Underwater Acoustic Modeling of Detonations of Unexploded Ordnance (UXO) for Orsted Wind Farm Construction, US East Coast

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Contents

1. Introduction

Orsted's offshore wind projects along the eastern US seaboard may encounter unexploded ordinances (UXO) on the seabed in the wind farm lease areas and along export cable routes. While non-explosive methods may be employed to lift and move these objects, some may need to be removed by explosive detonation. Underwater detonation explosions generate sound waves with high pressure levels that could cause disturbance and/or injury to marine fauna. Mitigation measures will likely be required to avoid Level-A (injurious) takes of animals, and Level-B (behavior) takes will need to be accounted for in the project letter of authorization (LOA) or incidental harassment authorization (IHA). The study described in this report has modeled acoustic source and sound propagation to estimate the sizes of Level-A and Level-B take zones for several species and for a selection of charge weights spanning the expected UXO types that may be encountered. The results provided here do not directly predict numbers of takes but they are intended for that purpose. Takes can be computed using approaches such as multiplication of zone areas by the corresponding animal densities (number of animals per unit area).

Most UXO assessment work in the US has been performed by or for the US Navy, who have worked closely with National Marine Fisheries Service (NMFS) to choose and define appropriate criteria for effects based on best available science. We have evaluated effects thresholds based on three key sound pressure metrics considered by the Navy and NMFS as indicators of injury and behavioral disturbance: unweighted peak compressional pressure level ($L_{\mathrm{pk,c}}$ and abbreviated here L_{pk}), frequency weighted sound exposure level (SEL or $L_{E,w}$), and acoustic impulse (J_p). A fourth metric, sound pressure level (SPL or L_p), which is often used for other impulsive sound assessments, has not been evaluated here because it is not presently used by NMFS as an assessment criterion for sounds from explosive detonations. The names and symbols used for the above metrics follow the terminology of International Organization of Standards (ISO) 18405 (ISO 2017), except where tables and equations have been copied from previous regulatory documents.

The thresholds applied here for each of the acoustic metrics have been obtained from three primary sources:

1.) *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III), June 2017* (Navy, 2017). This report provides thresholds for gastrointestinal and lung injury, and mortality to marine mammals, sea turtles and fish due to explosive pressure based on impulse and peak pressure.

2.) *Marine Mammal Acoustic Technical Guidance (2018 Revision to Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing*), Office of Protected Resources, NOAA Technical Memorandum NMFS-OPR-59, April 2018 (NMFS, 2018). This technical memorandum incorporates the report by J.J. Finneran (2016) that provides auditory weighting functions for SEL calculations and provides thresholds for hearing-related effects.

3.) *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014 (Popper et al., 2014). This report provides peak pressure thresholds for injury and mortality to fish.

The acoustic metrics and thresholds for effects depend on species and in some cases animal size and submersion depth. Specialized acoustic models and semiempirical formulae are applied to evaluate the threshold exceedance distances from explosive charges detonated on the seabed and exposed directly to seawater. The theory underlying these models is provided in the technical discussion sections of this report.

This assessment considers acoustic effects to marine mammals, sea turtles and fish from five possible charge sizes at sites with four water depths near Orsted's Revolution Wind project areas. The results are also relevant for sites with similar water depths at Orsted's Ocean Wind 1 project, Orsted's Sunrise Wind project, and possibly other wind farm sites with similar depths and seabed sediment properties. An unmitigated and mitigated scenario are considered at each site, with mitigation considering a 10 decibel (dB) reduction to L_{pk}, $J_{p,}$ and L_{E}, that might be obtained using an air bubble curtain or similar system. The results for unmitigated and mitigated UXO detonations are provided in Sections 8 and 9 respectively.

Because of the large number of result tables, the Summary (Section 10) provides cross-references for effects assessment criteria to the relevant tables for both unmitigated and mitigated scenarios.

A key assumption of the model predictions presented in this report is that the full weights of UXO explosive charges are detonated together with their donor charges. A recent review of UXO explosive removals in the North Sea indicates that in most cases the UXO charge weights either did not detonate or only partly detonated, with the result being that the pressure waves generated were produced by the donor charge and only a small fraction of the UXO charge (Bellman, 2021). As such, it is likely that the full UXO charge will not detonate in all cases and the results presented herein assume full UXO charge detonation and therefore should be considered the worst case.

2. UXO Charge Sizes

The UXO charges considered here are characterized by their equivalent trinitrotoluene (TNT) weight. Five charge weight “bins” were defined, with each bin representing a group of similar weapons using a categorization defined by the US Navy. The modeling performed here considered the largest charge weight for the corresponding bin. The final set of bins are listed in Table 1. We note that the effect of the donor charges used to detonate the UXO are assumed to be included in the TNT equivalent weight for the respective bin.

Table 1. Navy "bins" and corresponding maximum UXO charge weights (Maximum equivalent weight TNT) to be modeled.

Navy bin	Maximum equivalent weight TNT	
	(kg)	(lbs)
E4	2.3	5
E6	9.1	20
E8	45.5	100
E10	227	500
E12	454	1000

3. Modeling Locations and Depths

Sound propagation away from UXO detonations is affected by acoustic reflections from the sea surface and seabed. Water depth and seabed properties, which are site-dependent, will influence the sound exposure levels and sound pressure levels at distance from detonations. However, when water depths and seabed conditions are similar, the predictions from one site can be used to approximate the acoustic levels at other sites. The influence of the seabed and water depth on sound propagation away from the detonation site is complex but it can be predicted accurately by acoustic models.

Orsted’s recent projects under development in the US include the Revolution Wind project off Massachusetts, the Sunrise Wind project located just south of Revolution Wind, and the Ocean Wind 1 project on the Avalon Shoal off New Jersey. Each project is located in relative shallow waters of 20-54 meter (m) depth, and have sandy seabeds. The results of the present study are relevant for all three projects even though the specific locations modeled here were chosen inside the Revolution Wind project area. The key influencing parameter for these results is water depth; however, small variances of water depth (<10 m) are not expected to generate significant differences to the sound fields, so the propagation results will be relevant for each project area at sites with similar water depth as the sites modeled. The only possible exception is the shallowest site, located in a constrained channel of Narragansett Bay with nearby islands blocking sounds propagating in some directions. Maximum distances to specific sound level thresholds will be similar when islands are not nearby, but the area ensonified above the thresholds could be larger.

Four specific sites (S1 to S4) were chosen for this modeling assessment; two are along the export cable route and two are inside the wind lease area of the Revolution Wind project. The sites are shown on the map of Figure 1 and include:

In shallow waters along export cable route:

- Site S1: In the channel within Narragansett Bay in 12 m depth.
- Site S2: Intermediate waters outside of the Bay in 20 m depth.

Inside the lease area:

- Site S3: Shallower waters in southern portion of Hazard Zone 2 area, in 30 m depth.
- Site S4: Deeper waters in northern portion of Hazard Zone 2 area, in 45 m depth.

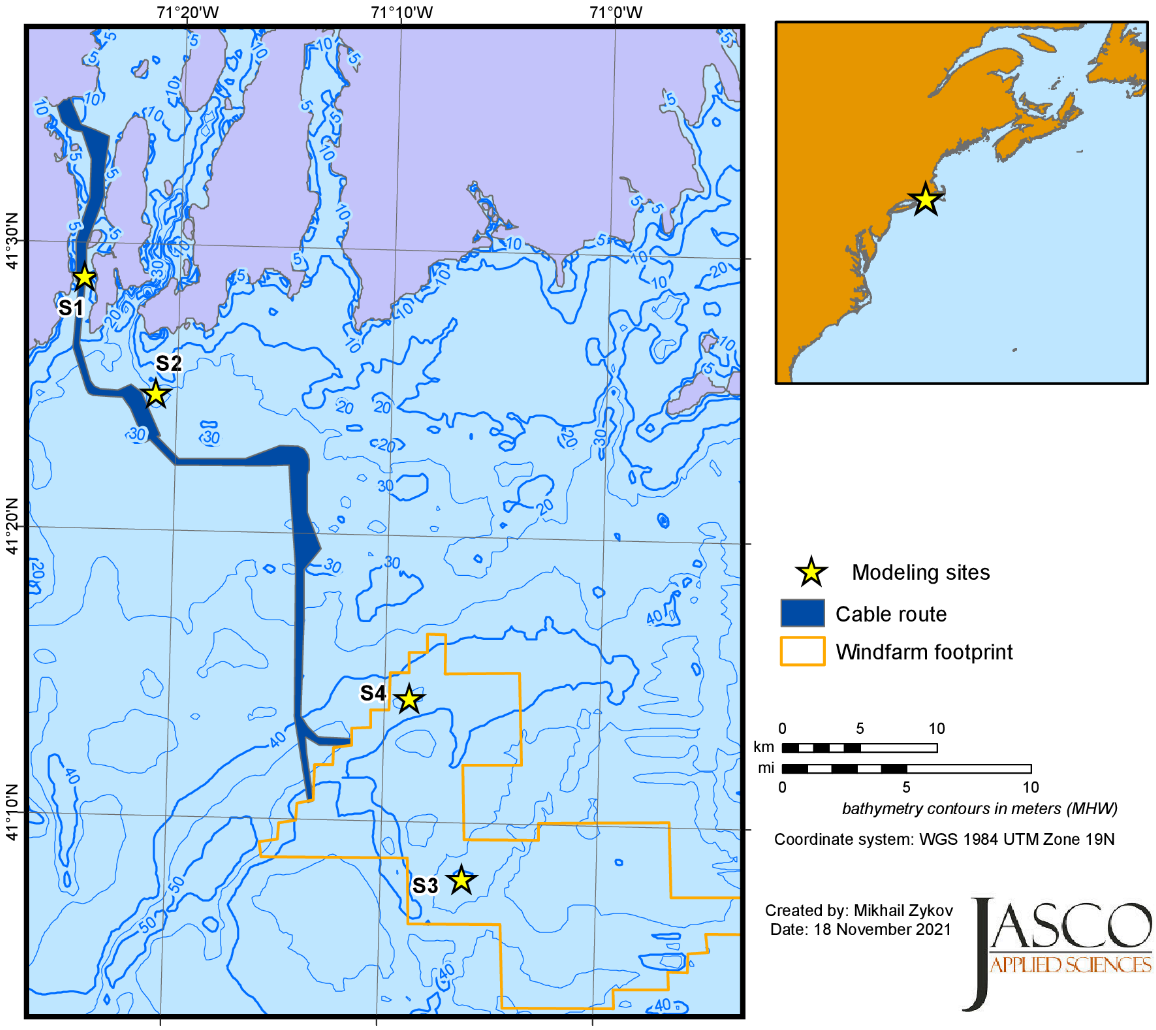

Figure 1. Map showing locations of the four modeling sites.

4. Blast Mitigation

Predictions of exceedance distances for effects to marine mammals were performed for unmitigated and mitigated scenarios, where the mitigated results were obtained by reducing the detonation source levels by 10 dB at all sound frequencies. The 10 dB reduction was applied to L_{pk} and decidecade band L_E and $L_{E,w}$. The corresponding reduction to J_p was applied using a multiplicative factor of $10^{-1/2}$. This amount of acoustic reduction is expected to be achievable by deploying an air bubble curtain or similar system around the detonation site. A review of the expected attenuation for modern bubble curtain systems is provided below.

There is a little published information available on direct measurements of bubble curtain effectiveness for reducing peak pressure, SEL and impulse produced by underwater explosives detonations. One measurement of a small bubble curtain showed good performance for 1 kilogram (kg) charges, providing approximately 16 dB attenuation at all frequencies greater than 1 kilohertz (kHz) using small curtains of less than 11.5 m diameter (Schmidke et al., 2009). The same study evaluated another relatively small bubble curtain (diameter 22 m in 20 m water depth) surrounding 300 kg mines. That bubble curtain

configuration produced smaller attenuations of approximately 2 dB at 100 hertz (Hz) to 6 dB at 10 kHz. These values are substantially smaller than observed attenuations at corresponding frequencies for modern bubble curtains applied to mitigate sounds from large pile installations. The smaller attenuation values observed by Schmidke et al are likely due to use of a small bubble curtain for a relatively large detonation charge size, even though the air flow rate per unit curtain length was similar. Modern curtains also apply bubble size optimization to maximize the frequency-dependent attenuation characteristics, but it is not clear if that was performed for the bubble curtains used in the Schmidke et al study.

