and typically ranges between 7.5% to 10% (Department of the Navy (DoN) 2015).

The C-BASS vibrosource signal has a relatively gentle rise and decay over time and as such it is clearly non-impulsive. Its duration is approximatley 8 seconds long which is intermediate between the MFAS and LFAS signal durations. Furthermore it has a duty cycle of 53% which allows for periods of silence between each signal. Based on the NMFS (2023) category definitions, this signal is therefore considered to be an intermittent, non-impulsive sound source. The airgun arrays in this study are classified as impulsive sound sources. It should be noted that the NMFS (2023) definitons are qualitive, not quantitative. Thus some measure of uncertainty remains in these definitions.

2.3.2. Effects Criteria—Marine Mammals

The Marine Mammal Protection Act (MMPA) prohibits the take of marine mammals. The term “take” is defined as: to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal. MMPA regulations define harassment in two categories relevant to the Field Trial geophysical survey operations in the Gulf of Mexico:

- **Level A**: Any act of pursuit, torment, or annoyance that has the potential to injure a marine mammal or marine mammal stock in the wild, and
- **Level B**: Any act of pursuit, torment or annoyance that has the potential to disturb a marine mammal or marine mammal stock in the wild by disrupting behavioral patterns, including, but not limited to, migrating, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild (16 U.S.C. 1362).

To assess the potential impacts of the underwater sound in the Lease Area, it is necessary to first establish the acoustic exposure criteria used by United States regulators to estimate marine mammal takes. In 2016, NOAA Fisheries issued a Technical Guidance document that provides acoustic thresholds for onset of PTS in marine mammal hearing for most sound sources, which was updated in 2018 (NMFS 2016, 2018). The Technical Guidance document also recognizes two main types of sound sources:

impulsive and non-impulsive. Non-impulsive sources are further separated into continuous or intermittent categories.

NMFS also provided guidance on the use of weighting functions when applying Level A harassment criteria. The Guidance recommends using a dual criterion for assessing Level A exposures, including a PK (unweighted/flat) sound level metric and a cumulative SEL metric with frequency weighting. Both acoustic criteria and the weighting function application are divided into functional hearing groups (low-, mid-, and high-frequency cetaceans and phocid pinnipeds) that species are assigned to based on their respective hearing sensitivities. The acoustic analysis herein applies the most recent sound exposure criteria used by NMFS to estimate acoustic harassment (NMFS 2018).

Based on observations of mysticetes (Malme et al. 1983, 1984, Richardson et al. 1986, 1990), sound levels thought to elicit disruptive behavioral responses are described using the SPL metric (NOAA 2005, NOAA Fisheries 2019). NMFS currently uses behavioral response thresholds of SPL 160 dB re 1 μPa^2 for marine mammals exposed to intermittent sounds (such as impact pile driving) and a threshold of SPL 120 dB re 1 μPa^2 for marine mammals exposed to continuous sounds (such as vibratory pile driving or drilling) (NMFS 2022). Alternative thresholds used in acoustic assessments include a graded probability of response approach and account for the frequency-dependence of animal hearing sensitivity (Wood et al. 2012).

ISO 18405 Underwater Acoustics–Terminology (ISO 2017) provides a dictionary of underwater bioacoustics (the previous standard was ANSI and ASA S1.1-2013). In the remainder of this report, we follow the definitions and conventions of ISO (2017), except where stated otherwise (Table 7).

Table 7. Summary of relevant acoustic terminology used by US regulators and in this report.

Metric	NMFS (2018)	Main text[a]	Equations/Tables[a]
Sound pressure level	n/a	SPL	$L_{p,w}$[c]
Peak pressure level	PK	PK	L_{pk}
Cumulative sound exposure level	SEL_{cum} [b]	SEL	$L_{E,W,T}$[d]

[a] Following ISO (2017), with modifications described in the footnotes.

[b] SEL_{cum} metric used by NOAA Fisheries (NMFS) describes the sound energy received by a receptor over a period of 24 h. Accordingly, following the ISO standard, this will be denoted as SEL in this report, except for in tables and equations where $L_{E,W,T}$ will be used.

[c] w in $L_{p,w}$ and $L_{E,w,T}$ describes frequency-weighting function, if used.

[d] T in $L_{E,w,T}$ describes the time window used to calculate SEL.

2.3.2.1. Marine Mammal Hearing Groups

Current data and predictions show that marine mammal species differ in their hearing capabilities, in absolute hearing sensitivity as well as frequency band of hearing (Richardson et al. 1995, Wartzok and Ketten 1999, Southall et al. 2007, Au and Hastings 2008). While hearing measurements are available for a small number of species based on captive animal studies, there are no direct measurements of many odontocetes or any mysticetes. As a result, hearing thresholds for many odontocetes are grouped with similar species, and predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001, Parks et al. 2007, Tubelli et al. 2012, Cranford and Krysl 2015); vocalizations (see reviews in Richardson et al. 1995, Wartzok and Ketten 1999, Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990, see review in Reichmuth et al. 2007). Southall et al. (2007) proposed that marine mammals be divided into hearing groups. This division was updated in 2016 and 2018 by NOAA Fisheries using more-recent best-available science (Table 8).

Southall et al. (2019) published an updated set of Level A sound exposure criteria (including the onset of temporary threshold shift [TTS] and permanent threshold shift [PTS] in marine mammals). While the authors proposed a new nomenclature and classification for the marine mammal functional hearing groups, the proposed thresholds and weighting functions do not differ in effect from those proposed by NOAA Fisheries (2018). The new hearing groups proposed by Southall et al. (2019) have not yet been adopted by NOAA. Table 8 presents the NOAA Fisheries (NMFS 2018) hearing groups used in this analysis.

Table 8. Marine mammal hearing groups (Sills et al. 2014, NMFS 2018).

Hearing group	Generalized hearing range [a]
Low-frequency (LF) cetaceans (mysticetes or baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (odontocetes: delphinids, beaked whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (other odontocetes)	275 Hz to 160 kHz
Phocid pinnipeds in water (PW)	50 Hz to 86 kHz
Phocid pinnipeds in air (PA)	50 Hz to 36 kHz [b]

[a] The generalized hearing range is for all species within a group. Individual hearing will vary.

[b] Sound from sources will not reach NOAA Fisheries thresholds for behavioral disturbance of seals in air (90 dB [rms] re 20 µPa for harbor seals and 100 dB [rms] re 20 µPa^2 for all other seal species) at the closest land-based sites where seals may spend time out of the water. Thus, in-air hearing is not considered further.

2.3.2.2. Marine Mammal Auditory Weighting Functions

The potential for anthropogenic sound to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well, unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal's ability to hear a sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS thresholds expressed in metrics that consider what is known about marine mammal hearing (e.g., SEL) (Southall et al. 2007, Erbe et al. 2016, Finneran 2016). Marine mammal auditory weighting functions for all hearing groups (see Table 8) published by Finneran (2016) are included in the NMFS (2018) Technical Guidance for use in conjunction with corresponding permanent threshold shift (PTS [Level A] onset acoustic criteria; Table 9. See Appendix B.2 for a detailed description of the weighting functions).

The application of marine mammal auditory weighting functions emphasizes the importance of taking measurements and characterizing sound sources in terms of their overlap with biologically important frequencies (e.g., frequencies used for environmental awareness, communication, and the detection of predators or prey), and not only the frequencies that are relevant to achieving the objectives of the sound producing activity (i.e., context of sound source; NMFS 2018).

2.3.2.3. Marine Mammal Auditory Injury Exposure Criteria

Injury to the hearing apparatus of a marine mammal may result from a fatiguing stimulus measured in terms of SEL, which considers the sound level and duration of the exposure signal. Intense sounds may damage hearing independent of the duration of the signal, so an additional metric of peak pressure (PK) is used to assess acoustic exposure injury risk.

This study applies the acoustic criteria from the current US regulatory guidance, which are summarized as follows:

1. Peak sound pressure levels (PK; L_{pk}) and frequency-weighted, accumulated, sound exposure levels (SEL; $L_{E,\text{24h}}$) are from the US National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) Technical Guidance for marine mammal injury thresholds (NMFS 2018).
2. Sound pressure levels (SPL; L_p) for marine mammal behavioral thresholds are based on the unweighted NOAA (2019) and the M-weighted Wood et al. (2012) criteria.
3. Peak sound pressure levels (PK; L_{pk}) and frequency-weighted, accumulated, sound exposure levels (SEL; $L_{E,\text{24h}}$) from Finneran et al. (2017) were used for the onset of permanent threshold shift (PTS) in sea turtles.
4. Behavioral response thresholds for sea turtles were obtained from McCauley et al. (2000), which was confirmed in Finneran et al. (2017).

A PTS in hearing may be considered injurious, and while there are publications of sound levels with direct causal links to PTS in marine mammals, there are no direct measurements of exposure levels that have led to onset of PTS. Several studies have directly measured the sound levels associated with onset of temporary threshold shift (TTS). PTS onset sound level thresholds have been derived from the TTS onset levels by an assumed growth function (Southall et al. 2007). The NMFS (2018) criteria incorporated the best available science at the time (use of the draft guidance, NMFS 2024, would not fundamentally change the methods or conclusion of this study), to estimate PTS onset in marine mammals from sound energy accumulated over 24 h (SEL; L_E), or very loud, instantaneous peak sound pressure levels. These dual threshold criteria of SEL and PK are used to calculate marine mammal exposures (Table 9). If a non-impulsive sound has the potential to exceed the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.

Different types of sounds affect the ear differently. Impulsive sounds are believed to be more damaging than non-impulsive sounds of the same level. For this reason, thresholds for exposure to impulsive sounds are lower than the thresholds for non-impulsive sounds (Table 9). In some cases, an animal may be exposed to a combination of impulsive and non-impulsive sounds, or an impulsive sound may follow exposure to a non-impulsive sound. When concurrent sounds of different types are received, the sound energy from all sources should be summed and the threshold for impulsive sounds should be used because the resultant sound can be thought of as impulses within a background of non-impulsive sound. When impulsive sound (such as impact pile driving) follows exposure to non-impulsive sound (such as vibratory pile driving), potential effects of the non-impulsive sound (vibratory pile driving) should be evaluated first followed by the potential effects of the impulsive sound (impact pile driving). The sound energy from the exposure to non-impulsive sound (vibratory pile driving), however, should be included in the total received energy during the impulsive sound (impact pile driving) if the non-impulsive sound occurs within the time window of evaluation (24 h).

Table 9. Summary of relevant permanent threshold shift (PTS) onset acoustic thresholds for marine mammal hearing groups (NMFS 2018).

Hearing group	Impulsive signals [a] L_{pk} (dB re 1 µPa)	Impulsive signals [a] $L_{E,\mathrm{W,24h}}$ (dB re 1 µPa^2·s)	Non-impulsive signals $L_{E,\mathrm{W,24h}}$ (dB re 1 µPa^2·s)
Low-frequency (LF) cetaceans	219	183	199
Mid-frequency (MF) cetaceans	230	185	198
High-frequency (HF) cetaceans	202	155	173
Phocid seals in water (PW)	218	185	201

[a] Dual-metric acoustic thresholds for impulsive sounds: PK and SEL thresholds are defined for PTS. The larger of the two corresponding to exposure distances is used to assess PTS onset zones. The PK threshold was also applied to non-impulsive sounds that had the potential for high PK levels.

2.3.2.4. Marine Mammal Behavioral Response Exposure Criteria

Numerous studies on marine mammal behavioral responses to sound exposure have not yet resulted in consensus among the scientific community of an appropriate metric for assessing behavioral reactions to underwater sound. It is recognized that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison et al. 2012). Due to the complexity and variability of marine mammal behavioral responses to acoustic exposure, NOAA has not yet released technical guidance for determining potential behavioral responses of marine mammals exposed to sounds (NMFS 2018) and currently uses a single threshold to assess behavioral impact (NOAA 2019). That is, if the received level is above the threshold a behavioral response is assumed to occur if the received level is below the threshold no response is expected. NMFS currently uses behavioral response thresholds of SPL 160 dB re 1 µPa^2 for non-explosive impulsive sounds, such as airgun pulses and impact pile driving, and SPL 120 dB re 1 µPa^2 for continuous sounds, such as vibratory pile driving, drilling, and sonar for all marine mammal species (NMFS 2022).

An extensive review of behavioral responses to sound was undertaken by Southall et al. (2007, their Appendix B). Southall et al. (2007) found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1 µPa^2, consistent with the HESS (1999) report, but a lack of convergence in the data prevented them from suggesting explicit step functions. In 2012, Wood et al. proposed a graded probability of response for impulsive sounds using a frequency weighted SPL metric (Table 10). Wood et al. (2012) also designated behavioral response categories for sensitive species (including harbor porpoises and beaked whales) and for migrating mysticetes. Wood et al. (2012) uses the M-weighting functions defined in Southall et al. (2007).

Table 10. Wood et al. (2012) probabilistic disturbance associated with received root mean square (rms) sound pressure level (SPL) thresholds.

Marine mammal group	Species	Probabilistic response			
		Frequency-weighted threshold (L_p; dB re 1 µPa)			
		120	140	160	180
Beaked whales and harbor porpoises	Harbor porpoise	50%	90%	—	—
Migrating mysticete whales	Minke whale	10%	50%	90%	—
	Sei whale				
All other species		—	10%	50%	90%

2.4. Sound Level Modeling

The seismic source is towed over a survey pattern that typically consists of several parallel tracks. Sound exposure modeling accounts for the positions of the source on its survey pattern relative to a 3-D grid of receiver locations. The sound levels for the track field are calculated by summing the per-pulse field placed at a series of points along the track, each point representing a single acoustic pulse from the source. The per-pulse levels were interpolated onto a Cartesian grid for each receiver depth independently, preserving the vertical dimension. This 3-D grid of the per-pulse field was used as input for calculating the sound field from a source track.

A sail line separation of 46 m (Figure 2) was used to compute the track field SEL for all airgun arrays and the C-BASS array for the Field Trial. The along sail shot offset was 27 m. The modeled N×2-D per-pulse field results for individual sources were gridded onto a cartesian grid with 23 x 27 m cell size. Prior to gridding, the received level data were subject to range averaging with a Gaussian smoothing operator width of 11%.

After calculating the acoustic field from the moving source along a section of track, the vertical dimension of the field grid was reduced using the maximum-over-depth rule. The isopleth contours and ranges to specific thresholds were calculated from the maximum-over-depth acoustic field grid. The threshold ranges are calculated based on the minimum distance from each grid cell to a point on the track; the maximum value of these distances to the given sound level threshold is reported.

2.5. Animal Movement Modeling and Exposure Estimation

JASMINE was used to estimate the probability of exposure of animals to sound during hypothetical survey operations using four different sources in the Gulf of Mexico. Sound exposure models such as JASMINE use simulated animals (animats) to sample the predicted 3-D sound fields with movement rules derived from animal observations (Appendix C, Figure 7). The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, and surface times) were determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. The predicted sound fields were sampled by the model receiver in a way that real animals are expected to by programming animats to behave like marine species in the study area. The output of the simulation is the exposure history for each animat within the simulation. An individual animat's sound exposure levels are summed over a specified duration, i.e., 24 h, to determine its total received acoustic energy (SEL) and maximum received PK and SPL. These received levels are then compared to the thresholds described in Section 2.3 within each analysis period.

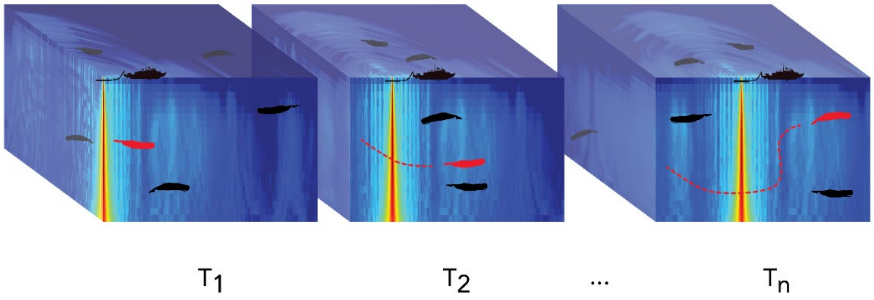

Figure 7. Depiction of animats in an environment with a moving sound field. Example animat (red) shown moving with each time step. The acoustic exposure of each animat is determined by where it is in the sound field, and its exposure history is accumulated as the simulation steps through time.

2.6. Estimating Monitoring Zones for Mitigation

Monitoring zones used for mitigation purposes have traditionally been estimated by determining the distance to injury and behavioral thresholds based only on acoustic information. This traditional method tacitly assumes that all receivers (animals) in the area remain stationary for the duration of the sound event. Because both where an animal is in a sound field, and the pathway it takes through the sound field, determine the received level of the animal, treating animals as stationary may not produce realistic estimates for monitoring zones.

Animal movement modeling can be used to account for the movement of receivers when estimating distances for monitoring zones. The closest point of approach (CPA) for each of the species-specific animats (simulated animals) in a simulation is recorded and then the CPA distance that accounts for 95% of the animats that exceed an acoustic impact threshold is determined (Figure 8). The $ER_{95\%}$ (95% exposure range) is the horizontal distance that includes 95% of the CPAs of animats exceeding a given impact threshold. $ER_{95\%}$ is reported for marine mammals and sea turtles. If used as an exclusion zone, keeping animals farther away from the source than the $ER_{95\%}$ will reduce exposure estimates by 95%.

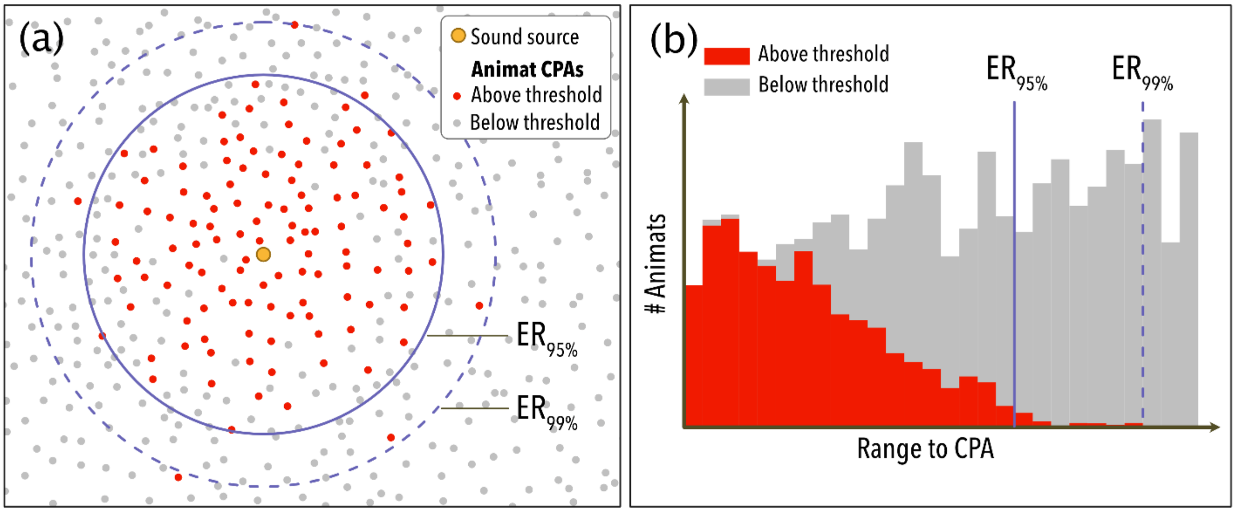

Figure 8. Example distribution of animat closest points of approach (CPAs). Panel (a) shows the horizontal distribution of animats near a sound source. Panel (b) shows a stacked bar plot of the distribution of ranges to animat CPAs. The 95% and 99% Exposure Ranges ($ER_{95\%}$ and $ER_{99\%}$) are indicated in both panels.

3. Marine Fauna Included in the Acoustic Assessment

Marine fauna included in the acoustic assessment are marine mammals and sea turtles.

All marine mammal species are protected under the MMPA. Some marine mammal stocks may be designated as 'Strategic' under the MMPA (2015), which requires the jurisdictional agency (NMFS for the offshore species considered in this application) to impose additional protection measures. A stock is considered Strategic if the following are true:

- Direct human-caused mortality exceeds its Potential Biological Removal (PBR) level (defined as the maximum number of animals, not including natural mortality, that can be removed from the stock while allowing the stock to reach or maintain its optimum sustainable population level);
- It is listed under the ESA;
- It is declining and likely to be listed under the ESA; or
- It is designated as 'Depleted' under the MMPA.

A depleted species or population stock is defined by the MMPA as any case in which the following are true:

- The Secretary, after consultation with the Marine Mammal Commission and the Committee of Scientific Advisors on Marine Mammals established under MMPA Title II, determines that a species or population stock is below its optimum sustainable population;
- A State, to which authority for the conservation and management of a species or population stock is transferred under Section 109 of the MMPA, determines that such species or stock is below its optimum sustainable population; or
- A species or population stock is listed as an endangered or threatened species under the Endangered Species Act (2002), and some species are further protected under the ESA (2002).

Under the ESA, a species is considered endangered if it is "in danger of extinction throughout all or a significant portion of its range." A species is considered threatened if it "is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range" (ESE 2002). Two marine mammal species and all five sea turtles found in the Gulf of Mexico are ESA listed (Table 11).

3.1. Marine Mammals that May Occur in the Area

Twenty marine mammal species (whales and dolphins) comprising have been documented in the Gulf of Mexico ([NMFS] National Marine Fisheries Service (US) 2023b). All marine mammal species identified in Table 11 are protected under the MMPA . The two ESA-listed marine mammal species found in the Gulf of Mexico are the sperm whale (*Physeter macrocephalus*) and Rice's whale (*Balaenoptera ricei*).

Table 11. Marine fauna that occurs in the Project Area.

Common Name	Species	Regulatory Status[a]	Abundance[b]
Rice's whale	*Balaenoptera ricei*	ESA-Endangered	51
Sperm whale	*Physeter macrocephalus*	ESA-Endangered	1,180
Dwarf sperm whale	*Kogia sima*	MMPA	336 [c]
Pygmy sperm whale	*Kogia breviceps*	MMPA	336 [c]
Goose-beaked whale	*Ziphius cavirostris*	MMPA	18
Blainville's beaked whale	*Mesoplodon densirostris*	MMPA	98
Gervais' beaked whale	*Mesoplodon europeaus*	MMPA	20
Short-finned pilot whale	*Globicephala macrorhynchus*	MMPA	1,321
Killer whale	*Orcinus orca*	MMPA	267
False killer whale	*Pseudorca crassidens*	MMPA	494
Pygmy killer whale	*Feresa attenuata*	MMPA	613
Melon-headed whale	*Peponocephala electra*	MMPA	1,749
Common bottlenose dolphin	*Tursiops truncatus*	MMPA	70,922
Atlantic spotted dolphin	*Stenella frontalis*	MMPA	21,506
Risso's dolphin	*Grampus griseus*	MMPA	1,974
Rough-toothed dolphin	*Steno bredanensis*	MMPA	unk
Fraser's dolphin	*Lagenodelphis hosei*	MMPA	213
Pantropical spotted dolphin	*Stenella attenuata*	MMPA	37,195
Striped dolphin	*Stenella coeruleoalba*	MMPA -Strategic	1,817
Clymene dolphin	*Stenella clymene*	MMPA -Strategic	513
Spinner dolphin	*Stenella longirostris*	MMPA -Strategic	2,991
Leatherback sea turtle	*Dermochelys coriacea*	ESA Endangered	unk
Loggerhead sea turtle	*Caretta caretta*	ESA Threatened	unk
Kemp's ridley sea turtle	*Lepidochelys kempii*	ESA Endangered	unk
Green sea turtle	*Chelonia mydas*	ESA Threatened	unk
Hawksbill sea turtle	*Eretmochelys imbricata*	ESA-Endangered	unk

[a] Denotes the highest federal regulatory classification. A strategic stock is defined as any marine mammal stock: 1) for which the level of direct human-caused mortality exceeds the potential biological removal level; 2) that is declining and likely to be listed as Threatened under the ESA; or 3) that is listed as Threatened or Endangered under the ESA or as depleted under the MMPA (NOAA Fisheries 2024).

[b] Best available abundance estimate is from NOAA Fisheries Stock Assessment Reports (NOAA Fisheries 2024).

[c] This estimate includes dwarf and pygmy sperm whales. Source: (NOAA Fisheries 2024).

3.2. Marine Fauna Density Estimates

Mean monthly marine fauna density estimates (animals per 100 square kilometers [animals/100 km^2]) were obtained using the 2022 Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS) model results (Rappucci et al. 2023).

The mean species density for each month was determined by calculating the unweighted mean of all 10 × 10 km grid cells partially or fully within the analysis perimeter (Figure 9). Densities were computed for an entire year and reported in Table 12.

There is one case in this study for which the GoMMAPPS models report densities for species guilds: beaked whales. Three species of beaked whales may be found in the study area. Likewise, there were six cetaceans and one sea turtle for which no density estimates were available. Melon headed whales, false killer whales, pygmy killer whales, killer whales, Fraser’s dolphin and rough-toothed dolphins all used the ‘blackfish’ group as their density surrogate. The whales in this list are all typically included in the informal ‘blackfish’ group. There was no density estimate for Hawksbill sea turtle, so the Kemps-ridley turtle estimate was used. Given that the purpose of this study is a comparison of results between different sources, no further effort was expended in refining density estimates for these seven species.