A recent review of bubble curtain effectiveness for pile driving noise mitigation by Bellman et al (2020) found the attenuation performance of modern bubble curtains increases with sound frequency from about 20 Hz to 1.5 kHz, and then decreases slowly with further increase in frequency. They tabulated attenuation results for a Big Bubble Curtain (BBC) that indicated attenuations of at least 10 dB at 32 Hz, increasing to approximately 35 dB near 1 kHz. A follow-up report indicates first results for attenuation of UXO acoustic levels by BBC of 11 dB for broadband L_E and up to 18 dB for L_{pk}, although particulars of the charge sizes and water depths in the study were not provided (Bellman, 2021).

The spectral energy distribution of the pressure waveforms of explosives detonated in water will differ from the spectral distribution of pile driving sounds. Nevertheless, the frequency-dependent attenuations are expected to be similar if the bubble curtain radius is large enough to avoid nearfield effects of the explosive detonations. The spectra of smaller charges contain relatively more high-frequency energy than the spectra of larger charges after accounting for the higher overall energy of the larger charges. This spectral shape dependence on charge size is discussed in detail in Section 7.2.1. The maximum spectral levels of all charge sizes considered in this report occur at less than 10 Hz, but their spectral roll-off is small so their maximum decidecade L_E band levels occur above a few hundred Hz. Pile driving spectra have maximum band levels at lower frequencies, which suggests bubble curtain performance for explosive charges should in general produce greater broadband attenuation than for pile driving. The minimum modern bubble curtain attenuation effectiveness for the frequency bands dominating explosive detonation L_E in shallow waters is well above 10 dB. Therefore, the choice of 10 dB as a broadband L_E attenuation is expected to be conservative.

The very rapid onset of the shock pulse, within a few microseconds (μs), and its rapid decay constant of less than 2 ms for the largest charge size considered (454 kg), suggests the shock pulse peak pressure is dominated by high frequencies that are likely much higher than 500 Hz. The results compiled by Bellman et al (2020) indicate the peak pressure attenuation at those frequencies by modern bubble curtains should be greater than 10 dB. As mentioned above, the first results that applied the use of BBC for UXO produced attenuations slightly larger than 10 dB.

As a final note regarding UXO removal detonation pressures: Bellman (2021) noted that many UXO charges are situated slightly below the seafloor elevation after removal of overlying sedimentation. These charges then lie slightly below the seafloor grade and are then partly shielded by surrounding sediments. The generated pressure waves propagating away in the horizontal direction must pass through the sediments, which have higher absorption characteristics than seawater. Bellman found that propagation loss coefficients were higher for these partially buried charges than for charges detonated in seawater. In this study we assumed no such shielding by sediments.

5. Environmental Parameters

5.1. Seafloor Geoacoustic Parameters

Sound propagation in the shallow water environments of Orsted's wind projects is influenced by the properties of the seafloor substrate. A general profile for the area has been used for all four modeling sites. The surficial sediments are primarily sand as described for the seabed at the adjacent South Fork Wind site (Denes et al. 2018). Table 2 shows the sediment layer geoacoustic property profile used for acoustic modeling of SEL in this study. The geoacoustic parameters are not considered by the peak and impulse models, as those metrics are dominated by direct path and surface reflected signals only. The geoacoustic properties are based on the sediment type and generic porosity-depth profile using a sediment grain-shearing model (Buckingham 2005). This general profile should be relevant for sites throughout the Sunrise Wind, Ocean Wind, and Revolution Wind lease areas.

Table 2. Estimated geoacoustic properties used for modeling at all sites, as a function of depth. Within each depth range, the parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm³)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–5	Sand	1.87	1,650–1,690	0.74–1.0	300	3.65
5–10		1.87–2.04	1,690–1,830	1.0		
10–100		2.04	1,830–2,140	1.0–1.67		
>100			2,140	1.67		

5.2. Ocean Sound Speed Profile

The gradients of the speed of sound in seawater affect acoustic refraction during sound propagation. The sound speed is a function of water temperature, salinity, and pressure (i.e., depth) (Coppens 1981). Monthly average sound speed profiles near the proposed construction areas, for the months of April to November, were obtained from the US Navy's Generalized Digital Environmental Model (GDEM; NAVO 2003) and are plotted in Figure 2. The sound speed profiles change little with depth, so these environments do not have strong seasonal dependence. The propagation modeling was performed using a sound speed profile representative of September, which is slightly downward refracting and represents the most likely time of year for UXO removal activities.

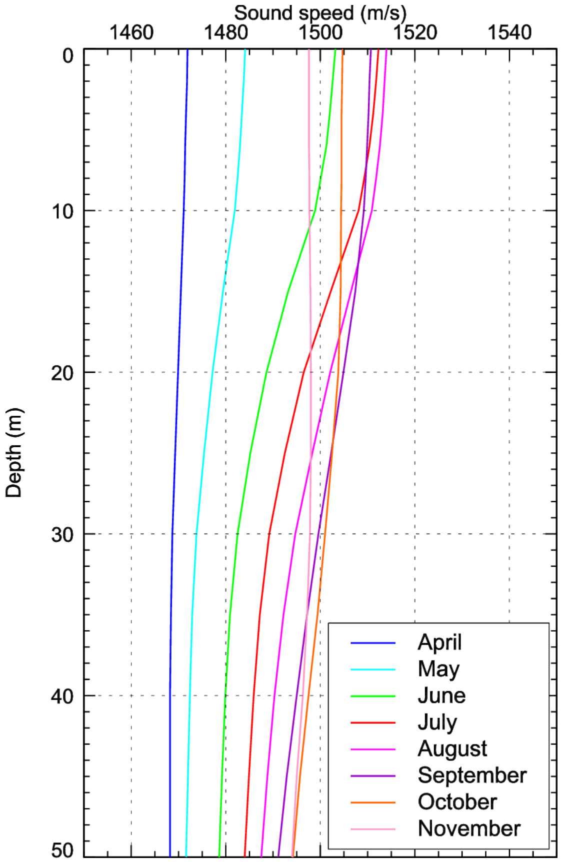

Figure 2. Monthly average sound speed profiles in proposed construction area (excluding winter season) (source: GDEM (NAVO 2003)).

6. Acoustic Thresholds for Mitigation Zones and Take Estimates

6.1. Marine Mammals and Sea Turtles: Auditory Injury (PTS)

The injury zones surrounding explosives detonations are of key importance for developing mitigation designed to minimize takes. Two injury mechanisms are assessed for marine mammals: auditory injury and non-auditory injury. We follow the US Navy approach for assessing both types of effects (Navy, 2017). Auditory injury (onset of permanent threshold shift (PTS)) is assessed using a dual criteria of L_{pk} and frequency-weighted SEL ($L_{E,w}$), where the frequency weighting functions are dependent on the species group (NMFS, 2018). The Navy follows NMFS's guidelines for assessing PTS and temporary threshold shift (TTS) using metrics L_{pk} and $L_{E,w}$ for marine mammals. These thresholds and additional thresholds for sea turtles are provided (Table 3). Note the TTS thresholds also listed in that table are used for Level-B take assessments (see Section 6.3). The Group column in Table 3 represents species groups from top to bottom: low-frequency cetaceans (LF), mid-frequency cetaceans (MF), high-frequency cetaceans (HF), sirenians (SI), otariids in water (OW), pinnipeds in water (PW), and sea turtles (TU).

Table 3. US Navy peak (2017) pressure and frequency-weighted sound exposure thresholds for onset of PTS and TTS. See text for a description of the Group abbreviations.

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

Note: the term "peak SPL" used in column 6 represents the peak pressure level (L_{pk}) metric as defined in ISO 18405. Peak pressure is not truly an SPL, as SPL is now defined as a root-mean-square pressure level.

6.2. Marine Mammals and Sea Turtles: Non-Auditory Injury and Mortality

Non-auditory injury and mortality mitigation zones are calculated using metrics representing onset of injury to animal's lungs and gastrointestinal tracts from compression of enclosed air volumes or bubbles. The relevant metrics are L_{pk} and J_p of the blast shock pulse. The peak pressure threshold for injury to gastrointestinal tract is provided in Table 6 as L_{pk} = 237 dB re µPa and this is independent of animal mass. However, that criterion originated from studies on mid-sized terrestrial animals and adult human divers, and it may not be conservative for smaller animals that could be more suspectable to blast injury than larger animals. Our recommendation is to avoid its use for animals with mass less than 100 kg until its validity for smaller animals can be confirmed. The impulse calculation for lung injury and mortality integrates pressure through the time of the shock pulse, with the integration period limited by the arrival of the surface-reflected path or 20% of the animal's lung oscillation period – whichever is smaller. These integration time limits are applied because the arrival of the phase-inverted surface reflection signal reduces or truncates the positive phase of the shock pulse, and because the excitation of lung compression is reduced if the impulse duration is greater than 20% of the lung's oscillation period. The lung oscillation limiting times are straightforward to calculate using the Goertner formulas (Goertner 1982) but they depend on animal mass and submersion depth. The surface reflection arrival time is determined by the geometry of the source and receiving animal relative to each other and the sea surface.

The Navy's impulse criteria for onset of lung injury and mortality are based on measurements of blast effects on a variety of mammals experimentally exposed to detonation pressures (Yelverton 1973). The Navy has published two sets of equations for effects thresholds for impulse that depend on animal mass and submersion depth. The first set of equations (Table 5) produces thresholds based on effects observed in 50% of exposed animals. The second set of equations (Table 6) represent thresholds for onset of effects, based on observed effects in 1% of the exposed animals. NMFS has asked that the more conservative (onset of effects) values also be used for take assessments for Orsted's projects if the distances exceed those of other take criteria.

The impulse thresholds for lung injury and mortality to marine mammals and sea turtles depend on the animal lung volume, which is dependent on animal mass and submersion depth. To be conservative,

maximum horizontal distances for threshold exceedances were calculated in 1 m submersion depth increments from the surface to seabed at the respective assessment location. The maximum distance over these depths was listed as the representative exceedance distance.

The animal masses used for exceedance calculations were obtained from a tabulation of animal masses (Table C.9, Navy, 2017). The Navy table provides conservative calf/pup and adult masses for all marine mammal species. The adult mass is the smallest mass from the range of adult masses for the respective species. Five animal groups are defined in Table 4 that represent and comprise similar-mass species to those that may be encountered at the project sites, including rare species for those areas. For each group, a representative species with the smallest calf and adult masses are used as conservative values for the entire animal group. Sperm whales were grouped with larger baleen whales due to their similar adult masses, but the sei whale calf mass was used for this group due to their smaller mass. The smallest animals of dolphin, kogia, pinniped, and sea turtle families had very similar mass to harbor seals. Harbor seal calf and adult masses were therefore used as the representative species for that animal group for conservatism. Table 4 lists the defined animal groups and the corresponding calf/pup and adult masses of representative species used for impulse threshold calculations. Table 7 and Table 8 provide the corresponding thresholds for onset of lung injury and onset of mortality, respectively, for all relevant animal masses at a selection of submersion depths.

Table 4. Representative calf/pup and adult mass estimates for the animal groups defined for this assessment. These mass values are based on the smallest expected animals for the species that might be present within project areas. Masses listed here are used for assessing impulse-based onset of lung injury and mortality threshold exceedance distances.

Impulse Animal Group	Representative Species	Calf/Pup Mass (kg)	Adult Mass (kg)
Baleen whales and Sperm whale	Sei whale calf (*Balaenoptera borealis*) Sperm whale adult (*Physeter macrocephalus*)	650	16,000
Pilot and Minke whales	Minke whale (*Balaenoptera acutorostrata*)	200	4,000
Beaked whales	Gervais' beaked whale (*Mesoplodon europaeus*)	49	366
Dolphins, Kogia, Pinnipeds, and Sea Turtles	Harbor Seal (*Phoca vitulina*)	8	60
Porpoises	Harbor Porpoise (*Phocoena phocoena*)	5	40

Table 5. US Navy impulse and peak pressure threshold equations for onset lung injury in marine mammals and sea turtles due to explosive detonations (Department of the Navy 2017). These thresholds are based on observed effects to 50% of exposed animals. Note that this table is provided for information purposes only. The threshold formula in Table 6 are used as the non-auditory injury and mortality criteria this assessment.

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

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

Table 6. US Navy impulse and peak pressure threshold equations for onset of lung injury in marine mammals and sea turtles due to explosive detonations (Department of the Navy 2017). These thresholds are based on observed effects to 1% of exposed animals and are used in this study for onset of non-auditory injury and mortality. The peak pressure criterion (third row) may not be suitable for application to small animals. We recommend avoiding its use for animals with mass less than 100 kg until its validity for smaller animals can be confirmed.

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

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

Table 7. Impulse thresholds (units of Pa·s) for Onset Injury from equation in Table 6 for all animal masses in Table 4, for selected animal submersion depths between 1 and 60 m. This assessment evaluated impulse exposures against thresholds at 1 m submersion depth intervals.

Submersion Depth (m)	Animal mass (kg) / Impulse Thresholds for Onset Lung Injury (Pa s)									
	5 kg	8 kg	40 kg	49 kg	60 kg	200 kg	366 kg	680 kg	4,000 kg	16,000 kg
1	82.5	96.5	165.0	176.6	188.9	282.2	345.2	424.3	766.0	1215.9
10	91.1	106.5	182.2	194.9	208.6	311.5	381.1	468.5	845.7	1342.4
20	97.4	114	194.9	208.5	223.1	333.2	407.6	501.1	904.5	1435.8
30	102.2	119.5	204.4	218.7	234	349.5	427.6	525.6	948.8	1506.2
40	106.1	124.1	212.1	227.0	242.8	362.8	443.7	545.5	984.7	1563.1
50	109.3	127.9	218.7	234.0	250.3	373.9	457.4	562.3	1015.0	1611.2
60	112.2	131.2	224.4	240.1	256.8	383.7	469.3	576.9	1041.4	1653.1

Table 8. Impulse thresholds (units of Pa·s) for Onset Mortality from equation in Table 6 for all animal masses in Table 4, for selected animal submersion depths between 1 and 60 m. This assessment evaluated impulse exposures against thresholds at 1 m submersion depth intervals.

Submersion Depth (m)	Animal mass (kg) / Impulse Thresholds for Onset Mortality (Pa s)									
	5 kg	8 kg	40 kg	49 kg	60 kg	200 kg	366 kg	680 kg	4,000 kg	16,000 kg
1	178.9	209.3	357.8	382.9	409.6	611.9	748.5	920.1	1661.0	2636.6
10	197.5	231	395.1	422.7	452.2	675.6	826.3	1015.8	1833.7	2910.9
20	211.3	247.1	422.6	452.1	483.7	722.6	883.8	1086.5	1961.4	3113.5
30	221.6	259.2	443.3	474.3	507.4	758.0	927.1	1139.8	2057.4	3266.0
40	230.0	269.0	460.0	492.2	526.6	786.6	962.2	1182.8	2135.2	3389.5
50	237.1	277.3	474.2	507.4	542.8	810.8	991.8	1219.3	2201	3493.8
60	243.3	284.5	486.5	520.6	556.9	831.9	1017.6	1250.9	2258.2	3584.6

6.3. Marine Mammals and Sea Turtles: Level-B takes and Disturbance

The acoustic criteria relevant for Level-B takes include L_{pk} and $L_{E,w}$ thresholds. All SEL modeling in this study assumes a single detonation per day as the assessment criteria and thresholds are different when more than one detonation occurs in a 24-hour period, as discussed below.

Single blast events within a 24-hour period are not presently considered by NMFS to produce behavior effects if received levels are below the onset of TTS thresholds for $L_{E,w}$ and L_{pk} (Table 3). When multiple blast events occur within a 24-hour period, the US Navy approach applies a disturbance threshold of TTS $L_{E,w}$ minus 5 dB. Thus, the effective Level-B take threshold for single events in each 24-hour period is the $L_{E,w}$ for TTS onset, and for multiple events it is the $L_{E,w}$ for TTS – 5 dB.

The calculation of TTS onset and behavioural effects (TTS – 5 dB) is more difficult when multiple blasts occur within a 24-hour period. In this case marine mammals and sea turtles could receive partial doses of SEL from multiple detonations. The individual event doses depend on the charge sizes, relative detonation timing, animal locations, and geoacoustic environment parameters along paths between the detonation and the exposed animals, most of which are not known in advance of the UXO detonations. If the parameters other than animal locations were known, then animal movement models could be used to provide exposure and take estimates. However, since Orsted plans on only one charge detonation per day, a single event SEL model scenario is sufficient to calculate an $L_{E,w}$ map around each charge, and the TTS zones can be evaluated using the TTS criteria from Table 3.

Note: For multiple blast events an SPL-based disturbance threshold of L_p = 175 dB re 1 μPa^2 would be relevant. Here we are considering only a single blast event per day, so we have not considered that threshold. The approach for calculating L_p is defined in ISO 18405, but that metric is not currently applied by the Bureau of Ocean Energy Management (BOEM) or NMFS for explosives effects assessment of single blast events. Modeling of SPL requires using full wave source and propagation models that are not required for SEL-based assessments. That has not been done here, but it could be added later if required.

6.4. Fish Injury

Injury to fish from exposures to blast pressure waves is attributed to compressive damage to tissue surrounding the swim bladder and gastrointestinal tract, which may contain small gas bubbles. Effects of detonation pressure exposures to fish have been assessed according to the L_{pk} limits for onset of mortality or injury leading to mortality due to explosives, as recommended by the American National Standards Institute (ANSI) expert working group (Popper et al. 2014) and provided in Table 9. The injurious effects thresholds for all fish species groups are the same: L_{pk} = 229–234 dB re 1 μPa. The present assessment has applied the lower range value of L_{pk} = 229 dB re 1 μPa for potential mortal injury and mortality.

Table 9. Recommended Fish Injury thresholds for explosives from Popper et al. (2014).

Type of Animal	Mortality and potential mortal injury	Impairment			Behavior
		Recoverable injury	TTS	Masking	
Fish: no swim bladder (particle motion detection)	229 - 234 dB peak	(N) High (I) Low (F) Low	(N) High (I) Moderate (L) Low	NA	(N) High (I) Moderate (F) Low
Fish where swim bladder is not involved in hearing (particle motion detection)	229 - 234 dB peak	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	NA	(N) High (I) High (F) Low
Fish where swim bladder is involved in hearing (primarily pressure detection)	229 - 234 dB peak	(N) High (I) High (F) Low	(N) High (I) High (F) Low	NA	(N) High (I) High (F) Low

6.5. Fish Disturbance

This assessment has not quantitatively assessed zones of non-injurious effects to fish from explosive detonations because the Popper et al. (2014) guidelines (see Table 9) are qualitative and vague on that subject. For fish species that use swim bladders for hearing, Popper et al suggest a high likelihood of TTS and recoverable injury at near and intermediate distances, where near refers to within a few tens of meters and intermediate refers to a few hundreds of meters. For fish species with swim bladders not used for hearing, the guidelines indicate high likelihood of recoverable impairment at near and intermediate distances but low levels of TTS at intermediate distances. For fish without swim bladders the guidelines indicate low likelihood of recoverable injury at intermediate distances and moderate likelihood of TTS at intermediate distances and low levels of both effects at far distances of a few kilometers.

7. Acoustic Modeling

7.1. Peak Pressure and Impulse

7.1.1. Shock Pulse Source Function

Modeling of acoustic fields generated by UXO detonations is performed using a combination of semi-empirical and physics-based computational models. The source pressure function used for estimating L_{pk} and J_p metrics is calculated using a semiempirical model that approximates the rapid conversion (within approximately 1 µs for high explosive) of solid explosive to gaseous form in a small gas bubble under high pressure, followed by an exponential pressure decay as that bubble expands outwards from the charge detonation location. This behavior imparts an initial pressure “shock pulse” into the water that is represented well by an instantaneous rise to peak pressure P_0 followed by an exponentially decaying pressure function of the form:

$$P(t) = P_0 e^{-t/\tau} \quad (1)$$

The shape and amplitude of the pressure versus time signature of the shock pulse changes with distance from the detonation location due to non-linear propagation effects caused by its high L_{pk}. Arons and Yennie (1949) made measurements of the detonations of a range of charge sizes in Vineyard Sound,

coincidentally just a few miles from Orsted's wind leases, and derived empirical formulae for P_0 in Pascals, and exponential time constant τ in seconds as functions of equivalent TNT charge weight W in kilograms, and distance from the detonation r in meters (note the original equations used different weight and distance units and are converted to metric system units in the formulae presented here.

$$P_0 = 5.24 \times 10^7 \left(\frac{W^{\frac{1}{3}}}{r}\right)^{1.13} \text{ Pa} \quad (2)$$

$$\tau = 9.25 \times 10^{-5} W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{r}\right)^{-0.22} \text{ s} \quad (3)$$

7.1.2. Shock Pulse Pressure Range Dependence

The shock pulse source function variation with distance described above is valid only close to the source. Beyond a certain distance R_0, the functional dependence of P_0 and τ on W and r are better-described by weak shock theory (Rogers 1977). The transition distance was defined by Gaspin (1983) as $R_0 = 4.76\, W^{1/3}$ meters. For example, R_0 is 47.6 m for a 1000 kg charge. At distances greater than R_0, the L_{pk} and time constant are obtained by modified formulae (Rogers 1977):

$$P_0(r > R_0) = \frac{P_0(R_0)\left\{\left[1 + \frac{2R_0}{L_0}\ln\frac{r}{R_0}\right]^{\frac{1}{2}} - 1\right\}}{\left(\frac{r}{L_0}\right)\ln\frac{r}{R_0}} \text{ Pa} \quad (4)$$

$$\tau(r > R_0) = \tau(R_0)\left[1 + 2\left(\frac{R_0}{L_0}\right)\ln\frac{r}{R_0}\right]^{\frac{1}{2}} \text{ s} \quad (5)$$

where $L_0 = (\rho_0 {c_0}^3 \tau(R_0))/(\beta P_0(R_0)$.

In Eq. 5, water density ρ_0=1026 kg/m^3, water sound speed c_0 = 1500 m/s, and β=3.5. These equations lead to a pressure decay with range r that transitions to spherical spreading at long distances. The time constant also increases as the higher frequencies of the shock pulse, responsible for its sharp peak, are preferentially attenuated by absorptive loss. The pressure calculations were performed for the charge sizes of Table 1 and these results are graphed as a function of distance from the charges in Figure 3. The corresponding shock pulse time constant versus distance from Eqs. 3 and 5 is plotted in Figure 4.