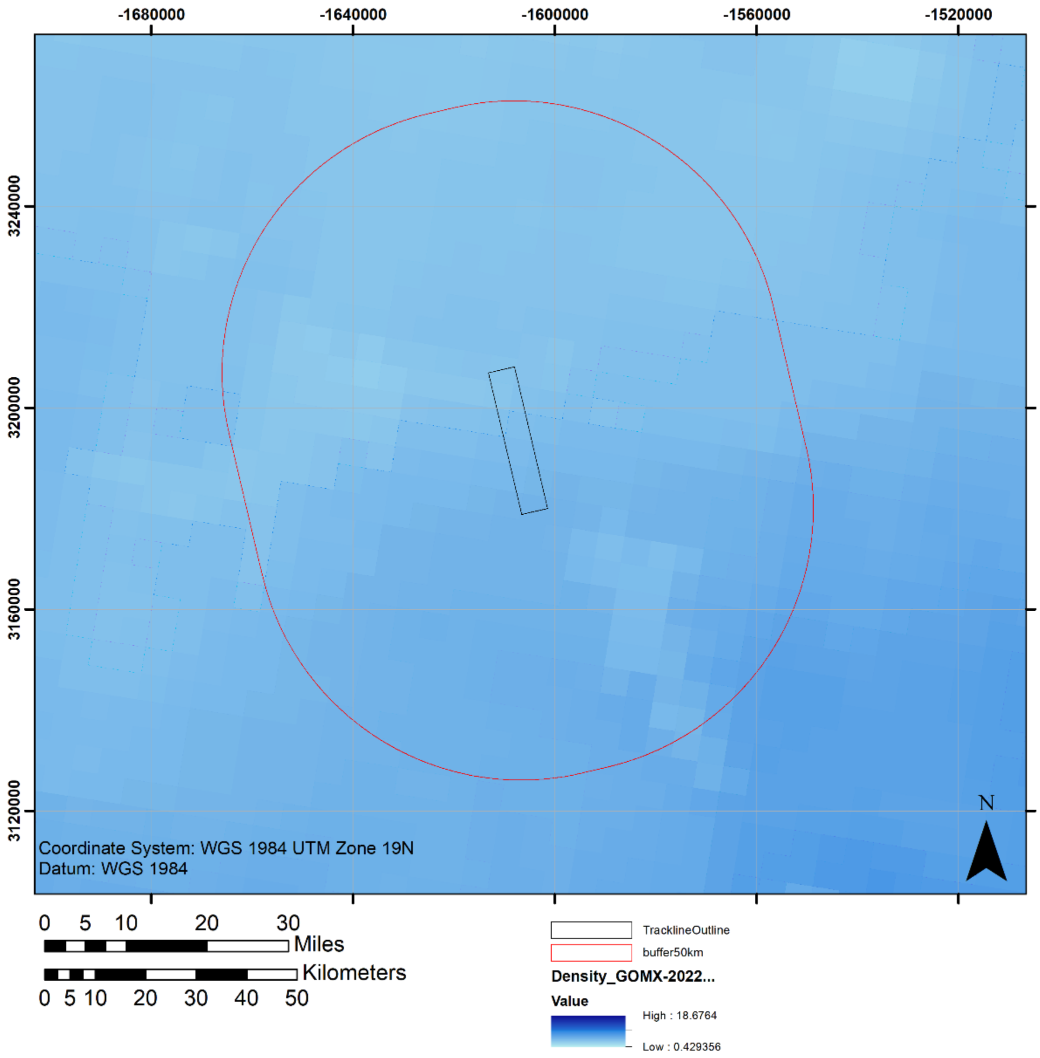

Figure 9. Marine mammal (e.g., Pantropical spotted dolphin]) density map demonstrating how grid cells are selected for the 50 km buffer perimeter. The black lines indicate the outline of the survey lines while the red shape indicates the extent of the 50 km buffer around the tracklines. This subset of grid cells within the red buffer was used to extract mean monthly species density estimates.

Table 12. Mean monthly marine mammal density estimates for all species in a 50 km perimeter around the proposed survey tracklines.

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean	May to December mean
Short fined pilot whale	0.188	0.218	0.283	0.290	0.415	0.476	0.596	0.655	0.553	0.437	0.256	0.214	0.382	0.450
Melon headed whale	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Dwarf sperm whale	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Rice's whale [b]	0.012	0.011	0.006	0.004	0.006	0.007	0.009	0.012	0.013	0.009	0.012	0.014	0.010	0.010
Green sea turtle	0.002	0.008	0.022	0.047	0.072	0.125	0.182	0.191	0.112	0.040	0.013	0.008	0.069	0.093
Atlantic Spotted Dolphin	0.192	0.199	0.203	0.209	0.246	0.291	0.223	0.204	0.212	0.202	0.185	0.187	0.213	0.219
Blainville's beaked whale	0.104	0.105	0.115	0.122	0.151	0.196	0.220	0.284	0.256	0.219	0.137	0.106	0.168	0.196
Goose-beaked whale	0.104	0.105	0.115	0.122	0.151	0.196	0.220	0.284	0.256	0.219	0.137	0.106	0.168	0.196
Gervais beaked whale	0.104	0.105	0.115	0.122	0.151	0.196	0.220	0.284	0.256	0.219	0.137	0.106	0.168	0.196
Clymene dolphin	1.025	0.868	0.556	0.299	0.092	0.183	0.402	0.510	0.540	0.552	0.774	1.063	0.572	0.515
False killer whale	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Frasers dolphin	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Hawksbill sea turtle [b]	0.751	1.442	1.620	0.960	0.693	1.201	1.621	1.841	1.340	0.973	0.593	0.760	1.149	1.128
Kemps ridley sea turtle [b]	0.751	1.442	1.620	0.960	0.693	1.201	1.621	1.841	1.340	0.973	0.593	0.760	1.149	1.128
Killer whale	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Leatherback turtle [b]	0.052	0.052	0.111	0.100	0.066	0.375	0.950	1.177	0.417	0.116	0.027	0.061	0.292	0.399
Loggerhead turtle	13.281	18.974	25.819	23.531	26.654	22.148	22.479	21.089	17.302	10.702	8.840	10.844	18.472	17.507
Pantropical spotted dolphin	7.589	8.838	6.102	4.582	5.216	9.822	9.932	10.622	11.882	10.765	7.785	7.660	8.399	9.210
Pygmy killer whales	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Pygmy sperm whale	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Rough-toothed dolphin	2.391	2.187	1.713	1.217	0.754	0.816	1.370	1.764	1.771	2.014	2.189	2.393	1.715	1.634
Sperm whale [b]	0.330	0.337	0.356	0.380	0.503	0.657	0.739	0.814	0.687	0.576	0.453	0.383	0.518	0.601
Spinner Dolphin	0.070	0.072	0.076	0.078	0.103	0.150	0.104	0.088	0.097	0.094	0.069	0.068	0.089	0.097
Striped Dolphin	2.909	2.244	1.402	0.868	0.459	0.785	1.218	1.584	1.513	1.526	1.952	2.563	1.585	1.450
Risso's Dolphin	0.189	0.181	0.179	0.184	0.265	0.531	0.310	0.290	0.383	0.327	0.170	0.183	0.266	0.307
Common bottlenose dolphin	0.974	1.117	1.443	1.519	1.240	1.652	1.281	1.110	1.350	1.211	0.752	0.840	1.207	1.180

[a] Density estimates are from habitat-based density modeling of the Gulf of Mexico (Rappucci et al. 2023).

[b] Listed as Endangered under the ESA.

[c] Density adjusted by relative abundance.

4. Results

Acoustic ranges to injury and behavior thresholds for marine mammals and sea turtles ([NMFS] National Marine Fisheries Service (US) 2018) are presented in Table 13 to Table 15. The C-BASS is classified as an intermittent source (duty cycle 53%), therefore impulsive thresholds were used to calculate acoustic ranges to PTS and behavioral thresholds. C-BASS acoustic ranges for impulsive cumulative SEL were not reached or are shorter than the modeling resolution; acoustic ranges to the continuous cumulative PTS thresholds are higher and were not reached for any hearing group. Table 13 presents the maximum range, R_{max}, and $R_{95\%}$ ranges to impulsive cumulative SEL PTS thresholds for all airgun arrays and the C-BASS sweep across the proposed tow tracks. Acoustic ranges to impulsive PK PTS thresholds are given in Table 14 for airgun arrays only, and PK levels to C-BASS are negligible in this case. Behavioral acoustic ranges for all source types are provided in Table 15.

4.1. Distances to Underwater thresholds

Table 13. Distances to SEL_{24h} thresholds for impulsive sources for marine mammals underwater, for permanent threshold shift (PTS), ([NMFS] National Marine Fisheries Service (US) 2018). The C-BASS ranges are provided for informational purposes only – it is not expected to be categorized as an impulsive source.

Hearing group	Impulsive Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	680 in³ airgun array		1000 in³ airgun array		5110 in³ airgun array		C-BASS Seismic Sweep	
		$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)
LF cetaceans	183	NA	<0.02	0.13	0.15	1.04	1.27	NA	<0.02
MF cetaceans	185	NA	<0.02	NA	<0.02	NA	<0.02	-	-
HF cetaceans	155	NA	<0.02	NA	<0.02	NA	<0.02	-	-
Phocid in water	185	NA	<0.02	NA	<0.02	NA	<0.02	-	-
Turtles in water	204	NA	<0.02	NA	<0.02	NA	<0.02	-	-

A dash indicates the threshold was not reached. <0.02 indicates the threshold was reached at a range less than the modeling resolution.

NA: $R_{95\%}$ values cannot be accurately computed for ranges below modeling resolution or beyond the limits of the domain.

Table 14. Distances to PK thresholds for marine mammals underwater, for permanent threshold shift (PTS), ([NMFS] National Marine Fisheries Service (US) 2018)

Hearing group	Impulsive Threshold L_{pk} (dB re 1 µPa)	680 in3 airgun array		1000 in3 airgun array		5110 in3 airgun array	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (m)	$R_{95\%}$ (km)
LF cetaceans	219	0.017	0.014	0.017	0.014	0.026	0.022
MF cetaceans	230	<0.02	NA	<0.02	NA	<0.02	NA
HF cetaceans	202	0.088	0.085	0.137	0.133	0.278	0.272
Phocid in water	218	0.017	0.014	0.017	0.014	0.038	0.036
Turtles in water	232	<0.02	NA	<0.02	NA	<0.02	NA

A dash indicates the threshold was not reached. <0.02 indicates the threshold was reached at a range less than the modeling resolution. NA: $R_{95\%}$ values cannot be accurately computed for ranges below modeling resolution or beyond the limits of the domain.

Table 15. Distances to SPL behavioral thresholds for impulsive sources for fish, marine mammals, and sea turtles underwater using the (NOAA Fisheries 2019) unweighted sound pressure level criteria.

Hearing group	Impulsive Threshold L_p (dB re 1 µPa²)	680 in3 airgun array		1000 in3 airgun array		5110 in3 airgun array		C-BASS Seismic Sweep	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Marine Mammals	160	4.65	3.33	6.48	4.99	18.2	13.9	0.20	0.19
Sea Turtles	175	0.37	0.36	0.55	0.54	3.49	1.91	0.04	0.04

A dash indicates the threshold was not reached. >40 indicates the threshold was reached beyond the domain of the modeling. NA: $R_{95\%}$ values cannot be accurately computed for ranges below modeling resolution or beyond the limits of the domain.

4.2. Isopleth Map

The maximum-over-depth distances to marine mammals and sea turtle SPL behavioral thresholds for the C-BASS source and the three different airgun arrays are shown in Figure 10 to 12. Acoustic propagation is mainly omnidirectional, with slightly longer ranges extending in the along-slope direction to the East. For the C-BASS, the isopleths to both marine mammals and sea turtle behavioral thresholds are inside the Proposed Modeling Site symbol (star) and are much less than 1 km.