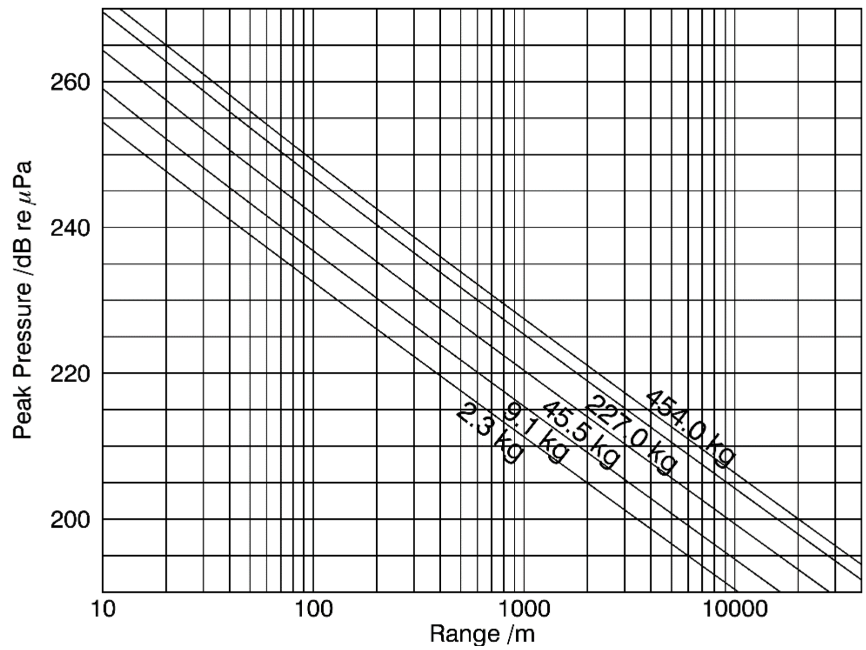

Figure 3. Peak pressures versus distance from detonations of the charge weights listed in Table 1, calculated with Eqs. 2 and 4.

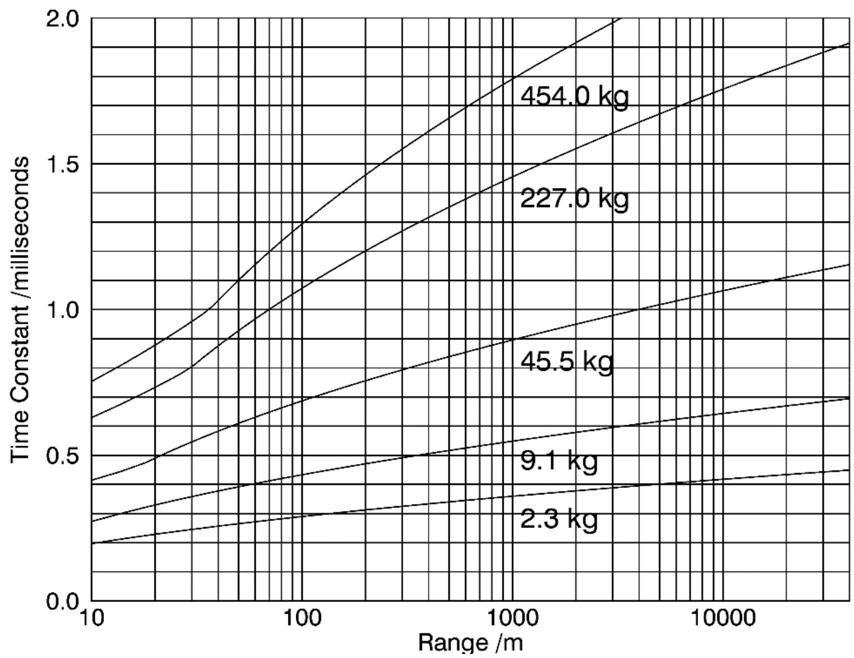

Figure 4. Time constants calculated with Eqs. 3 and 5 and converted to milliseconds for the exponential decay approximation of the shock pulse, for each of the charge weights listed in Table 1.

7.1.3. Impulse

Acoustic impulse is defined as the integral of pressure through time. Assuming the onset of the pressure signal of the direct acoustic path starts at $t = 0$ and ends at $t = T$, the impulse is given by:

$$J_p = \int_0^T P(t)\,dt \tag{6}$$

If the integration end time T is within the part of the shock pulse pressure waveform approximated well by the exponential function (Eq. 1) then Eq. 6 can be expressed:

$$J_p(r) = P_0(r)\tau(r)\left(1 - e^{-T/\tau(r)}\right) \tag{7}$$

In practice, this approximation is accurate for integration times much larger than the time constant because most of the contribution to impulse occurs near the shock pulse onset and the right bracketed term in Eq. 7 approaches 1.0 as the integration time exceeds a few time constants (e.g., see Figure 4).

The US Navy applies an integration time window starting at the onset of the shock pulse and ending at the lesser of the arrival time of the surface reflection and 20% of the oscillation period of an exposed animal's lung, i.e., T = *minimum*(T_{surf}, 0.2 T_{lung}). The arrival time of the surface-reflected path relative to the direct path can be calculated from the depths of the source charge z_s and the exposed animal z_r, their horizontal separation x and the water sound speed c_0:

$$T_{surf} = \left(\sqrt{x^2 + (z_s + z_r)^2} - \sqrt{x^2 + (z_s - z_r)^2}\right)/c_0 \tag{8}$$

The lung oscillation period can be approximated by the oscillation period of a gas sphere of the same volume. The lung volume of animals at atmospheric pressure is approximately proportional to the animal's mass M in kilograms, and this volume decreases with animal submersion depth z_r due to compression by hydrostatic pressure. Goertner (1982) provides the following approximation for lung volume V and equivalent volume fundamental oscillation period t_{osc} for a submerged animal:

$$V = 3.5 \times 10^{-5}\, M \frac{p_{atm}}{(\rho_0 g z_r + p_{atm})} \quad \mathrm{m}^3 \tag{9}$$

$$t_{osc} = 97.1\,(V4\pi/3)^{\frac{1}{3}}/\sqrt{\rho_0 g z_r + p_{atm}} \quad \mathrm{s} \tag{10}$$

where $g = 9.81\ m/s^2$ is the gravitational acceleration and p_{atm} is the atmospheric pressure in pascals at the sea surface. Figure 5 shows lung fundamental oscillation periods calculated from Eq. 10 for four animal masses, versus submersion depth.

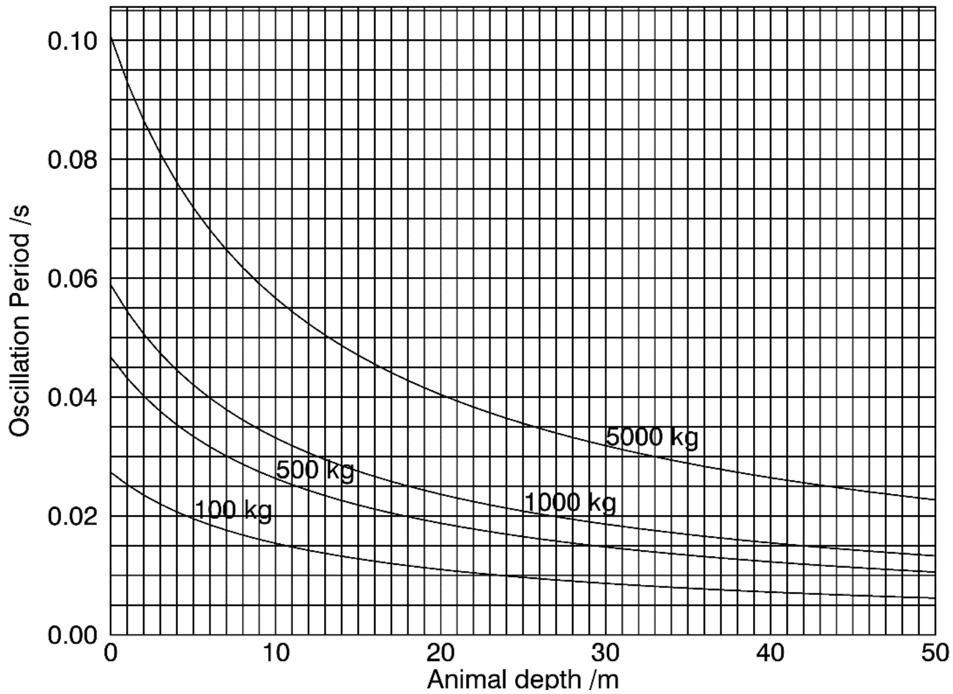

Figure 5. Lung oscillation periods for animal masses of 100 kg, 500 kg, 1000 kg, and 5000 kg versus submersion depth, calculated using Eq. 10.

7.2. Sound Exposure Level Model

SEL and SPL calculations for blast pressure waveforms depend on the characteristics of the initial shock pulse, as described above, and the subsequent oscillation of the detonation gas bubble. The oscillations lead to a series of alternating negative and positive pressure phases trailing the initial positive pressure shock pulse (Figure 6). The positive pressures (relative to hydrostatic pressure) occur when the bubble volume is small, and the negative pressures occur when the bubble volume is large. The shape of the resulting pressure waveform can be calculated using an explosive waveform model (e.g., Wakeley 1977) that includes the shock pulse model of Eq. 1 and extends the pressure prediction in time through several oscillations of the bubble. The negative phase pressure troughs and bubble pulse peaks following the shock pulse are responsible for most of the low frequency energy of the overall blast waveform.

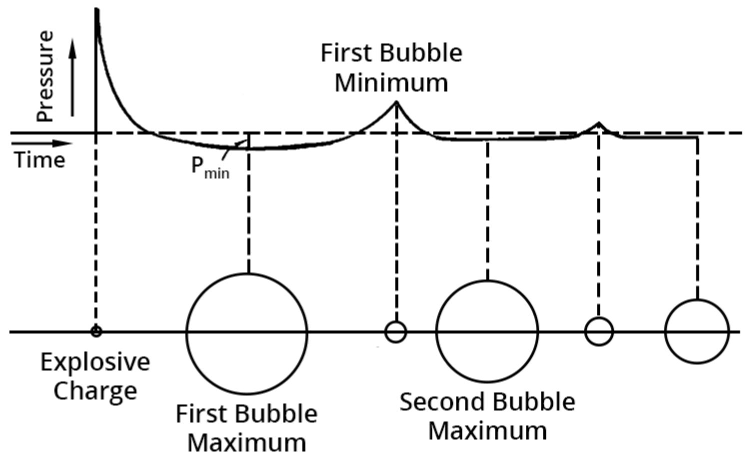

Figure 6. Pictorial representation of the relationship between the radiated pressure signal and the volume of the gas bubble as it oscillates in size after the detonation. This figure is reproduced from Discovery of Sound in the Sea (DOSITS) website https://dosits.org/galleries/technology-gallery/basic-technology/explosive-sound-sources.

The SEL thresholds for PTS and TTS occur at distances of several water depths in the relatively shallow waters of Orsted's Sunrise Wind, Ocean Wind, and Revolution Wind's wind farm environments. The sound field at becomes increasingly influenced by the contributions of sound energy reflected from the sea surface and sea bottom multiple times. In many instances the reflected paths become dominant over the direct acoustic path at horizontal distances greater than a few water depths. Some acoustic energy is also transmitted into the seafloor on each reflection and that energy can propagate partly through the seafloor before re-emerging into the water column and interacting in a complex way with waterborne energy. We apply acoustic propagation models to account for the effects of multiple reflections and sound propagation partly in the seabed. The modeling of SEL does not require use of a full waveform signature model. Nevertheless, the rate of decay of L_E with distance from the detonation varies in a complex way with sound frequency, so a source model that accounts for frequency dependence is necessary. The modeling of $L_{E,w}$ performed here was carried out by first modeling L_E in decidecade frequency bands using the marine operations noise model (MONM, JASCO Applied Sciences). This model uses an energy source level model, described in the next section, and then calculates acoustic propagation loss using parabolic equation (PE) approach for frequencies below 4 kHz, and a Gaussian beam ray trace model at higher frequencies. The PE model applied here also accounts for shear wave conversion losses from reflections at layer interfaces.