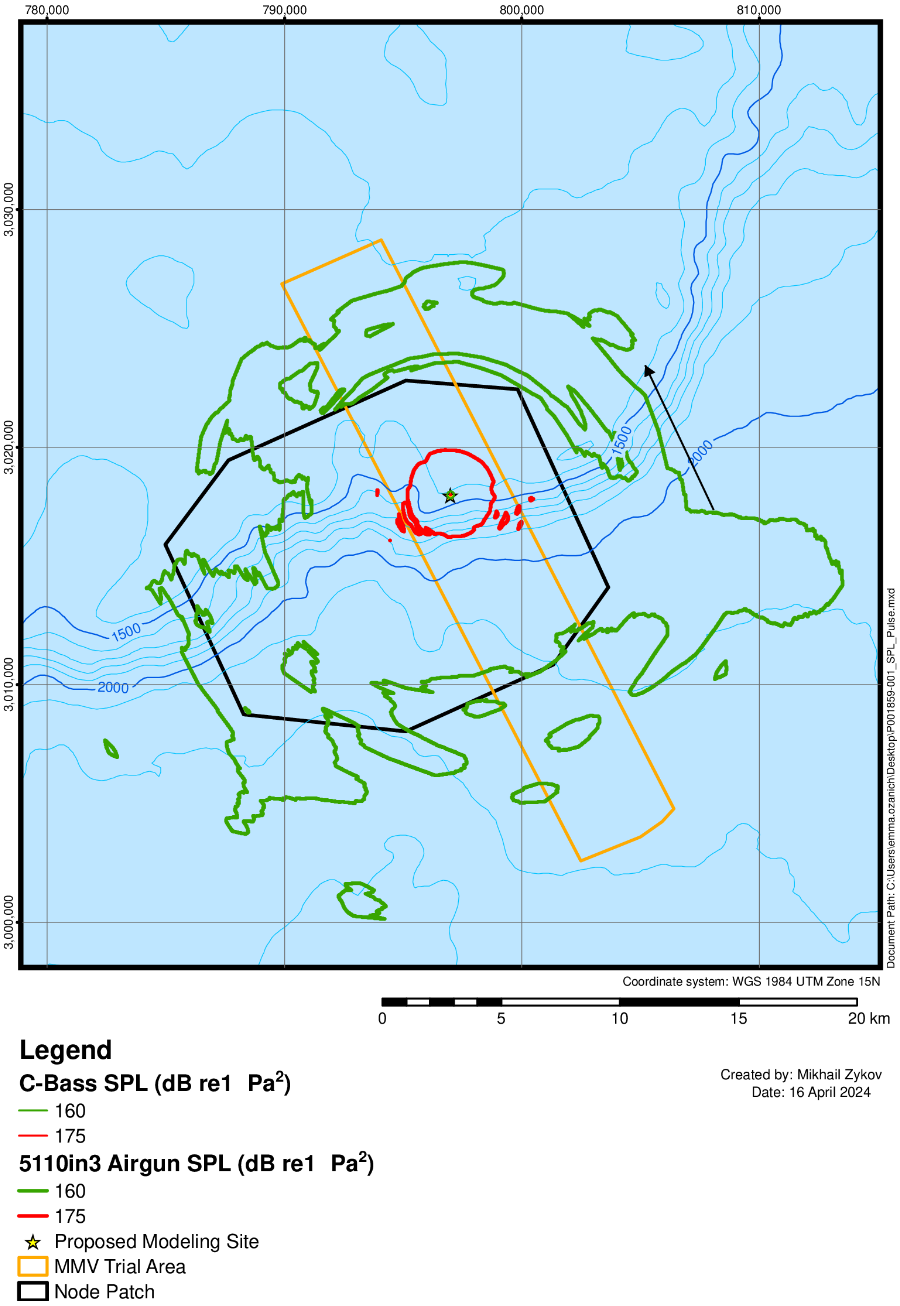

Figure 10. Contour map of SPL behavioral thresholds for the C-BASS source and 5110 in^3 airgun array.

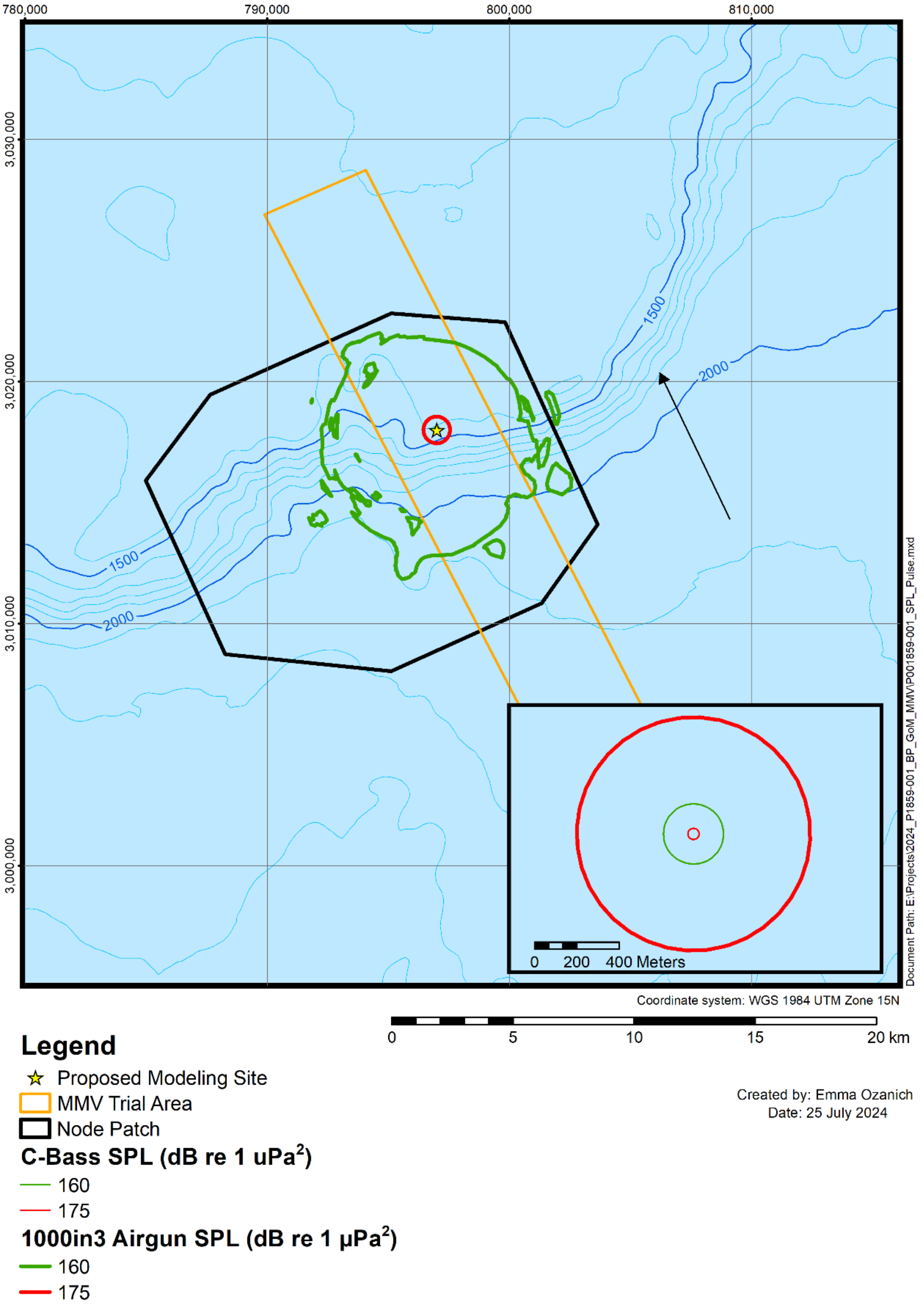

Figure 11. Contour map of SPL behavioral thresholds for the C-BASS source and 1000 in^3 airgun array.

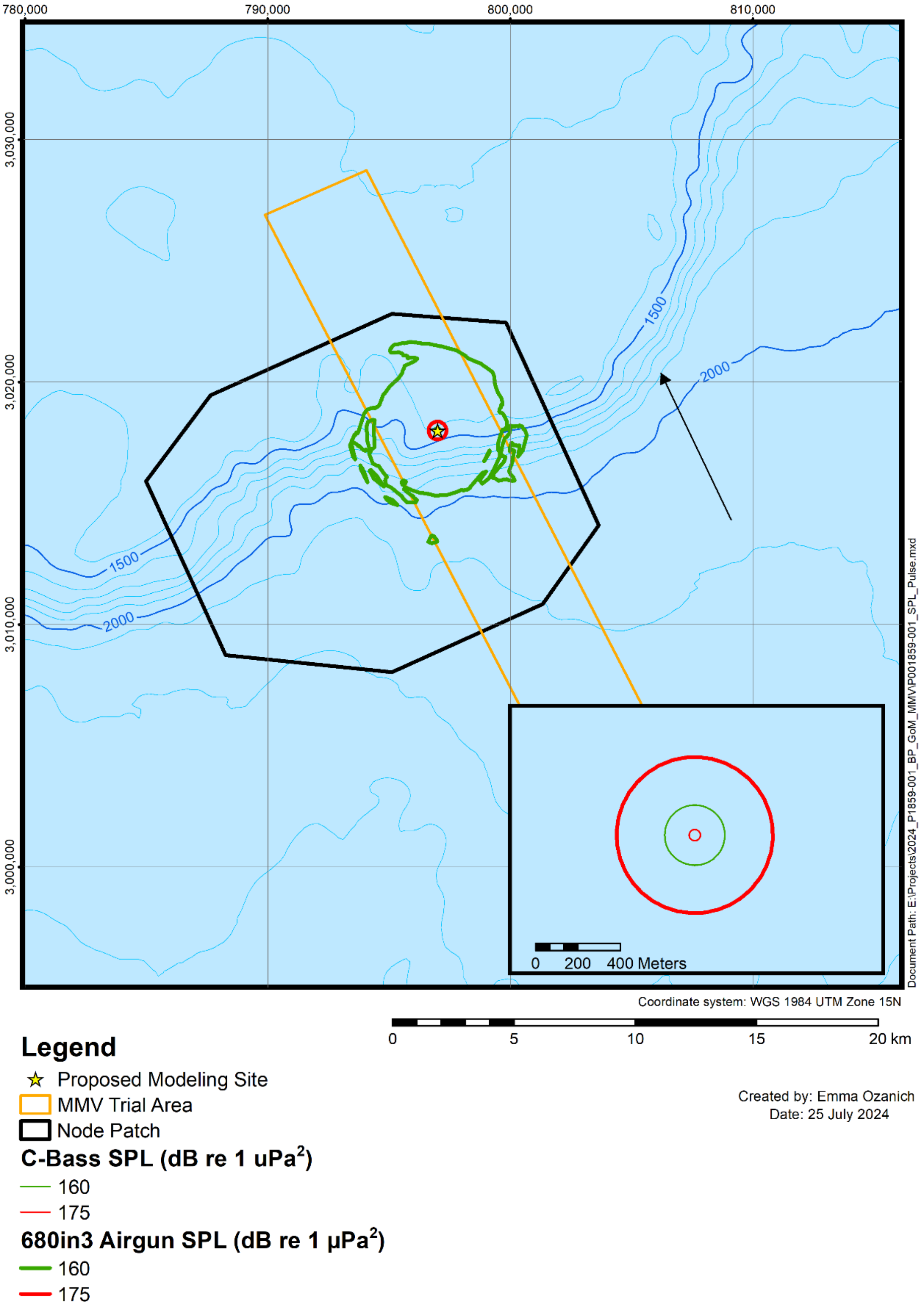

Figure 12. Contour map of SPL behavioral thresholds for the C-BASS source and 680 in^3 airgun array.

4.3. Exposure Estimates

One-day exposure estimates were predicted for each species and array type using the maximum monthly density for each species. These estimates are all based on the propagation predictions made considering the environmental conditions for September. The behavioral criteria used to evaluate the exposures were the unweighted NOAA Fisheries (2019) criteria. Because all sources are considered to be intermittent, the 160 dB re 1μPa^2 NOAA threshold value was used. Additional behavioral criteria used included Wood et al. (2012) for cetaceans using the Southall et al. (2007) M-weighting functions for marine mammals and Finneran et al. (2017) for sea turtles. This report considered both the SEL-based metrics for TTS and PTS because those metrics can be predicted for both impulsive and non-impulsive sources.

4.3.1. NOAA 160 dB Behavior

The unweighted behavioral metric had the largest number of exposures and thus best illustrate the differences between the effects of the different array types. These behavioral exposure predictions are presented graphically as well as in tabular form. The plots are broken into four parts, each representing different groups of species for clarity of presentation (Figure 13 to 16). The remaining metrics for marine mammals are presented in tabular form alone.

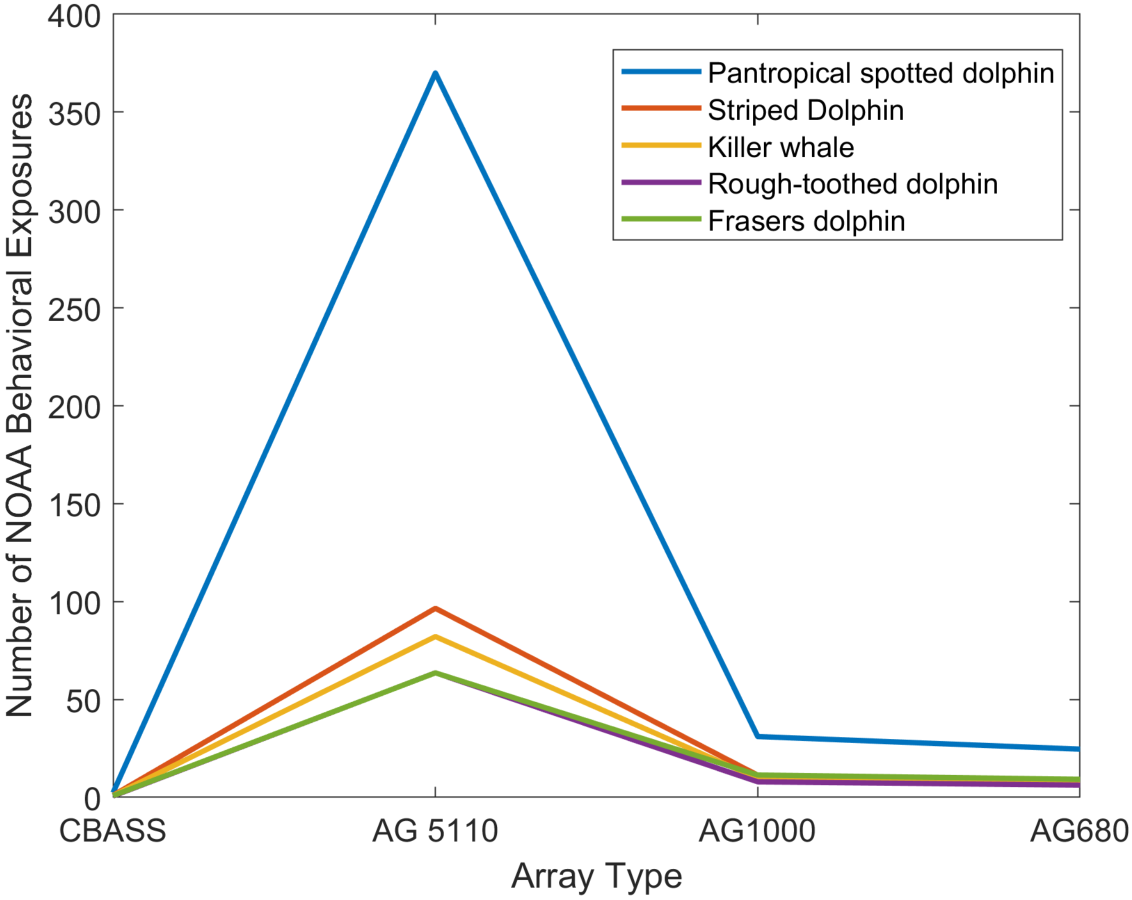

Figure 13. Numbers of unweighted behavioral exposures for marine mammal species presented by array type Part 1.