7.2.1. Energy Source Levels in Decidecade Frequency Bands

A key input for the MONM model is the energy source level (ESL), which quantifies the acoustic energy (SEL) and its distribution across different frequency bands for each of the charges considered. The distribution depends on the charge weight and detonation depth. The ESL is calculated using an approach described by Urick (1971 and 1983). A series of energy source level spectral density curves for normalized underwater explosion events at various depths (Figure 7) are defined in terms of frequency relative to the frequency of the first bubble pulse. The first bubble pulse frequency is calculated using an equation provided by Chapman (1985):

$$f_{b1} = (2.11 W^{\frac{1}{3}} z_0^{-5/6})^{-1}, \quad (11)$$

where W is the weight of the charge in kg of equivalent TNT and z_0 is the hydrostatic depth of the charge ($z_0 = z_s + 10.1$ meters).

The energy source level scaling factor for charge weight is calculated as:

$$\Delta \mathrm{ESL} = 13.3 \log W. \quad (12)$$

The ESL in decidecade bands is calculated as follows:

1. The appropriate energy source level spectral density (ESLSD) curve is selected from the chart (Figure 7) based on the charge depth;
2. The first bubble pulse frequency f_{b1} is calculated using Equation 11 and absolute frequencies for the ESLSD curve are obtained by scaling their normalized frequency by multiplying by f_{b1};
3. The spectral levels are adjusted for the charge weight using Equation 12;
4. The ESLs are calculated by integrating the corrected ESLSD spectral function through the bandwidth of each decidecade band.

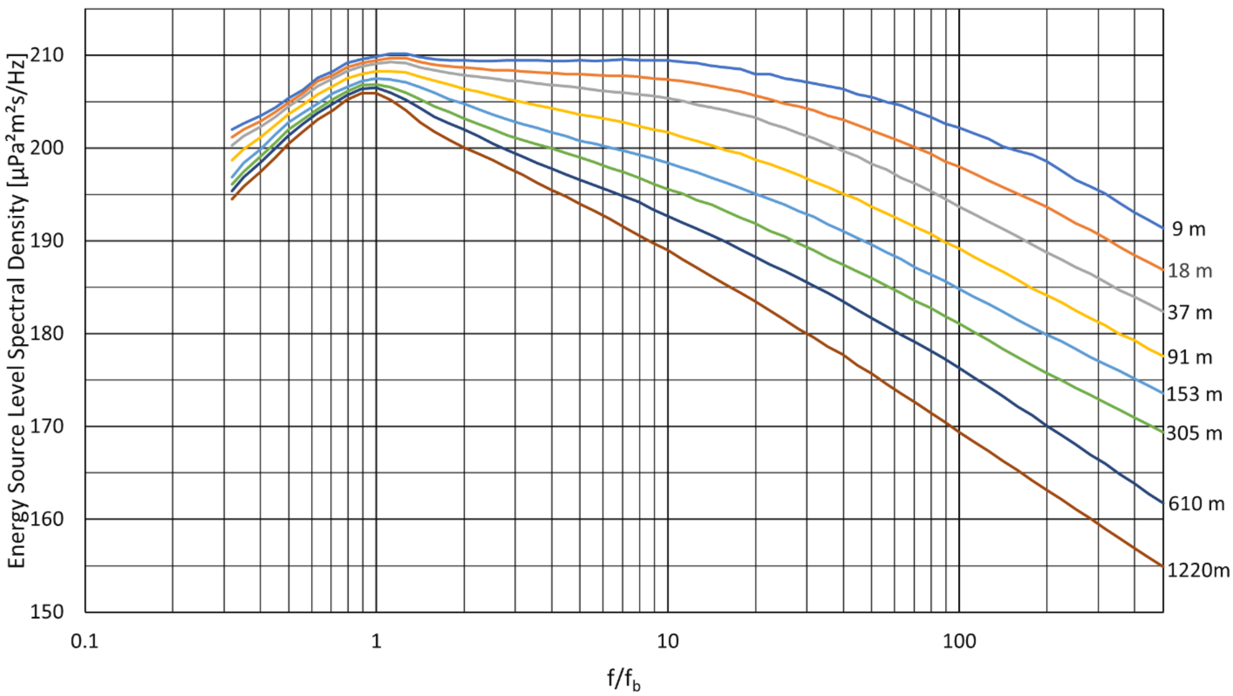

Figure 7. Energy source level spectral density curves for underwater explosion events at various depths expressed in normalized frequency, relative to the frequency f_{b1} of the first bubble pulse (after Urick 1983).

8. Exceedance Distance Results (Unmitigated)

8.1. Marine Mammals and Sea Turtles TTS and PTS by Peak Pressure Distances

Peak pressure exceedance distances are not dependent on water depth or seabed properties, so the results of Table 10 are relevant for all sites.

Table 10. Marine mammals and sea turtles PTS and TTS maximum exceedance distances for peak pressure for various UXO charge sizes for all sites.

Marine mammal group	TTS / PTS L_{pk} threshold (dB re 1 µPa)	Maximum distances (meters) to TTS and PTS thresholds for peak pressure									
		E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
Low-frequency cetaceans	213 / 219	826	426	1306	678	2233	1162	3817	1982	4813	2497
Mid-frequency cetaceans	224 / 230	246	130	394	206	674	350	1150	602	1450	758
High-frequency cetaceans	196 / 202	5357	2761	8476	4373	14490	7476	24764	12775	31202	16098
Phocid pinnipeds	212 / 218	922	478	1458	754	2493	1294	4261	2213	5369	2785
Otariid pinnipeds and sea turtles	226 / 232	198	102	314	166	542	282	926	486	1170	610

8.2. Marine Mammals and Sea Turtles Gastrointestinal Injury by Peak Pressure Distances

The threshold exceedances in Table 11 are for Onset Gastrointestinal Injury (effects observed in 1% of exposed animals). The peak pressure threshold listed here is based on studies on humans and mid-sized terrestrial animals and may not be conservative for smaller marine animals, less than approximately 100 kg. Further examination of that threshold is recommended before it is applied for smaller animals.

Table 11. Maximum exceedance distances for Gastrointestinal Injury (1% of exposed animals) due to peak pressure exposures for five UXO charge sizes. The peak pressure thresholds applied here are from Table 6. We do not recommend applying these criteria for animals with mass less than 100 kg.

Effect	L_{pk} Threshold (dB re 1 µPa)	All sites: Maximum distance to L_{pk} threshold for gastrointestinal injury (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
Onset Gastrointestinal Injury (1% of exposed animals)	237	61 m	97 m	167 m	285 m	359 m

8.3. Marine Mammals and Sea Turtles Onset Lung Injury by Impulse Distances

The exceedance distances in this section represent the onset of lung injury based on the threshold formula in Table 6. These thresholds represent effects observed in 1% of exposed animals.

Impulse levels and thresholds are depth-dependent, so maximum exceedance distances vary between sites with different depths. The results for the four sites evaluated are presented in Table 12 through Table 15.

Table 12. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S1 (12 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 1: 12 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	24	7	62	19	150	59	247	129	291	160
Minke whales	38	12	93	33	199	93	310	174	361	210
Beaked whales	63	30	144	76	268	174	399	277	461	325
Dolphins, Kogia, Pinnipeds and Sea Turtles	114	58	234	136	383	257	548	385	628	446
Porpoises	132	67	261	153	418	280	594	413	680	478

Table 13. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S2 (20 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion-depth and based on the threshold formula in Table 6.

Marine mammal group	Site 2: 20 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	22	6	62	18	172	60	352	161	431	219
Minke whales	36	11	96	31	249	97	455	234	546	300
Beaked whales	62	28	152	78	362	208	599	402	707	487
Dolphins, Kogia, Pinnipeds and Sea Turtles	117	58	263	142	541	344	839	576	975	681
Porpoises	137	67	297	162	591	380	913	623	1059	733

Table 14. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S3 (30 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 3: 30 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	21	6	60	17	177	58	432	168	563	251
Minke whales	33	10	96	29	261	98	583	260	730	369
Beaked whales	59	26	155	77	392	216	775	505	966	644
Dolphins, Kogia, Pinnipeds and Sea Turtles	118	54	274	145	589	371	1044	747	1289	929
Porpoises	138	65	312	166	644	412	1110	804	1364	1004

Table 15. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S4 (45 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 4: 45 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	19	6	52	16	181	51	463	172	648	262
Minke whales	31	10	92	27	270	95	631	270	843	402
Beaked whales	51	25	156	71	412	222	846	546	1084	746
Dolphins, Kogia, Pinnipeds and Sea Turtles	115	47	283	145	630	389	1148	815	1421	1052
Porpoises	137	57	324	167	695	435	1228	878	1518	1127

8.4. Marine Mammals and Sea Turtles Onset of Mortality by Impulse Distances

The exceedance distances in this section represent the onset of mortality based on the threshold formula in Table 6. These thresholds represent effects observed in 1% of exposed animals.

Impulse exposure levels and impulse effects thresholds are depth-dependent, so maximum exceedance distances vary between sites with different depths. Interestingly, the trends of maximum horizontal exposure effects distance with water depth at each site are not always consistent. That occurs due to three reasons:

1.) Impulse exposure, for a given animal submersion depth, depends on water depth because the seabed (and charge location) is further from the animal in deeper environments.

2.) The impulse exposure is site and submersion depth-dependent because the impulse integration time depends on the minimum of arrival time of surface reflection and 20% of the lung oscillation period (which also depends on submersion depth)

3.) The impulse criteria decrease with increased animal submersion depth.

The trends would be consistent had we calculated each table at a fixed animal submersion depth, but instead we search for the maximum criterion exceedance distance over all possible animal submersion depths, in 1 m depth increments from the surface to seafloor. The maximum horizontal effects criteria exceedance distances over all submersion depths are presented in Table 16 through Table 19.

Table 16. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S1 (12 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 1: 12 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	9	5	27	7	78	26	155	72	189	97
Pilot and Minke whales	15	5	43	13	113	43	199	104	238	132
Beaked whales	27	12	69	34	161	95	261	177	307	213
Dolphins, Kogia, Pinnipeds and Sea Turtles	52	25	123	64	242	154	364	252	422	296
Porpoises	62	29	140	74	266	169	396	271	458	319

Table 17. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S2 (20 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion-depth and based on the threshold formula in Table 6.

Marine mammal group	Site 2: 20 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	9	5	25	7	81	24	203	76	266	116
Pilot and Minke whales	14	5	41	12	121	42	275	120	346	173
Beaked whales	25	11	70	32	186	99	376	238	458	305
Dolphins, Kogia, Pinnipeds and Sea Turtles	52	23	128	65	293	176	534	360	644	441
Porpoises	61	27	147	75	319	197	573	393	702	477

Table 18. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S3 (30 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 3: 30 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	8	5	23	7	80	22	219	77	316	120
Pilot and Minke whales	14	5	37	12	123	38	308	124	421	188
Beaked whales	23	11	68	30	194	100	425	262	552	367
Dolphins, Kogia, Pinnipeds and Sea Turtles	47	22	130	63	310	183	586	406	736	536
Porpoises	58	25	150	73	343	206	633	440	786	575

Table 19. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S4 (45 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 4: 45 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	8	5	22	6	76	21	227	72	334	121
Pilot and Minke whales	13	5	34	11	123	36	325	125	453	194
Beaked whales	22	10	61	28	199	98	455	275	602	392
Dolphins, Kogia, Pinnipeds and Sea Turtles	39	20	129	55	328	186	637	434	814	580
Porpoises	49	23	152	67	361	212	690	477	868	628

8.5. Fish Injury by Peak Pressure Distances

Table 20. Maximum exceedance distances for Onset of Injury for fish without and with a swim bladder due to peak pressure exposures for various UXO charge sizes. The threshold of 229 dB re 1 µPa is the minimum of the threshold range from Popper et al. (2014).

Fish Hearing Group	Onset Injury L_{pk} (dB re 1 µPa)	All sites: Maximum distance to L_{pk} onset injury threshold exceedance (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
All fish hearing groups	229	145	230	393	671	847

8.6. Marine Mammals and Sea Turtles: PTS by SEL Distances

The methods discussed in Section 7.2 were applied to calculate SEL, at receiver depths from the surface to the seabed, versus distance and direction from each charge detonation. The maxima of these results over depth were extracted over depth to create noise maps of the type shown in Figure 8. This map and similar maps for the other sites modeled for the 2.3 kg and 454 kg charge sizes are provided in Appendix A.