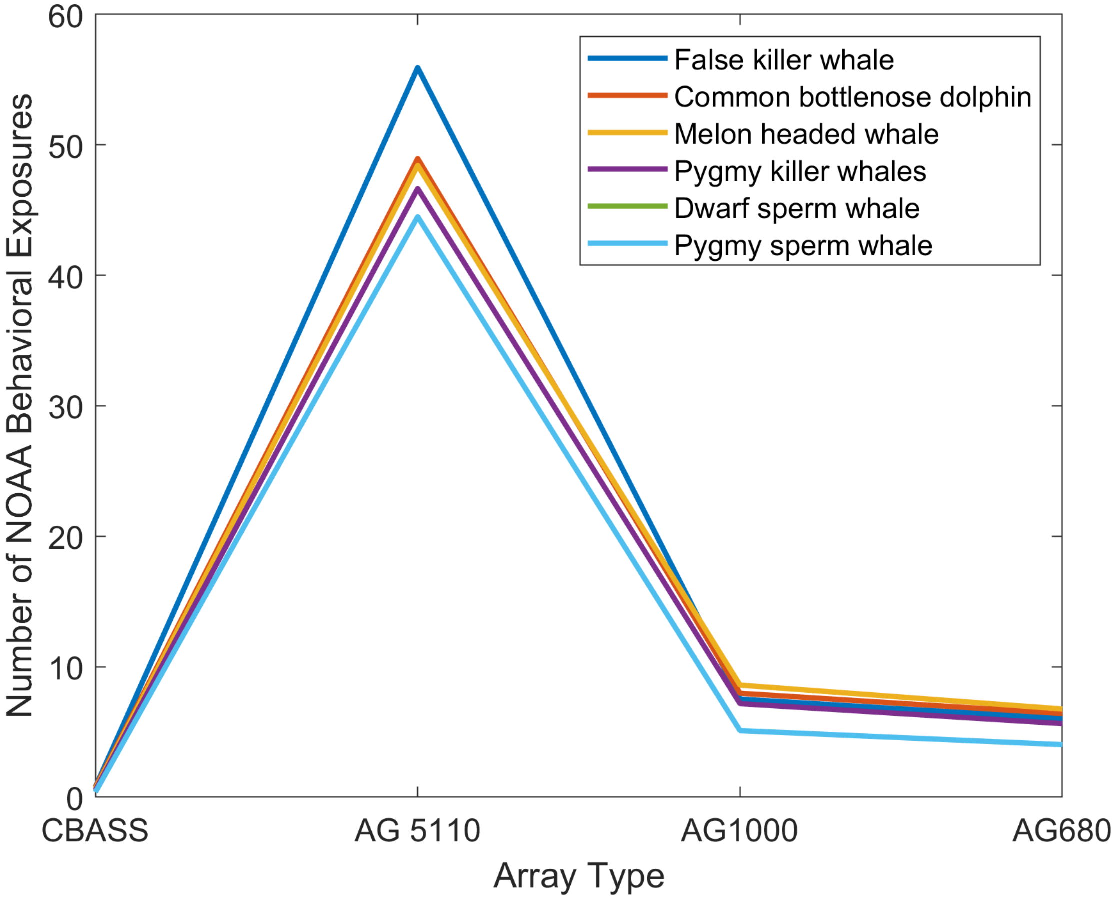

Figure 14. Numbers of unweighted behavioral exposures for marine mammal species presented by array type Part 2.

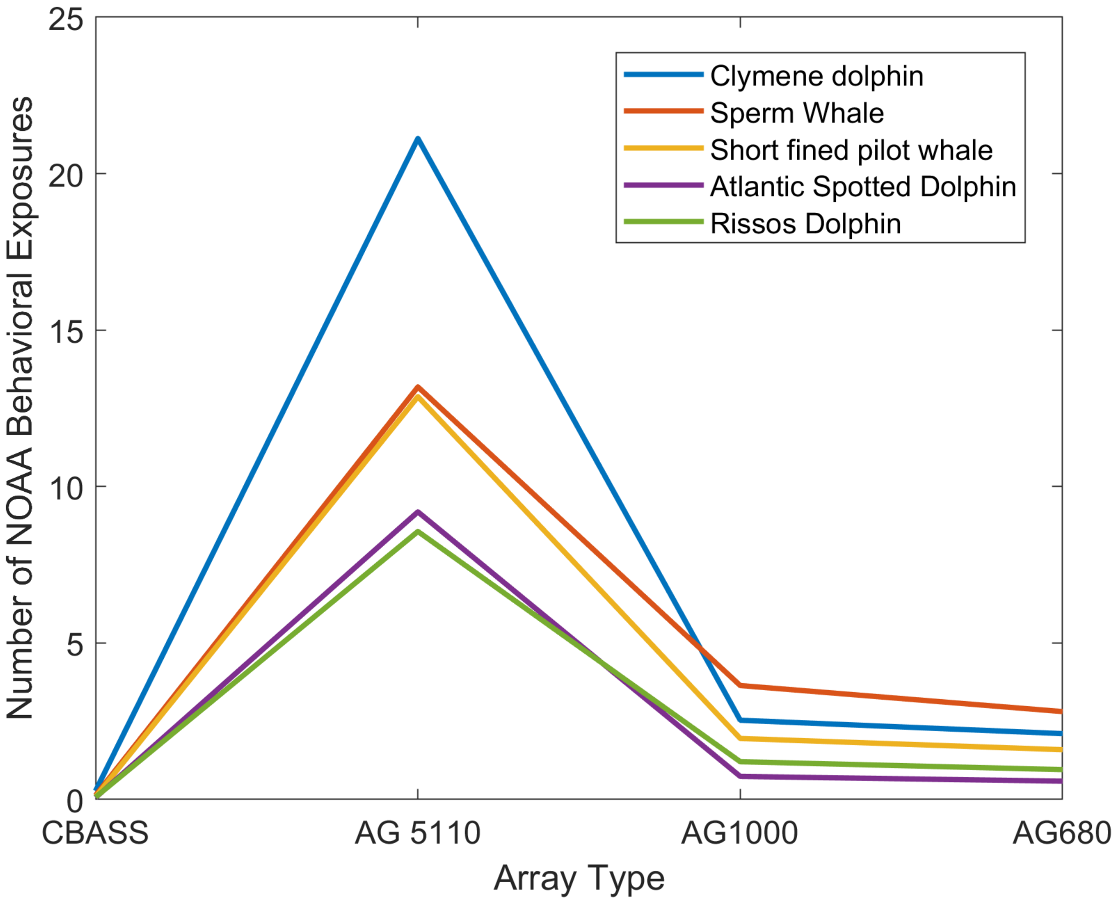

Figure 15. Numbers of unweighted behavioral exposures for marine mammal species presented by array type Part 3.

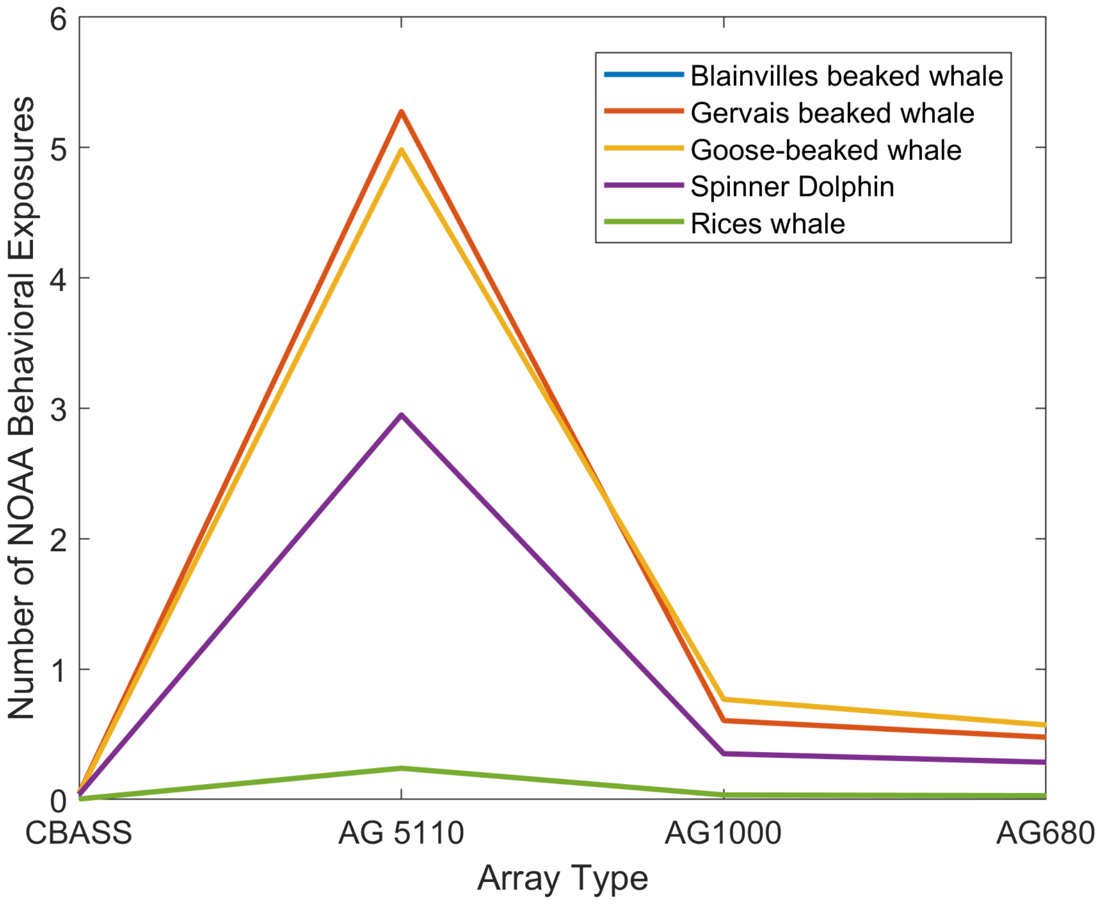

Figure 16. Numbers of unweighted behavioral exposures for marine mammal species presented by array type Part 4.

Table 16. The maximum NOAA 160 dB behavioral exposure estimate for month with highest density for each species and the four array types.

Species	CBASS	AG 5110	AG1000	AG680
Atlantic spotted dolphin	0.058	9.191	0.736	0.585
Blainville's beaked whale	0.045	5.276	0.605	0.477
Clymene dolphin	0.274	21.124	2.532	2.104
Common bottlenose dolphin	0.749	48.956	7.963	6.410
Dwarf sperm whale	0.379	44.496	5.100	4.026
False killer whale	0.774	55.928	7.516	6.016
Frasers dolphin	0.821	63.586	11.400	9.237
Gervais' beaked whale	0.045	5.276	0.605	0.477
Goose-beaked whale	0.041	4.982	0.768	0.571
Killer whale	0.868	82.123	9.711	7.516
Melon headed whale	0.616	48.428	8.590	6.758
Pantropical spotted dolphin	2.352	370.005	31.049	24.620
Pygmy killer whales	0.521	46.659	7.169	5.637
Pygmy sperm whale	0.379	44.496	5.100	4.026
Rice's whale	0.004	0.240	0.034	0.029
Risso's dolphin	0.073	8.565	1.207	0.954
Rough-toothed dolphin	0.647	63.618	7.927	6.253
Short fined pilot whale	0.082	12.872	1.949	1.590
Sperm whale	0.129	13.183	3.641	2.808
Spinner dolphin	0.037	2.949	0.351	0.286
Striped dolphin	1.017	96.561	11.307	8.850

4.3.2. Wood et al. (2012) Behavior

The Wood et al. (2012) behavioral results follow the trends shown in the NOAA 160 dB results. These values are presented only in tabular form.

Table 17. The maximum (Wood et al. 2012) behavioral exposure estimates are shown for the four array types and calculated using the maximum monthly density for each species

Species	CBASS	AG 5110	AG1000	AG680
Atlantic Spotted Dolphin	0.004	1.448	0.598	0.251
Blainville’s beaked whale	0.105	15.347	12.422	9.727
Clymene dolphin	0.014	4.190	2.093	1.093
Common bottlenose dolphin	0.030	9.181	4.085	2.106
Dwarf sperm whale	0.014	5.965	2.359	1.612
False killer whale	0.049	10.483	4.862	2.368
Frasers dolphin	0.030	12.341	5.628	2.926
Gervais’ beaked whale	0.105	15.347	12.422	9.727
Goose-beaked whale	0.109	14.723	11.964	9.390
Killer whale	0.046	13.744	5.980	2.826
Melon headed whale	0.035	9.708	4.554	2.381
Pantropical spotted dolphin	0.196	59.386	24.691	10.562
Pygmy killer whales	0.024	9.011	4.173	2.042
Pygmy sperm whale	0.014	5.965	2.359	1.612
Rice’s whale	0.003	0.165	0.079	0.059
Risso’s Dolphin	0.004	1.524	0.722	0.370
Rough-toothed dolphin	0.033	11.563	5.538	2.560
Short fined pilot whale	0.003	2.455	1.087	0.533
Sperm Whale	0.006	2.920	1.176	0.638
Spinner Dolphin	0.002	0.580	0.276	0.139
Striped Dolphin	0.033	16.421	6.755	3.358

4.3.3. Sea Turtle Behavioral Exposures

The sea turtle results also follow the trends shown in the marine mammal exposure predictions. These are presently graphically as well as in tabular form. The major difference in raw exposure numbers between Loggerhead turtles and the other species is due the difference in species density (Table 12).

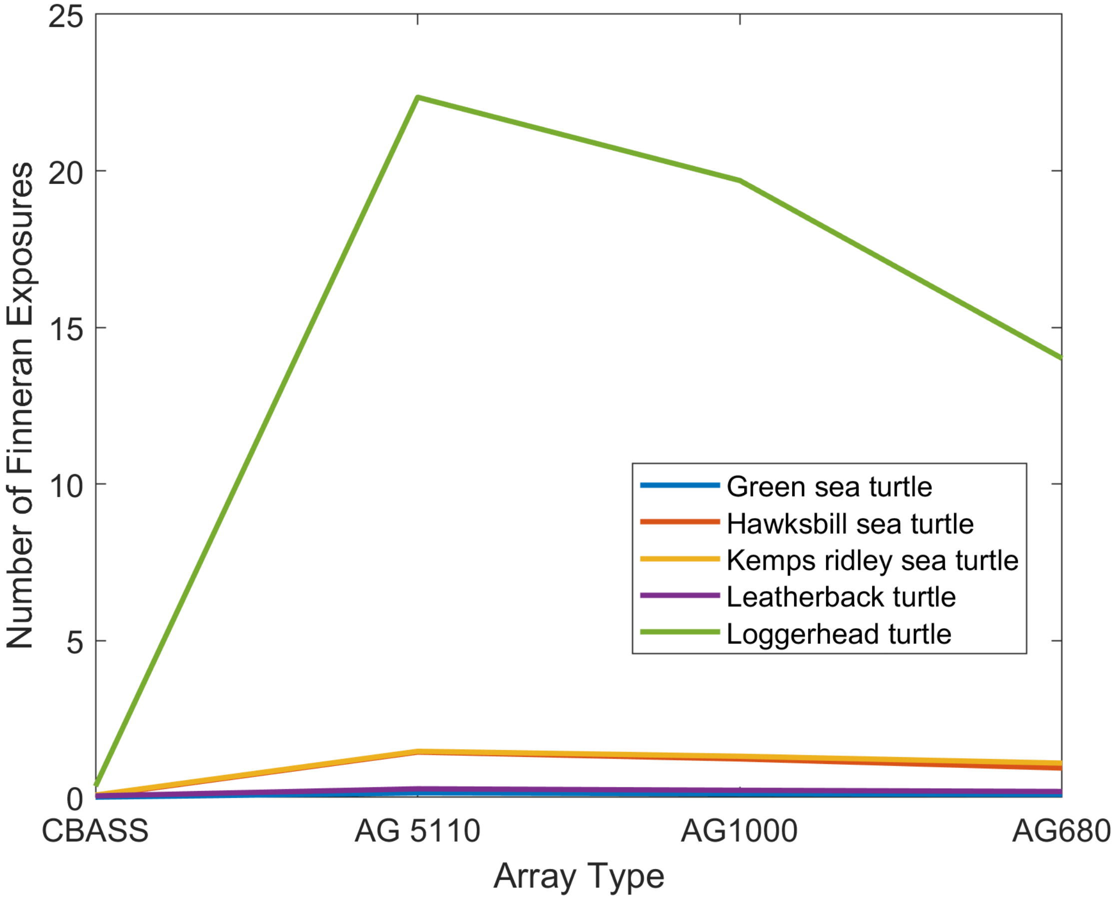

Figure 17. Numbers of unweighted behavioral exposures for sea turtles presented by array.

Table 18. The maximum Finneran 175 dB behavioral exposure estimates are shown for the four array types and calculated using the maximum monthly density for each species.

Species	CBASS	AG 5110	AG1000	AG680
Green sea turtle	0.006	0.142	0.114	0.093
Hawksbill sea turtle	0.049	1.445	1.227	0.935
Kemps ridley sea turtle	0.073	1.470	1.312	1.093
Leatherback turtle	0.047	0.272	0.225	0.186
Loggerhead turtle	0.355	22.350	19.689	14.013

Table 19. The maximum TTS SEL exposure estimates are shown for the four array types and calculated using the maximum monthly density for each species.

Species	CBASS	AG 5110	AG1000	AG680
Atlantic Spotted Dolphin	0	0	0	0
Blainville's beaked whale	0	0	0	0
Clymene dolphin	0	0.007	0	0
Common bottlenose dolphin	0	0	0	0
Dwarf sperm whale	0	0.300	0	0
False killer whale	0	0	0	0
Frasers dolphin	0	0	0	0
Gervais' beaked whale	0	0	0	0
Goose-beaked whale	0	0	0	0
Green sea turtle	0.001	0.018	0.006	0.003
Hawksbill sea turtle	0	0.340	0.158	0.085
Kemps ridley sea turtle	0	0.231	0.182	0.146
Killer whale	0	0.016	0	0
Leatherback turtle	0	0.171	0.078	0.039
Loggerhead turtle	0	4.080	2.661	1.064
Melon headed whale	0	0	0	0
Pantropical spotted dolphin	0	0	0	0
Pygmy killer whales	0	0	0	0
Pygmy sperm whale	0	0.300	0	0
Rice's whale	0	0.089	0.025	0.014
Risso's dolphin	0	0	0	0
Rough-toothed dolphin	0	0	0	0
Short fined pilot whale	0	0	0	0
Sperm whale	0	0	0	0
Spinner dolphin	0	0	0	0
Striped dolphin	0	0	0	0

Table 20. The maximum PTS SEL exposure estimates are shown for the four array types and calculated using the maximum monthly density for each species.

Species	CBASS	AG 5110	AG1000	AG680
Atlantic Spotted Dolphin	0	0	0	0
Blainville’s beaked whale	0	0	0	0
Clymene dolphin	0	0	0	0
Common bottlenose dolphin	0	0	0	0
Dwarf sperm whale	0	0	0	0
False killer whale	0	0	0	0
Frasers dolphin	0	0	0	0
Gervais’ beaked whale	0	0	0	0
Goose-beaked whale	0	0	0	0
Green sea turtle	0	0	0	0
Hawksbill sea turtle	0	0.024	0	0
Kemps ridley sea turtle	0	0	0	0
Killer whale	0	0	0	0
Leatherback turtle	0	0	0	0
Loggerhead turtle	0	0	0	0
Melon headed whale	0	0	0	0
Pantropical spotted dolphin	0	0	0	0
Pygmy killer whales	0	0	0	0
Pygmy sperm whale	0	0	0	0
Rice’s whale	0	0.007	0.002	0.001
Risso’s dolphin	0	0	0	0
Rough-toothed dolphin	0	0	0	0
Short fined pilot whale	0	0	0	0
Sperm whale	0	0	0	0
Spinner dolphin	0	0	0	0
Striped dolphin	0	0	0	0

4.4. Exposure Ranges

4.4.1. Marine Mammals

Sections 4.4.1.1 and 4.4.1.2summarize the exposure ranges ($ER_{95\%}$) to injury and behavior thresholds for marine mammals.

4.4.1.1. Behavioral Exposure Ranges

The marine mammal behavioral exposure ranges reflect the exposure numbers. The C-BASS source had the lowest exposure ranges and the ranges for the different airgun arrays all scaled with array size.

Table 21. Exposure ranges (m) of marine mammals for the four different array types using the NOAA (2005), 160 dB threshold.

Species	CBASS	AG 5110	AG1000	AG680
Atlantic Spotted Dolphin	123	11,691	705	619
Blainville's beaked whale	96	11,380	1,078	1,021
Clymene dolphin	139	11,833	708	580
Common bottlenose dolphin	181	13,599	1,547	1,234
Dwarf sperm whale	96	11,380	1,078	1,021
False killer whale	164	12,777	1,546	1,184
Frasers dolphin	167	13,581	1,697	1,383
Gervais beaked whale	96	11,380	1,078	1,021
Goose-beaked whale	155	12,008	2,679	1,818
Killer whale	172	13,017	1,182	917
Melon headed whale	136	13,359	1,618	1,271
Pantropical spotted dolphin	128	11,604	749	605
Pygmy killer whales	186	13,224	1,240	968
Pygmy sperm whale	96	11,380	1,078	1,021
Rice's whale [a]	173	12,841	1,270	1,124
Risso's Dolphin	158	11,787	1,211	927
Rough-toothed dolphin	176	13,333	1,125	948
Short fined pilot whale	160	12,520	1,854	1,447
Sperm Whale [a]	97	13,184	2,394	1,747
Spinner Dolphin	98	11,859	725	631
Striped Dolphin	185	12,564	1,359	1,131

[a] Listed as Endangered under the ESA.

Table 22. Exposure ranges (m) of marine mammals for the four different array types using the Wood et al (2012) thresholds.

Species	CBASS	AG 5110	AG1000	AG680
Atlantic Spotted Dolphin	5	913	601	420
Blainville’s beaked whale	788	38,341	36,931	34,721
Clymene dolphin	0	982	617	381
Common bottlenose dolphin	9	1,508	772	455
Dwarf sperm whale	0	812	462	281
False killer whale	3	1,456	700	460
Frasers dolphin	3	1,481	735	438
Gervais beaked whale	788	38,341	36,931	34,721
Goose-beaked whale	760	38,455	37,195	35,164
Killer whale	0	1,182	679	422
Melon headed whale	9	1,466	723	424
Pantropical spotted dolphin	10	879	608	383
Pygmy killer whales	7	1,375	726	433
Pygmy sperm whale	0	812	462	281
Rice’s whale [a]	174	11,742	1,294	1,102
Risso’s Dolphin	0	1,060	685	370
Rough-toothed dolphin	0	1,155	664	436
Short fined pilot whale	0	1,467	667	436
Sperm Whale [a]	7	1,782	698	376
Spinner Dolphin	0	1,011	635	412
Striped Dolphin	0	1,371	694	453

[a] Listed as Endangered under the ESA.

4.4.1.2. Injury Exposure Ranges

Injury exposure ranges were all zero, apart from the one low-frequency species, Rice's whale. For that whale, only airgun arrays produced injury exposure ranges, and those ranges scaled with airgun array size. It is worth noting that all predicted injury ranges are less than 500 meters.

Table 23. Exposure ranges (m) of marine mammals for the four different array types using the SEL PTS criteria (NMFS, 2018).

Species	CBASS	AG 5110	AG1000	AG680
Atlantic Spotted Dolphin	0	0	0	0
Blainville's beaked whale	0	0	0	0
Clymene dolphin	0	0	0	0
Common bottlenose dolphin	0	0	0	0
Dwarf sperm whale	0	0	0	0
False killer whale	0	0	0	0
Frasers dolphin	0	0	0	0
Gervais beaked whale	0	0	0	0
Goose-beaked whale	0	0	0	0
Killer whale	0	0	0	0
Melon headed whale	0	0	0	0
Pantropical spotted dolphin	0	0	0	0
Pygmy killer whales	0	0	0	0
Pygmy sperm whale	0	0	0	0
Rice's whale [a]	0	184	51	20
Risso's Dolphin	0	0	0	0
Rough-toothed dolphin	0	0	0	0
Short fined pilot whale	0	0	0	0
Sperm Whale [a]	0	0	0	0
Spinner Dolphin	0	0	0	0
Striped Dolphin	0	0	0	0

[a] Listed as Endangered under the ESA.