Exceedance distances to each of the marine mammal, sea turtle, and fish SEL PTS thresholds listed in Table 3, were obtained from these maps in two ways:

- R_{max}: represents the maximum distance in any direction that the threshold was exceeded. This metric is often overly conservative for take estimates because it reflects the influence of coherent constructive interference effects, produced by most propagation loss models, due to model approximations of highly uniform environments. In practice, these coherent effects are almost always disrupted by rough interfaces and ocean inhomogeneities.
- $R_{95\%}$: represents the radius of a circle that encompasses 95% of the area predicted by the model to exceed the threshold. The circle radius is typically larger than the maximum distances in most directions, but it cuts off "fingers" of ensonification that protrude in a small number of directions. This metric is typically also conservative, but less so than the R_{max} distance.

The SEL effects thresholds are not dependent on animal depth, but SEL exposure levels generally do depend on depth. The PTS threshold exceedance distances provided in Tables 21 to 24 are maxima over depth. The site-to-site variations in final exceedance distances are typically less then 20% between sites and attributed to dependence of propagation loss on water depth and bathymetry variations. The spectral shape of larger charges has greater relative low frequency sound energy than small charges, so propagation loss frequency dependence also affects the exceedance distance trends by charge size between sites. These features of location and charge size effects combine to produce non-uniform trends in exceedance distances with site depth and charge size, although the trend variations are relatively small.

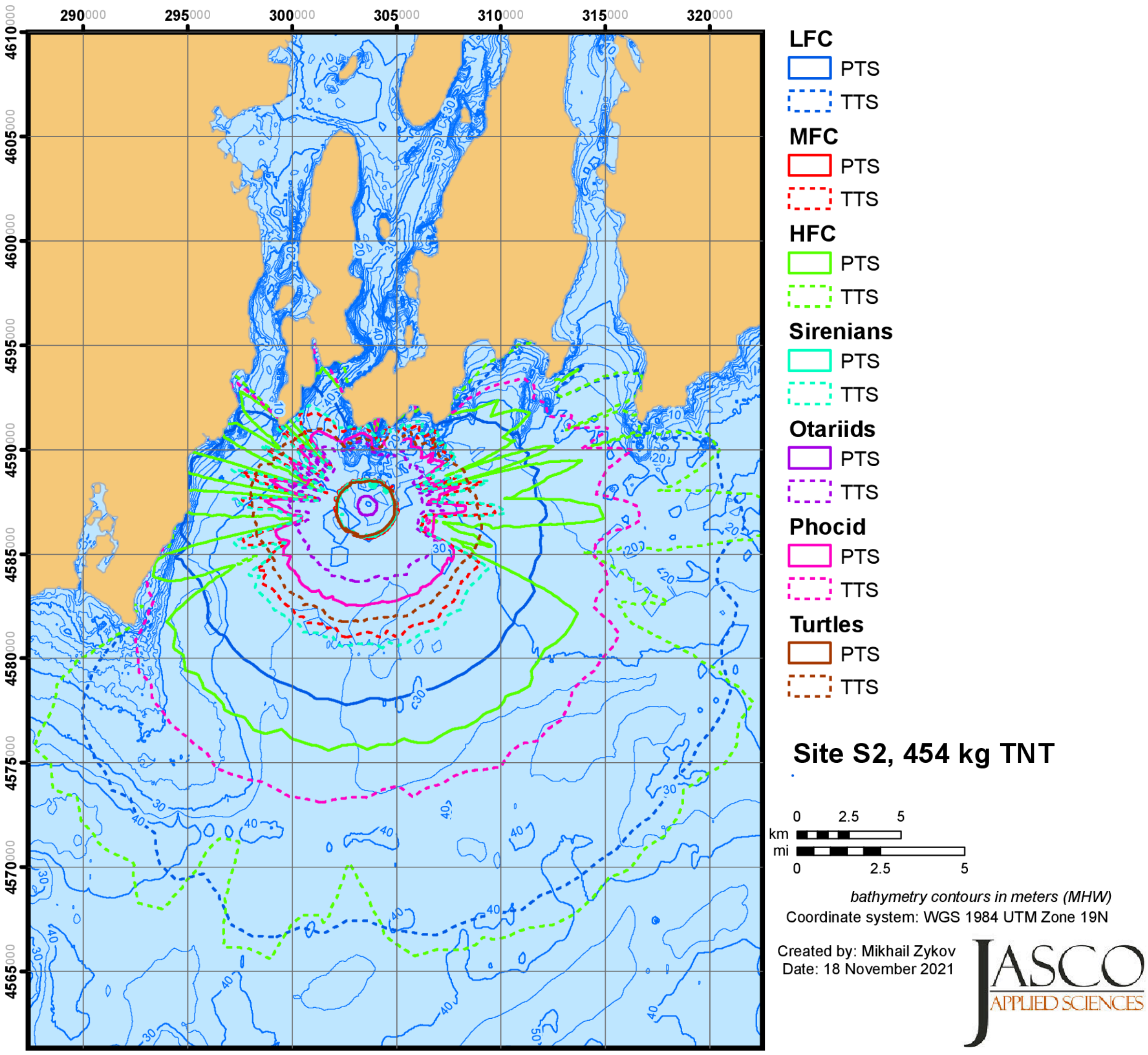

Figure 8. Frequency-weighted SEL PTS and TTS exceedance zone maps for the 454 kg charge size at Site S2, for each species group.

Table 21. SEL-based criteria ranges to PTS-onset at Site S1 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	2010	1710	3060	2640	4710	4140	7280	6460	8490	7640
Mid-frequency cetaceans	185	252	214	455	385	822	714	1500	1220	1840	1540
High-frequency cetaceans	155	4930	4250	6500	5700	8590	7610	11100	10200	12200	11300
Phocid pinnipeds	185	970	804	1520	1310	2530	2190	4040	3580	4990	4340
Otariid pinnipeds	203	59	56	119	106	240	221	539	466	720	615
Sea turtles	204	110	104	259	241	637	545	1180	946	1370	1150

Table 22. SEL-based criteria ranges to PTS-onset at Site S2 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	1820	1590	3110	2810	5460	4880	8170	7520	9580	8800
Mid-frequency cetaceans	185	148	139	372	332	761	633	1300	1130	1590	1450
High-frequency cetaceans	155	4760	4290	6280	5750	8510	7810	10900	10000	12000	11000
Phocid pinnipeds	185	741	644	1380	1210	2500	2190	4190	3660	4900	4500
Otariid pinnipeds	203	<50	<50	66	62	165	155	377	346	508	456
Sea turtles	204	76	76	190	182	535	473	1160	1030	1580	1390

Table 23. SEL-based criteria ranges to PTS-onset at Site S3 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	1630	1540	2890	2720	5080	4750	7810	7270	9130	8440
Mid-frequency cetaceans	185	181	161	388	358	734	636	1290	1140	1630	1480
High-frequency cetaceans	155	4790	4300	6390	5750	8510	7710	10700	9760	12100	10700
Phocid pinnipeds	185	653	592	1230	1120	2370	2170	3930	3620	4900	4450
Otariid pinnipeds	203	<50	<50	60	57	134	128	333	313	501	462
Sea turtles	204	<50	<50	184	181	444	416	980	931	1400	1220

Table 24. SEL-based criteria ranges to PTS-onset at Site S4 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	1620	1470	2870	2610	5090	4640	8060	7280	9510	8540
Mid-frequency cetaceans	185	108	89	362	272	749	684	1260	1120	1640	1410
High-frequency cetaceans	155	4650	4170	6400	5660	8520	7670	11100	9890	12300	10900
Phocid pinnipeds	185	666	607	1140	1010	2360	2140	4100	3740	4970	4520
Otariid pinnipeds	203	<50	<50	<50	<50	89	89	233	221	400	372
Sea turtles	204	<50	<50	144	141	350	340	884	852	1330	1260

8.7. Marine Mammals and Sea Turtles: TTS by SEL Distances

The SEL distances thresholds are not dependent on animal depth, but the SEL exposure levels are. The TTS threshold exceedance distances provided in Tables 25 to 28 are maxima over depth.

Table 25. SEL-based criteria ranges to TTS-onset at Site S1 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	7600	6830	10700	9780	14300	13100	18000	16700	19900	18300
Mid-frequency cetaceans	170	1820	1520	2660	2290	3760	3340	5650	4970	6660	5860
High-frequency cetaceans	140	12100	11200	14600	13400	17400	16000	20600	19100	21900	20200
Phocid pinnipeds	170	4780	4120	6840	6080	9630	8750	13000	11900	14500	13300
Otariid pinnipeds	188	681	569	1230	965	1930	1670	3210	2760	3830	3400
Sea turtles	189	822	708	1380	1160	2290	1920	3180	2750	3810	3220

Table 26. SEL-based criteria ranges to TTS-onset at Site S2 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	8000	7340	11200	10300	15200	13900	19500	17500	21300	19200
Mid-frequency cetaceans	170	1590	1430	2520	2160	4030	3460	5510	5020	6380	5850
High-frequency cetaceans	140	12000	11000	14200	13100	17500	15900	20800	18800	22200	20200
Phocid pinnipeds	170	4630	4200	6730	6200	9760	9060	13000	11800	14500	13200
Otariid pinnipeds	188	444	406	926	788	1790	1560	3120	2720	3950	3440
Sea turtles	189	706	639	1540	1350	2780	2520	4660	4340	5670	5260

Table 27. SEL-based criteria ranges to TTS-onset at Site S3 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	7610	7000	10600	9790	14700	13400	19100	17400	21100	19300
Mid-frequency cetaceans	170	1600	1450	2510	2210	3890	3490	5590	5020	6500	5840
High-frequency cetaceans	140	12000	10700	14200	12700	17500	15600	20800	18700	22400	20200
Phocid pinnipeds	170	4420	4070	6690	6070	9700	8780	12800	11500	14400	12800
Otariid pinnipeds	188	412	394	796	756	1720	1600	3000	2730	3750	3400
Sea turtles	189	605	581	1340	1200	2550	2340	4440	4150	5500	5070

Table 28. SEL-based criteria ranges to TTS-onset at Site S4 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	7650	6950	11100	9850	15600	13600	20600	17400	22500	19000
Mid-frequency cetaceans	170	1580	1350	2400	2160	3760	3420	5710	5040	6540	5810
High-frequency cetaceans	140	12100	10700	14900	13000	18400	15800	22300	18700	23700	20000
Phocid pinnipeds	170	4260	3940	6680	6010	10000	8850	13800	12000	15300	13300
Otariid pinnipeds	188	283	261	782	725	1640	1470	3100	2810	3820	3460
Sea turtles	189	495	480	1290	1190	2480	2340	4320	4030	5220	4870

9. Exceedance Distance Results with 10 dB Mitigation

This section provides exceedance distances assuming 10 dB reduction to the exposure pressures and SEL achieved via mitigation measures (e.g., bubble curtain or similar system).

9.1. Marine Mammals and Sea Turtles TTS and PTS by Peak Pressure Distances with 10 dB mitigation

L_{pk} exceedance distances are not dependent on water depth or seabed properties, so Table 29 is relevant for all sites.

Table 29. Marine mammals and sea turtles PTS and TTS maximum exceedance distances for peak pressure for maximum charge weights for various UXO charge sizes with 10 dB mitigation, relevant for all sites.