4.4.2. Sea Turtles

Similar to the results presented for marine mammals (see Section 4.4), the following sections summarize the exposure ranges ($ER_{95\%}$) for sea turtles.

Table 24. Exposure Ranges (m) to the Finneran et al. (2017) 175 dB threshold for all four array types.

Species	CBASS	AG 5110	AG1000	AG680
Green sea turtle	18	236	186	155
Hawksbill sea turtle [a]	28	295	259	197
Kemps ridley sea turtle [a]	23	233	183	154
Leatherback turtle [a]	32	385	357	147
Loggerhead turtle	27	298	294	187

[a] Listed as Endangered under the ESA.

Table 25. Exposure Ranges (m) to the SEL PTS thresholds for all four array types.

Species	CBASS	AG 5110	AG1000	AG680
Green sea turtle	0	0	0	0
Hawksbill sea turtle [a]	0	10	0	0
Kemps ridley sea turtle [a]	0	0	0	0
Leatherback turtle [a]	0	0	0	0
Loggerhead turtle	0	0	0	0

[a] Listed as Endangered under the ESA.

5. Discussion and Conclusion

Ranges to SEL_{24h} PTS thresholds for marine mammals and sea turtles across the modelled survey area were not reached, or were less than the modeling resolution, except in the case of the 5110 in^3 airgun array, where the $R_{95\%}$ acoustic range to the low-frequency cetacean threshold was 1.04 km. For impulsive thresholds, which are more conservative than the continuous-source thresholds, sound levels associated with the C-BASS source is not expected to reach PTS thresholds. The largest PK PTS $R_{95\%}$ acoustic range of 278 m occurred for the 5110 in^3 airgun array for high-frequency cetaceans; all other hearing groups had PK ranges less than 100 m.

The NMFS (2023) sound source category definitions for behavioral effects considers sources to be either continuous or intermittent/impulsive. Based on these definitions, the C-BASS source, which has a 53% duty cycle, was considered to be intermittent and the airgun arrays were considered impulsive. For both sources the marine mammal behavioral threshold of 160 dB SPL was used. For marine mammals, a behavioral $R_{95\%}$ acoustic range of 200 m was predicted for the C-BASS source and an $R_{95\%}$ range of 13.9 km for the 5110 in^3 airgun array. Similarly, the $R_{95\%}$ range to behavioral threshold for sea turtles was only 40 m for the C-BASS and 1.9 km for the 5110 in^3 airgun array.

The animal movement modeling results found that for all species and all metrics, C-BASS had the lowest predicted number of animals exposure above threshold values. Cetacean behavioral ‘takes’ for the C-BASS system were approximately 1% of the number predicted for the 5,110 in^3 airgun array. Turtle behavioral ‘takes’ were approximately 6%. Very few TTS or PTS exposures were predicted for any array. However, for those species that did experience these exposures, the C-BASS array had less than 8% of the exposures predicted for the large airgun array. The exposure range ($ER_{95\%}$) predictions for all species and sources were lower than the acoustics ranges. The only injury exposure ranges greater than zero were for Rice’s whale. Those were between 20 and 184m for the three airgun arrays, well within the 500m shutdown distance that is typically required.

Together, both the acoustic and animal movement modeling predictions find that the use of C-BASS will produce less impact to all modeled marine fauna than any of the traditional airgun sources.

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Glossary of Acoustics Terms

Unless otherwise stated in an entry, these definitions are consistent with ISO 18405 (2017).

Light blue text indicates related terms that might be in this glossary. Dark blue text indicates clickable links to related terms in this glossary.

attenuation

The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium. Attenuation depends on frequency—higher frequency sounds are attenuated faster than lower frequency sounds.

A-weighting

Frequency-selective weighting for human hearing in air that is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies.

azimuth

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

bandwidth

A range within a continuous band of frequencies. Unit: hertz (Hz).

cetacean

Member of the order Cetacea. Cetaceans are aquatic mammals and include whales, dolphins, and porpoises.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called a longitudinal wave. In seismology/geophysics, it’s called a primary wave or P-wave. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

continuous sound

A sound whose sound pressure level remains above the background noise during the observation period and may gradually vary in intensity with time, e.g., sound from a marine vessel.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006). For example, one decade up from 1000 Hz is 10,000 Hz, and one decade down is 100 Hz.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Especially suited to quantify variables with a large dynamic range.

decidecade

One tenth of a decade. Approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct), and for this reason sometimes referred to as a 1/3 octave.

decidecade band

Frequency band whose bandwidth is one decidecade. The bandwidth of a decidecade band increases with increasing center frequency.

delphinid

Member of the family of oceanic dolphins (Delphinidae), composed of approximately 35 extant species, including dolphins, porpoises, and killer whales.

energy source level

A property of a sound source equal to the sound exposure level measured in the far field plus the propagation loss from the acoustic center of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^2 m^2 s.

ensonified

Exposed to sound.

far field

The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears to radiate from a single point.

frequency

The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

frequency weighting

The process of applying a frequency-weighting function.

frequency-weighting function

The squared magnitude of the sound pressure transfer function (ISO 18405:2017). For sound of a given frequency, the frequency-weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

- *Auditory frequency-weighting function*: compensatory frequency-weighting function accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.
- *System frequency-weighting function*: frequency-weighting function describing the sensitivity of an acoustic recording system, which typically consists of a hydrophone, one or more amplifiers, and an analog-to-digital converter.

functional hearing group

Category of animal species when classified according to their hearing sensitivity, hearing anatomy, and susceptibility to sound. For marine mammals, initial groupings were proposed by Southall et al. (2007), and revised groupings are developed as new research/data becomes available. Revised groupings proposed by Southall et al. (2019) include low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, phocid carnivores in water, other carnivores in water, and sirenians.

geoacoustic

Relating to the acoustic properties of the seabed.

hearing threshold

For a given species or functional hearing group, the sound level for a given signal that is barely audible (i.e., that would be barely audible for a given individual in the presence of specified background noise during a specific percentage of experimental trials).

hertz (Hz)

Unit of frequency defined as one cycle per second. Often expressed in multiples such as kilohertz (1 kHz = 1000 Hz).

high-frequency (HF) cetaceans

See **functional hearing group**. The mid- and high-frequency cetaceans groups proposed by Southall et al. (2007) were renamed high- and very-high-frequency cetaceans, respectively, by Southall et al. (2019).

intermittent sound

A sound whose level abruptly drops below the background noise level multiple times during an observation period.

impulsive sound

Qualitative term meaning sounds that are typically transient, brief (less than 1 s), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Sources of impulsive sound include, among others, explosives, seismic airguns, and impact pile drivers.

isopleth

A line drawn on a map through all points having the same value of some specified quantity (e.g., sound pressure level isopleth).

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. For example, a value of sound pressure level with reference to 1 μPa^2 can be written in the form *x* dB re 1 μPa^2.

low-frequency (LF) cetaceans

See **functional hearing group**.

mid-frequency (MF) cetaceans

See **functional hearing group**. The mid-frequency cetaceans group proposed by Southall et al. (2007) was renamed high-frequency cetaceans by Southall et al. (2019).

M-weighting

A set of auditory frequency-weighting functions proposed by Southall et al. (2007).

mysticete

Member of the Mysticeti, a suborder of cetaceans. Also known as baleen whales, mysticetes have baleen plates (rather than teeth) that they use to filter food from water (or from sediment as for gray whales). This group includes rorquals (Balaenopteridae, such as blue, fin, humpback, and minke whales), right and bowhead whales (Balaenidae), and gray whales (*Eschrichtius robustus*).

non-impulsive sound

Sound that is not an impulsive sound. Not necessarily a continuous sound.

octave

The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete

Member of Odontoceti, a suborder of cetaceans. These whales, dolphins, and porpoises have teeth (rather than baleen plates). Their skulls are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

otariid

Member of the family Otariidae, one of the three groupings of pinnipeds (along with phocids and walrus). These eared seals, commonly called fur seals and sea lions, are adapted to semi-aquatic life; they use their large fore flippers for propulsion underwater and can walk on all four limbs on land.

particle acceleration, particle displacement, particle motion, particle velocity

See sound particle acceleration, sound particle displacement, sound particle motion, and sound particle velocity.

peak sound pressure level (PK), zero-to-peak sound pressure level

The level (L_{pk}) of the squared maximum magnitude of the sound pressure (p_{pk}^2) in a stated frequency band and time window. Defined as $L_{pk} = 10\log_{10}(p_{\mathrm{pk}}^2/p_0^2) = 20\log_{10}(p_{pk}/p_0)$. Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa^2.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. Considered auditory injury. Compare with temporary threshold shift.

phocid

Member of the family Phocidae, one of the three groupings of pinnipeds (along with otariids and walrus). These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves underwater.

pinniped

Member of the superfamily Pinnipedia, which is composed of phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

point source

A source that radiates sound as if from a single point.

power spectral density

Generic term, formally defined as power in a unit frequency band. Unit: watt per hertz (W/Hz). The term is sometimes loosely used to refer to the spectral density of other parameters such as squared sound pressure. Ratio of energy spectral density, E_f, to time duration, Δt, in a specified temporal observation window. In equation form, the power spectral density P_f is given by $P_f = E_f/\Delta t$. Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement).

propagation loss (PL)

Difference between a source level (SL) and the level at a specified location, PL(x) = SL − $L(x)$. Unit: decibel (dB). See also transmission loss.

received level

The level of a given field variable measured (or that would be measured) at a given location.

reference value

Standard value of a quantity used for calculating underwater sound level. The reference value depends on the quantity for which the level is being calculated:

Quantity	Reference value
Sound pressure	p_0^2 = 1 μPa^2 or p_0 = 1 μPa
Sound exposure	E_0 = 1 μPa^2 s
Sound particle displacement	δ_0^2 = 1 pm^2
Sound particle velocity	u_0^2 = 1 nm^2/s^2
Sound particle acceleration	a_0^2 = 1 μm^2/s^4

shear wave

A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called a secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium. In common meaning, a form of energy that propagates through media (e.g., water, air, ground) as pressure waves.

sound exposure

Time integral of squared sound pressure over a stated time interval in a stated frequency band. The time interval can be a specified time duration (e.g., 24 h) or from start to end of a specified event (e.g., a pile strike, an airgun pulse, a construction operation). Unit: pascal squared second (Pa^2 s). Symbol: E.

sound exposure level (SEL)

The level (L_E) of the sound exposure (E) in a stated frequency band and time window: $L_E = 10\log_{10}(E/E_0)$ (ISO 18405:2017). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa^2 s.

sound field

Region containing sound waves.

sound particle acceleration

The rate of change of sound particle velocity. Unit: meter per second squared (m/s^2). Symbol: a.

sound particle velocity

The velocity of a particle in a material moving back and forth in the direction of the pressure wave. Unit: meter per second (m/s). Symbol: u.

sound pressure

The contribution to total pressure caused by the action of sound (ISO 18405:2017). Unit: pascal (Pa). Symbol: p.

sound pressure level (SPL), rms sound pressure level

The level (L_p) of the time-mean-square sound pressure (p_{rms}^2) in a stated frequency band and time window: $L_p = 10\log_{10}(p_{\mathrm{rms}}^2/p_0^2) = 20\log_{10}(p_{\mathrm{rms}}/p_0)$, where rms is the abbreviation for root-mean-square. Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 µPa^2. SPL can also be expressed in terms of the root-mean-square (rms) with a reference value of p_0 = 1 µPa. The two definitions are equivalent.

sound speed profile

The speed of sound in the water column as a function of depth below the water surface.

source level (SL)

A property of a sound source equal to the sound pressure level measured in the far field plus the propagation loss from the acoustic center of the source to the receiver position. Unit: decibel (dB). Reference value: 1 µPa^2 m^2.

spectrum

Distribution of acoustic signal content over frequency, where the signal's content is represented by its power, energy, mean-square sound pressure, or sound exposure.

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity caused by noise exposure. Compare with permanent threshold shift.

transmission loss (TL)

The difference between a specified level at one location and that at a different location: TL(x_1,x_2) = $L(x_1) - L(x_2)$ (ISO 18405:2017). Unit: decibel (dB). See also propagation loss.

unweighted

Term indicating that no frequency-weighting function is applied.

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Appendix A. Underwater Acoustics

A.1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 µPa. Because the perceived loudness of sound —especially pulsed sound such as from seismic airguns, pile driving, and sonar—is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. This Section describes metrics relevant to this report. Where possible, we follow the ISO standard definitions and symbols for sound metrics, but these standards are not always consistent (ISO 2017).

The zero-to-peak sound pressure, or peak sound pressure (PK or $L_{p,pk}$; dB re 1 µPa), is the decibel level of the maximum instantaneous acoustic pressure in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \tag{A-1}$$

The sound exposure level (SEL) (L_E; dB re 1 µPa^{2}s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right) , \tag{A-2}$$

where T_0 is a reference time interval of 1 s. The SEL represents the total acoustic energy received at some location during an acoustic event; it measures the sound energy to which an organism at that location would be exposed.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to pulsed sounds, SEL can be calculated by summing the SEL of the *N* individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, SEL can be computed by summing (in linear units) the SEL of the *N* individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right) . \tag{A-3}$$

A.2. Decidecade bands

Table A-1 shows decidecade bands according to IEC (2014), for decidecade frequency bands with center frequencies 10 Hz (n = −20) Hz to 63 kHz (n = +18).