Marine mammal group	TTS / PTS threshold (dB re 1 µPa)	Maximum distances (meters) to TTS and PTS thresholds for peak pressure									
		E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
Low-frequency cetaceans	213 / 219	278	142	438	230	750	390	1282	670	1618	846
Mid-frequency cetaceans	224 / 230	82	42	134	70	226	118	390	206	494	258
High-frequency cetaceans	196 / 202	1778	922	2813	1458	4813	2493	8228	4261	10367	5369
Phocid pinnipeds	212 / 218	310	158	490	254	838	438	1430	746	1802	942
Otariid pinnipeds and sea turtles	226 / 232	66	34	106	54	182	98	314	166	398	210

9.2. Marine Mammals and Sea Turtles Gastrointestinal Injury by Peak Pressure Distances with 10 dB mitigation

The threshold exceedances in Table 30 are for Onset Gastrointestinal Injury (effects observed in 1% of exposed animals) and Gastrointestinal Injury (effects observed in 50% of exposed animals).

Table 30. Maximum exceedance distances for Gastrointestinal Injury (1% exposed animals) due to peak pressure exposures for five UXO charge sizes with 10 dB mitigation. The peak pressure thresholds applied here are from Table 6. We do not recommend applying these criteria for animals with mass less than 100 kg.

Effect	L_{pk} Threshold (dB re 1 µPa)	All sites: Maximum distance to L_{pk} threshold exceedance (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
Onset Gastrointestinal Injury (1% of exposed animals)	237	21 m	34 m	58 m	99 m	125 m

9.3. Marine Mammals and Sea Turtles Onset of Lung Injury Distances for Impulse with 10 dB mitigation

Impulse thresholds are depth-dependent, so maximum exceedance distances could vary between sites with different depths with 10 dB mitigation. The results for each of the sites evaluated are presented in Table 31 through Table 34.

Table 31. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S1 (12 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6.

Marine mammal group	Site 1: 12 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	6	5	17	5	54	16	121	50	151	73
Pilot and Minke whales	10	5	28	8	80	28	158	77	192	103
Beaked whales	17	8	47	22	121	66	210	139	250	171
Dolphins, Kogia, Pinnipeds and Sea Turtles	35	16	86	44	189	115	297	202	347	241
Porpoises	42	19	99	50	210	128	323	219	377	260

Table 32. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S2 (20 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6.

Marine mammal group	Site 2: 20 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	6	5	16	5	54	15	147	51	204	80
Pilot and Minke whales	9	5	26	8	83	26	208	83	272	126
Beaked whales	16	7	46	20	131	68	290	176	366	237
Dolphins, Kogia, Pinnipeds and Sea Turtles	32	15	88	42	211	123	404	277	508	351
Porpoises	39	17	102	50	235	139	433	303	541	381

Table 33. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S3 (30 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6.

Marine mammal group	Site 3: 30 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	15	5	51	14	153	49	226	81
Pilot and Minke whales	9	5	24	7	83	25	221	84	310	131
Beaked whales	15	7	41	19	135	66	310	186	413	267
Dolphins, Kogia, Pinnipeds and Sea Turtles	29	14	88	38	223	126	441	298	557	400
Porpoises	34	16	103	46	248	144	471	325	594	429

Table 34. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S4 (45 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6.

Marine mammal group	Site 4: 45 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	14	5	45	13	156	44	237	78
Pilot and Minke whales	8	5	22	7	79	23	230	81	330	132
Beaked whales	14	6	37	18	135	59	331	192	448	282
Dolphins, Kogia, Pinnipeds and Sea Turtles	26	13	83	34	231	126	471	315	606	429
Porpoises	29	15	100	39	261	145	512	347	648	465

9.4. Marine Mammals and Sea Turtles Onset of Mortality Distances by Impulse with 10 dB mitigation

The exceedance distances in this section represent the onset of mortality based on the threshold formula in Table 6 and assuming 10 dB of sound level reduction is obtained through a noise mitigation device. These thresholds represent effects observed in 1% of exposed animals.

Impulse levels and thresholds are depth-dependent, so maximum exceedance distances vary between sites with different depths. The results for the four sites evaluated are presented in Table 35 through Table 38.

Table 35. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S1 (12 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 1: 12 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	7	5	23	6	66	21	90	34
Pilot and Minke whales	5	5	11	5	37	11	93	36	120	56
Beaked whales	7	5	19	9	60	29	130	79	161	105
Dolphins, Kogia, Pinnipeds and Sea Turtles	14	6	39	18	101	56	190	124	228	154
Porpoises	17	7	46	21	112	64	209	136	248	167

Table 36. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S2 (20 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion-depth and based on the threshold formula in Table 6.

Marine mammal group	Site 2: 20 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	6	5	21	6	69	20	105	34
Pilot and Minke whales	5	5	10	5	35	10	103	35	150	58
Beaked whales	6	5	18	8	60	27	151	85	206	127
Dolphins, Kogia, Pinnipeds and Sea Turtles	13	6	37	17	105	56	220	144	285	198
Porpoises	15	7	45	19	119	65	239	158	307	215

Table 37. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S3 (30 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 3: 30 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	6	5	20	6	68	19	109	31
Pilot and Minke whales	5	5	10	5	32	10	106	32	157	57
Beaked whales	6	5	17	8	58	25	160	86	220	132
Dolphins, Kogia, Pinnipeds and Sea Turtles	12	5	31	16	108	54	233	152	308	211
Porpoises	14	6	40	18	122	63	258	168	330	231

Table 38. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S4 (45 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6.

Marine mammal group	Site 4: 45 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	6	5	18	5	63	18	108	29
Pilot and Minke whales	5	5	9	5	29	9	105	30	162	50
Beaked whales	6	5	15	7	50	23	164	83	234	135
Dolphins, Kogia, Pinnipeds and Sea Turtles	11	5	26	14	106	44	247	155	332	224
Porpoises	12	6	29	16	122	56	270	173	353	243

9.5. Fish Injury Distances for Peak Pressure with 10 dB mitigation

Table 39. Mitigated exceedance distances for Onset of Injury for fish without and with a swim bladder due to peak pressure exposures, for various UXO charge sizes with 10 dB mitigation. Water depth 50 m. The threshold of 229 dB re 1 µPa is from Popper et al. (2014).

Species	Onset injury L_{pk} (dB re 1 µPa)	All sites: Maximum distance to L_{pk} threshold exceedance (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
All fish hearing groups	229	49	80	135	230	290

9.6. Marine Mammals and Sea Turtles: PTS distances by SEL with 10 dB mitigation

The SEL effects thresholds are not dependent on animal depth, but the exposure levels are. The PTS threshold exceedance distances provided in Tables 40 to 43 are maxima over depth.

Table 40. Mitigated SEL-based criteria ranges to PTS-onset at Site S1 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	632	552	1230	982	2010	1720	3080	2660	3640	3220
Mid-frequency cetaceans	185	<50	<50	79	75	175	156	419	337	535	461
High-frequency cetaceans	155	2100	1820	2940	2590	4220	3710	6090	5340	6960	6200
Phocid pinnipeds	185	192	182	413	357	822	690	1410	1220	1830	1600
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	100	98	147	136
Sea turtles	204	<50	<50	<50	<50	166	159	366	348	518	472

Table 41. Mitigated SEL-based criteria ranges to PTS-onset at Site S2 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	450	421	954	850	1990	1730	3370	2970	4270	3780
Mid-frequency cetaceans	185	<50	<50	52	51	120	113	332	280	444	386
High-frequency cetaceans	155	1960	1680	3020	2550	4400	3860	5880	5390	6750	6190
Phocid pinnipeds	185	124	113	294	248	656	590	1340	1140	1630	1430
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	62	61	93	89
Sea turtles	204	<50	<50	<50	<50	140	137	309	293	451	422

Table 42. Mitigated SEL-based criteria ranges to PTS-onset at Site S3 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	405	385	789	753	1660	1580	3040	2870	3900	3610
Mid-frequency cetaceans	185	<50	<50	<50	<50	100	85	349	323	484	412
High-frequency cetaceans	155	1960	1750	2940	2590	4330	3900	6000	5400	6840	6190
Phocid pinnipeds	185	89	89	221	204	566	538	1140	1020	1600	1480
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	57	57	72	72
Sea turtles	204	<50	<50	<50	<50	89	89	242	228	385	369

Table 43. Mitigated SEL-based criteria ranges to PTS-onset at Site S4 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	288	269	800	757	1770	1580	3190	2930	3940	3610
Mid-frequency cetaceans	185	<50	<50	<50	<50	85	80	279	261	449	412
High-frequency cetaceans	155	1890	1700	2800	2550	4200	3790	6130	5400	6860	6160
Phocid pinnipeds	185	72	72	152	144	577	468	1100	988	1520	1350
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	<50	<50	63	63
Sea turtles	204	<50	<50	<50	<50	63	63	190	189	297	288

9.7. Marine Mammals and Sea Turtles: TTS distances by SEL with 10 dB mitigation

The SEL effects thresholds are not dependent on animal depth, but the exposure levels are. The TTS threshold exceedance distances provided in Tables 44 to 47 are maxima over depth.

Table 44. Mitigated SEL-based criteria ranges to TTS-onset at Site S1 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	3140	2710	4820	4160	7320	6500	10500	9610	12000	11000
Mid-frequency cetaceans	170	535	453	910	773	1520	1240	2400	2120	2820	2550
High-frequency cetaceans	140	6920	6160	8970	8000	11100	10200	14000	12900	15400	14100
Phocid pinnipeds	170	1730	1470	2710	2350	4080	3620	6460	5700	7480	6750
Otariid pinnipeds	188	131	125	254	238	539	472	1070	898	1310	1130
Sea turtles	189	214	203	498	448	1040	865	1720	1440	2020	1710

Table 45. Mitigated SEL-based criteria ranges to TTS-onset at Site S2 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	3110	2820	5230	4680	8160	7490	11500	10500	13200	11900
Mid-frequency cetaceans	170	444	379	781	658	1450	1200	2310	1980	2930	2430
High-frequency cetaceans	140	6700	6140	8630	7960	11200	10300	13700	12600	15000	13800
Phocid pinnipeds	170	1450	1300	2510	2200	4340	3820	6490	5980	7610	6990
Otariid pinnipeds	188	70	68	165	155	392	364	803	721	1110	974
Sea turtles	189	169	165	441	383	985	870	2020	1780	2510	2250

Table 46. Mitigated SEL-based criteria ranges to TTS-onset at Site S3 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	2910	2740	4860	4450	7760	7210	10900	10100	12500	11500
Mid-frequency cetaceans	170	484	410	777	653	1430	1230	2350	2030	2820	2480
High-frequency cetaceans	140	6770	6140	8620	7840	11200	10000	13700	12200	15000	13300
Phocid pinnipeds	170	1300	1210	2430	2180	4150	3810	6410	5840	7580	6900
Otariid pinnipeds	188	63	63	134	128	374	341	777	728	1010	922
Sea turtles	189	171	134	372	358	810	773	1780	1610	2270	2130

Table 47. Mitigated SEL-based criteria ranges to TTS-onset at Site S4 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	2890	2630	4860	4400	7820	7130	11700	10300	13500	11800
Mid-frequency cetaceans	170	437	400	800	707	1330	1180	2270	2000	2730	2480
High-frequency cetaceans	140	6720	6030	8650	7790	11300	10100	14600	12600	15600	13700
Phocid pinnipeds	170	1290	1130	2340	2130	4150	3800	6640	5970	7820	7020
Otariid pinnipeds	188	<50	<50	89	89	247	234	768	716	982	888
Sea turtles	189	120	108	286	283	833	796	1680	1590	2130	2000

10. Summary and Guide for Use of Results

This study has produced a large number of result tables containing effects threshold exceedance distances for multiple species or species groups, five charge sizes, and four locations. While the specific sites were chosen inside Orsted's Revolution Wind project area, the model results are expected to be valid for sites inside the Sunrise Wind and Ocean Wind 1 project areas and other sites having the same water depths and seabed properties. The results presented here also assume the full explosive weight of the combined UXO and donor charge are detonated, with a total equivalent-TNT weight matching the values in Table 1. A recent review of UXO detonations in the North Sea has found UXO detonations of charges that have remained underwater for more than 75 years yielded very little explosive energy. More research is needed to determine if older underwater UXO degrade over time to become partly benign, in which case methods such as deflagration may be preferred over explosive removal. Until that question is answered, for conservancy and for personnel safety reasons we recommend assuming their full explosive weights will detonate.