Table A-1. Decidecade frequency bands, as defined by IEC (2014), with center frequencies between 1 Hz (n = -30) and 1 MHz (n = +30) (after Ainslie et al. 2018). Band edge and center frequencies are stated to 5 significant figures.

Band index	***Lower bound***	***Center frequency***	***Upper bound***	***(Nominal center frequency)***
n	f_{min}/Hz	f_{c}/Hz	f_{max}/Hz	$f_{\mathrm{c,nom}}$
-20	8.9125	10	11.220	(10 Hz)
-19	11.220	12.589	14.125	(12.5 Hz)
-18	14.125	15.849	17.783	(16 Hz)
-17	17.783	19.953	22.387	(20 Hz)
-16	22.387	25.119	28.184	(25 Hz)
-15	28.184	31.623	35.481	(32 Hz)
-14	35.481	39.811	44.668	(40 Hz)
-13	44.668	50.119	56.234	(50 Hz)
-12	56.234	63.096	70.795	(63 Hz)
-11	70.795	79.433	89.125	(80 Hz)
-10	89.125	100	112.20	(100 Hz)
-9	112.20	125.89	141.25	(125 Hz)
-8	141.25	158.49	177.83	(160 Hz)
-7	177.83	199.53	223.87	(200 Hz)
-6	223.87	251.19	281.84	(250 Hz)
-5	281.84	316.23	354.81	(320 Hz)
-4	354.81	398.11	446.68	(400 Hz)
-3	446.68	501.19	562.34	(500 Hz)
-2	562.34	630.96	707.95	(630 Hz)
-1	707.95	794.33	891.25	(800 Hz)
0	891.25	1000	1122	(1 kHz)
1	1122.0	1258.9	1412.5	(1.25 kHz)
2	1412.5	1584.9	1778.3	(1.6 kHz)
3	1778.3	1995.3	2238.7	(2 kHz)
4	2238.7	2511.9	2818.4	(2.5 kHz)
5	2818.4	3162.3	3548.1	(3.2 kHz)
6	3548.1	3981.1	4466.8	(4 kHz)
7	4466.8	5011.9	5623.4	(5 kHz)
8	5623.4	6309.6	7079.5	(6.3 kHz)
9	7079.5	7943.3	8912.5	(8 kHz)
10	8912.5	10000	11220	(10 kHz)
11	11220	12589	14125	(12.5 kHz)
12	14125	15845	17783	(16 kHz)
13	17783	19953	22387	(20 kHz)
14	22387	25119	28184	(25 kHz)

Appendix B. Marine Mammal Impact Criteria

B.1. Marine Mammals Auditory Injury Impact Criteria

It has been long recognized that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggest that communication distances of fin whales are reduced by shipping noises. Subsequently, similar concerns arose regarding effects of other underwater sound sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater sound sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed.

The NMFS SPL criteria for auditory injury to marine mammals from acoustic exposure were set according to recommendations for cautionary estimates of sound levels leading to onset of permanent hearing threshold shift (PTS). These criteria prescribed auditory injury thresholds of 190 dB re 1 µPa SPL for pinnipeds and 180 dB re 1 µPa SPL for cetaceans, for all types of sound sources except tactical sonar and explosives (NMFS 2018). These auditory injury thresholds are applied to individual pulses or instantaneous sound levels and do not consider the overall duration of the sound or its acoustic frequency distribution.

In recognition of shortcomings of the SPL-only based auditory injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new sound exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual auditory injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted, whereas SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and pinnipeds in water (Pws)[1]. These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for humans). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

There is consensus in the research community that an SEL-based method is preferable, either separately or in addition to an SPL-based approach, to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalized technical guidance for assessing the effect of anthropogenic noise on marine mammal hearing (NMFS 2016, NMFS 2018). The guidance describes auditory injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2018 (NMFS 2018). Southall et al. (2019) revisited the interim criteria published in 2007. All sound exposure criteria in NMFS (2018) and Southall et al. (2019) are identical (for impulsive and non-impulsive sounds); however the mid-frequency cetaceans from NMFS (2018) are classified as high-frequency cetaceans in Southall et

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[1] Pinnipeds in air were also included but are not applicable here.

al. (2019), and high-frequency cetaceans from NMFS (2018) are classified as very-high-frequency cetaceans in Southall et al. (2019). Table B-1 provides the recommended thresholds.

Table B-1. Peak sound pressure level (PK; dB re 1 µPa) and sound exposure level (SEL; dB re 1 µPa^2 s) thresholds for auditory injury (PTS onset) and TTS onset for marine mammals for impulsive sounds, as proposed by Southall et al. (2019).

Hearing group	Auditory injury (PTS)		TTS	
	Weighted SEL$_{24h}$ (dB re 1 µPa^2 s)	PK (dB re 1 µPa)	Weighted SEL$_{24h}$ (dB re 1 µPa^2 s)	PK (dB re 1 µPa)
Low-frequency cetaceans	183	219	168	213
High-frequency cetaceans	185	230	170	224
Very high-frequency cetaceans	155	202	140	196
Sirenians	190	226	175	220
Phocid carnivores in water	185	218	170	212
Other carnivores in water	203	232	188	226

B.2. Marine Mammal Auditory Frequency Weighting Southall (2019)

The potential for sound to affect animals of a certain species depends on how well the animals can hear it. Sounds are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal’s sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

In 2015, a US Navy technical report by Finneran (2015) recommended new auditory weighting functions. The auditory weighting functions for marine mammals are applied in a similar way as A-weighting for sound level assessments for humans. The new frequency-weighting functions are expressed as:

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

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA’s technical guidance that assesses acoustic impacts on marine mammals (NMFS 2018), and in the latest guidance by Southall (2019). The updates did not affect the content related to either the definitions of frequency-weighting functions or the threshold values. However, Southall (2019) added one more functional hearing group and updated the names of existing functional hearing groups and the species allocation between groups. Table B-2 lists the frequency-weighting parameters for each hearing group. Figure B-1 shows the resulting frequency-weighting curves.

Table B-2. Parameters for the auditory weighting functions recommended by NMFS (2018) and Southall (2019).

Functional hearing group		***a***	***b***	***f_1* (Hz)**	***f_2* (Hz)**	***K* (dB)**
NMFS (2018)	**Southall (2019)**					
Low-frequency cetaceans	Low-frequency cetaceans	1.0	2	200	19,000	0.13
Mid-frequency cetaceans	High-frequency cetaceans	1.6	2	8800	110,000	1.20
High-frequency cetaceans	Very high-frequency cetaceans	1.8	2	12,000	140,000	1.36
n/a	Sirenians	1.8	2	4300	25,000	2.62
Phocid pinnipeds in water	Phocid carnivores in water	1.0	2	1900	30,000	0.75
Otariid pinnipeds in water	Other carnivores in water	2.0	2	940	25,000	0.64

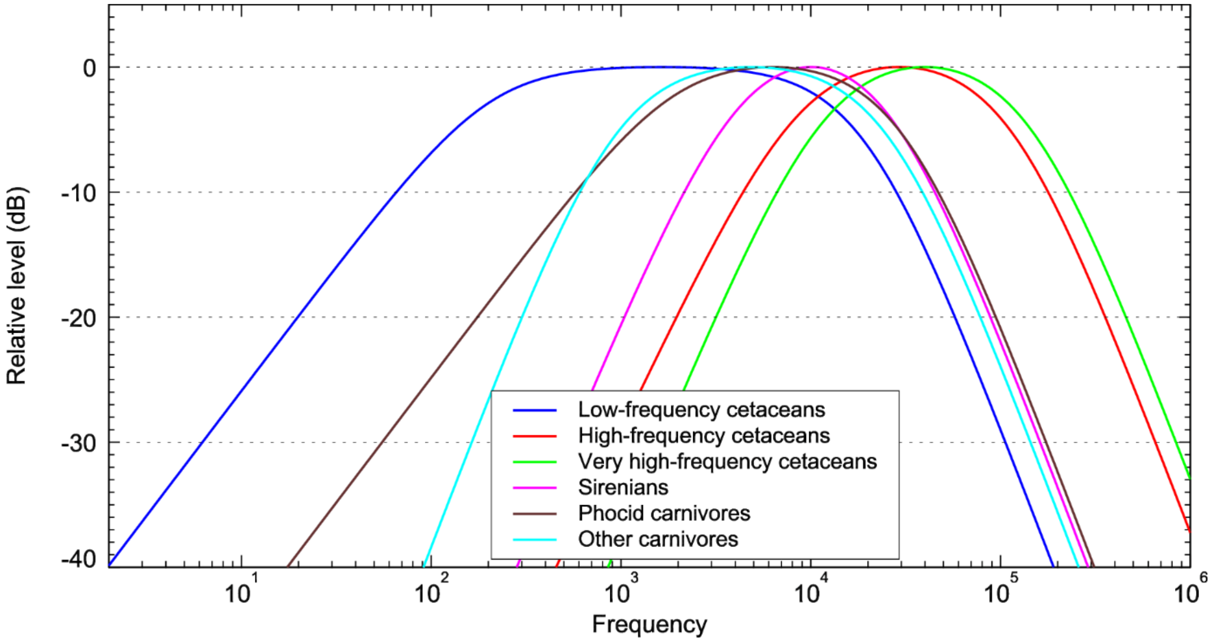

Figure B-1. Auditory weighting functions for the functional marine mammal hearing groups as recommended by Southall (2019).

Appendix C. Animal Movement and Exposure Modeling

To assess the risk of impacts from anthropogenic sound exposure, an estimate of the received sound levels for individuals of each species known to occur in the Project Area during the assessed activities is required. Both sound sources and animals move. The sound fields may be complex, and the sound received by an animal is a function of where the animal is at any given time. To a reasonable approximation, the locations of the project sound sources are known, and acoustic modeling can be used to predict the individual and aggregate 3-D sound fields of the sources. The location and movement of animals within the sound field, however, is unknown. Realistic animal movement within the sound field can be simulated. Repeated random sampling (Monte Carlo method simulating many animals within the operations area) is used to estimate the sound exposure history of the population of simulated animals (animats) during the operation.

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more animats, the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practical allowing for computation time. The animat density is much higher than the real-world density to ensure good representation of the PDF. The resulting PDF is scaled using the real-world density.

Several models for marine mammal movement have been developed (Ellison et al. 1999, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behavior. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth distances can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source marine mammal movement and behavior model (3MB; Houser 2006) and used to predict the exposure of animats (virtual marine mammals and sea turtles) to sound arising from sound sources in simulated representative surveys. Inside JASMINE, the sound source location mimics the movement of the source vessel through the proposed survey pattern. Animats are programmed to behave like the marine animals likely to be present in the survey area. The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, surface times, etc.) are determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modeled sound exposure levels are summed over the total simulation duration, such as 24 hours or the entire simulation, to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as the 3MB model (Houser 2006) but has been extended to be directly compatible with MONM and FWRAM acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioral states based on time and space dependent modeled variables such as received levels for aversion behavior (Ellison et al. 2016).

C.1. Animal Movement Parameters

JASMINE uses previously measured behavior to forecast behavior in new situations and locations. The parameters used for forecasting realistic behavior are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behavior of a species are available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behavior states. The probability of an animat starting out in or transitioning into a given behavior state can in turn be defined in terms of the animat's current behavioral state, depth, and the time of day. In addition, each travel parameter and behavioral state has a termination function that governs how long the parameter value or overall behavioral state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. A description of parameters relating to travel in these two planes are briefly described below. JASCO maintains species-specific choices of values for the behavioral parameters used in this study. The parameter values are available for limited distribution upon request.

Travel sub-models

- **Direction**–determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to distance from strongly biased to undirected. A random walk model can be used for behaviors with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006).
- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Bottom following**–determines whether an animat returns to the surface once reaching the ocean floor, or whether it follows the contours of the bathymetry.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behavior is used to emulate the foraging behavior of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

C.1.1. Exposure Integration Time

The interval over which acoustic energy (*SEL*) should be integrated and maximal sound pressure (*SPL*) determined is not well defined. Both Southall et al. (2007) and the NMFS (2018) recommend a 24 h baseline accumulation period, but state that there may be situations where this is not appropriate (e.g., a high-level source and confined population). Resetting the integration after 24 h can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behavior collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. Therefore, the simulation time should be limited to a few weeks, the approximate scale of the collected data (e.g., marine mammal tag data) (Houser 2006). For this study, three-day simulations were modeled.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that might be present in the Project Area during sound-producing activities is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited in this analysis to a maximum distance of 50 km modeling site in the middle of the survey track. In the simulation, every animat that reaches and leaves a border of the simulation area is replaced by another animat entering at an opposite border—e.g., an animat departing at the northern border of the simulation area is replaced by an animat entering the simulation area at the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a depth suited to its species definition. The exposures of all animats (including those leaving the simulation and those entering) are kept for analysis. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.