All threshold distances presented here are relevant to address NMFS's assessment requirements for species-dependent effects criteria for assessing injurious or lethal (Level-A) and disturbance or behavioural (Level-B) takes of marine mammals and sea turtles, and for assessing injurious effects on fish. The take criteria are based on three specific acoustic metrics: L_{pk}, J_p, and $L_{E,w}$. The frequency weighted SEL levels, $L_{E,w}$, are dependent on species group while the impulse levels are dependent on animal mass and submersion depth. All three metrics also have species or animal size dependent thresholds. The SEL and impulse levels vary with water depth or location. Five charge sizes are considered at four separate modeling sites with different depths. The consideration of these many results for estimating marine mammal and sea turtle takes, and fish effects zones is clearly not straightforward. To assist in that assessment, a summary of the Level-A and Level-B take context for each assessment metric is provided here, together with cross-references to the tables that contain the relevant exceedance distance information for each type of take. Examples of the maximum exceedance distance, resulting from the largest UXO charge weight, on the most-sensitive species group are provided here but the user will need to review the referenced exceedance distance tables to look up the relevant distances for other species groups and charge sizes. We expect the peak pressure based gastrointestinal tract injury distances and impulse based onset of lung injury and onset of mortality distances will be used primarily for setting mitigation zone requirements, but these distances could be used for Level A take estimates if animals could not be excluded from the respective zones.

10.1. Unmitigated Take Distances

10.1.1. Unmitigated Level-A Takes

The tables of threshold exceedance distances from UXO detonations relevant for Level-A (injurious) effects to marine mammals and sea turtles are:

- L_{pk}: Table 10 contains PTS (auditory injury) exceedance distances valid for all sites. The greatest PTS distance is 16,098 m from the 454 kg charge, for high-frequency cetaceans.
- L_{pk}: Table 11 contains mitigated onset of gastrointestinal injury (1% of exposed animals) exceedance distances valid for all sites and species. The greatest onset of effects distance is 359 m from the 454 kg charge. We note that the gastrointestinal injury distances for small animals using the L_{pk} criterion can be smaller than those for onset of mortality using the J_p criterion (next bullet). That occurs because the L_{pk} criterion originates from studies on mid-sized terrestrial animals and adult humans. We recommend against using this criterion for animals smaller than approximately 100 kg.
- J_p: Tables 12 to 15 contain onset of lung injury (1% of animals) distances for Sites S1 to S4, respectively. Note for each species group there are separate distances for small (calves/pups) and adult animals representative of the group. Smaller animals in each group have lower

thresholds, leading to larger exceedance distances. The deeper sites often, but not always, have larger exceedance distances than shallower sites. The unusual dependence of exceedance distances on site depth and charge size is discussed in Section 8.6. The greatest distance for onset of lung injury is 1518 m from the unmitigated 454 kg charge at site S4 for porpoise calves.

- SEL (species-group frequency weighted): Tables 21 to 24 contain PTS threshold exceedance distances at Sites S1 to S4, respectively. These tables contain R_{max} and $R_{95\%}$ distances, and we recommend using the $R_{95\%}$ distances because R_{max} is often influenced by an artefact of the type of models used, as discussed in Section 8.6. The greatest distance is 11,300 m for high-frequency cetaceans at Site S1.
- SEL and peak pressure auditory injury distances are always larger than the impulse non-auditory injury exceedance distances, so the impulse threshold exceedance distances will not dictate Level-A takes. Nevertheless, they are important and relevant for assessments of non-auditory injuries.

10.1.2. Unmitigated Level-B Takes

The tables relevant for Level-B (disturbance or behavioral effects) takes are:

- L_{pk}: Table 10 contains TTS (temporary effect not considered injurious) exceedance distances valid for all sites. The greatest TTS distance is 31,202 m from the 454 kg charge, for high-frequency cetaceans.
- SEL (species-group weighted): Tables 25 to 28 contain TTS threshold exceedance distances at Sites S1 to S4, respectively. We recommend using the $R_{95\%}$ distances as discussed in this report. The greatest distance is 20,200 m for high-frequency cetaceans at Sites S1, S2 and S3.
- Note: NMFS uses TTS onset as the threshold for Level-B takes by SEL for single detonations in a 24-hour period. NMFS applies a different threshold (TTS minus 5 dB) for multiple detonations in day, but its application is more difficult because it requires considering if animals receive SEL doses from more than one of the detonations. TTS zones for multiple blasts in a single day were not assessed.

10.1.3. Unmitigated Effects on Fish

- L_{pk}: Table 20 provides onset of injury distances relevant for all fish groups. The unmitigated distances for mortality or injury likely to lead to mortality range from 145 m from the 2.3 kg charge to 847 m from the 454 kg charge. These distances are relevant for all sites.
- A quantitative assessment of non-mortal effects to fish has not been included, but the guidelines of Popper et al. (2014) provide qualitative assessment information. This is discussed in Sections 6.4 and 6.5.

10.2. Mitigated Take Distances (10 dB Reduction)

Reduced effects threshold distances were calculated with a flat 10 dB reduction of pressure to all metrics, as an approximation of noise abatement that could be achieved, for example, using a bubble curtain. The mitigated results tables are provided in Section 9 and discussed here.

10.2.1. Mitigated Level-A Takes

The tables of threshold exceedance distances relevant for Level A (injurious) effects to marine mammals and sea turtles are:

- L_{pk}: Table 29 contains mitigated PTS (auditory injury) exceedance distances valid for all sites. The greatest PTS distance is 5,369 m from the 454 kg charge, for high-frequency cetaceans. The mitigated PTS distances from peak pressure for all other species groups are less than 1,000 m.
- L_{pk}: Table 30 contains mitigated onset of gastrointestinal injury (1% of exposed animals) exceedance distances valid for all sites and species. The greatest onset of effects distance is 125 m from the 454 kg charge. We note that the gastrointestinal injury distances for small animals using the L_{pk} criterion can be smaller than those for onset of mortality using the J_p criterion (next bullet). That occurs because the L_{pk} criterion originates from studies on mid-sized terrestrial animals and adult humans. We recommend against using this criterion for animals smaller than approximately 100 kg.
- J_p: Tables 31 to 34 contain onset of lung injury (1% of animals) exceedance distances for Sites S1 to S4, respectively. The greatest distance for onset of lung injury is 648 m from the 454 kg charge at Site S4, for porpoise calves.
- SEL (species-group weighted): Tables 40 to 43 contain PTS threshold exceedance distances at Sites S1 to S4, respectively. The greatest $R_{95\%}$ distance is 6,200 m for high-frequency cetaceans at Site 1.

10.2.2. Mitigated Level-B Takes

The tables relevant for mitigated Level-B (disturbance or behavioral effects) takes of marine mammals and sea turtles are:

- Peak pressure: Table 29 contains TTS (temporary effect not considered injurious) exceedance distances valid for all sites. The greatest TTS distance is 10,367 m from the 454 kg charge, for high-frequency cetaceans.
- SEL (species-group weighted): Tables 44 to 47 contain TTS threshold exceedance distances at Sites S1 to S4, respectively. The greatest $R_{95\%}$ distance is 14,100 m for high-frequency cetaceans at Site S1.

10.2.3. Mitigated Effects on Fish

- Peak pressure: Table 39 provides mitigated onset of injury for all fish groups. The unmitigated distances range from 49 m from the 2.3 kg charge to 290 m from the 454 kg charge. These values are relevant for all sites.
- A quantitative assessment of non-mortal effects to fish has not been included, as discussed in Section 6.4 and 6.5. Those sections provide a qualitative assessment approach.

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Appendix A. PTS and TTS Exceedance Zone Maps (Unmitigated)

This appendix presents PTS and TTS exceedance zone maps for various marine mammal hearing groups and sea turtles for 2.3 and 454 kg charges (minimum and maximum charge weights modeled) at each of the four sites.

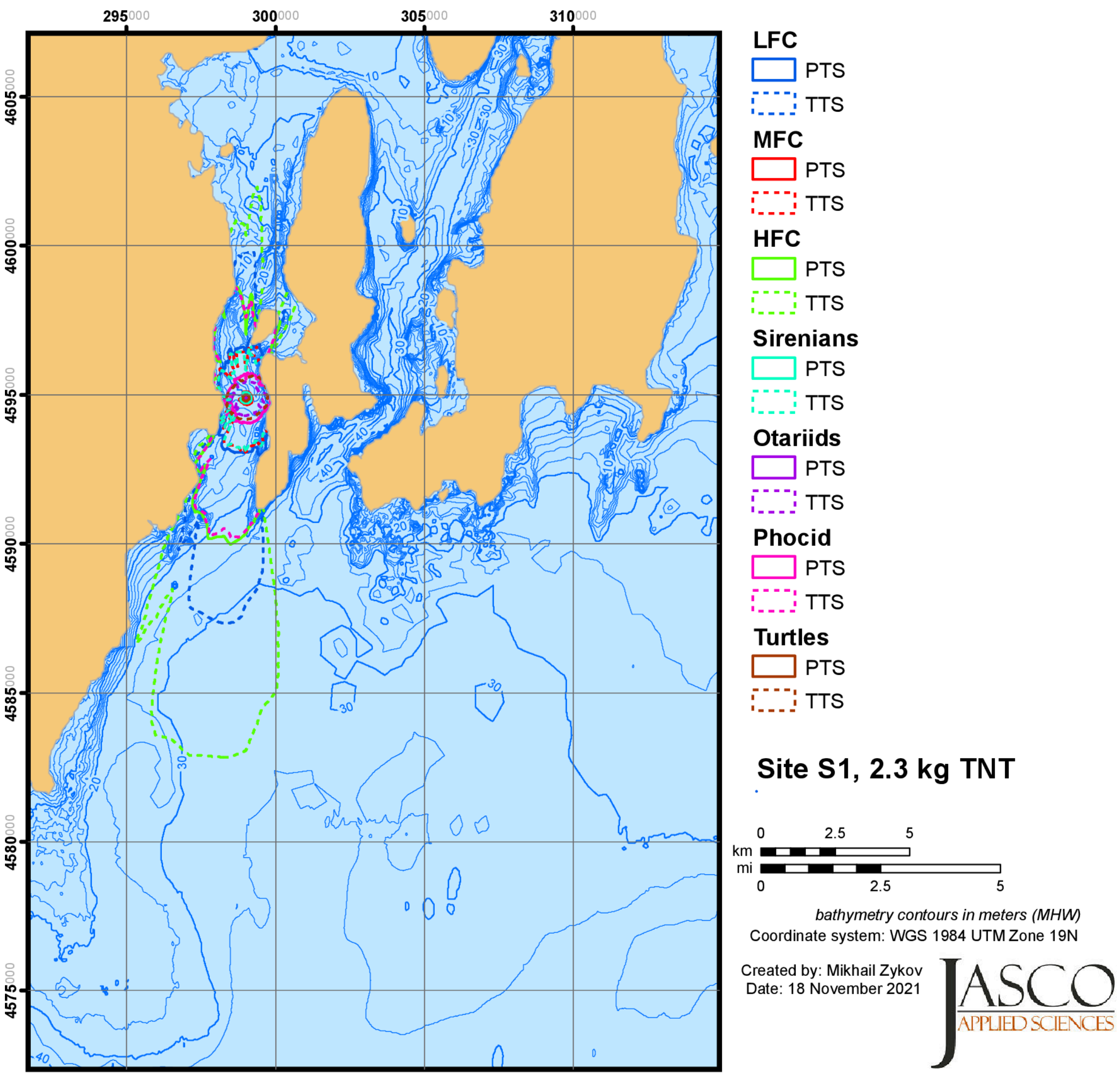

Figure A-1. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S1.

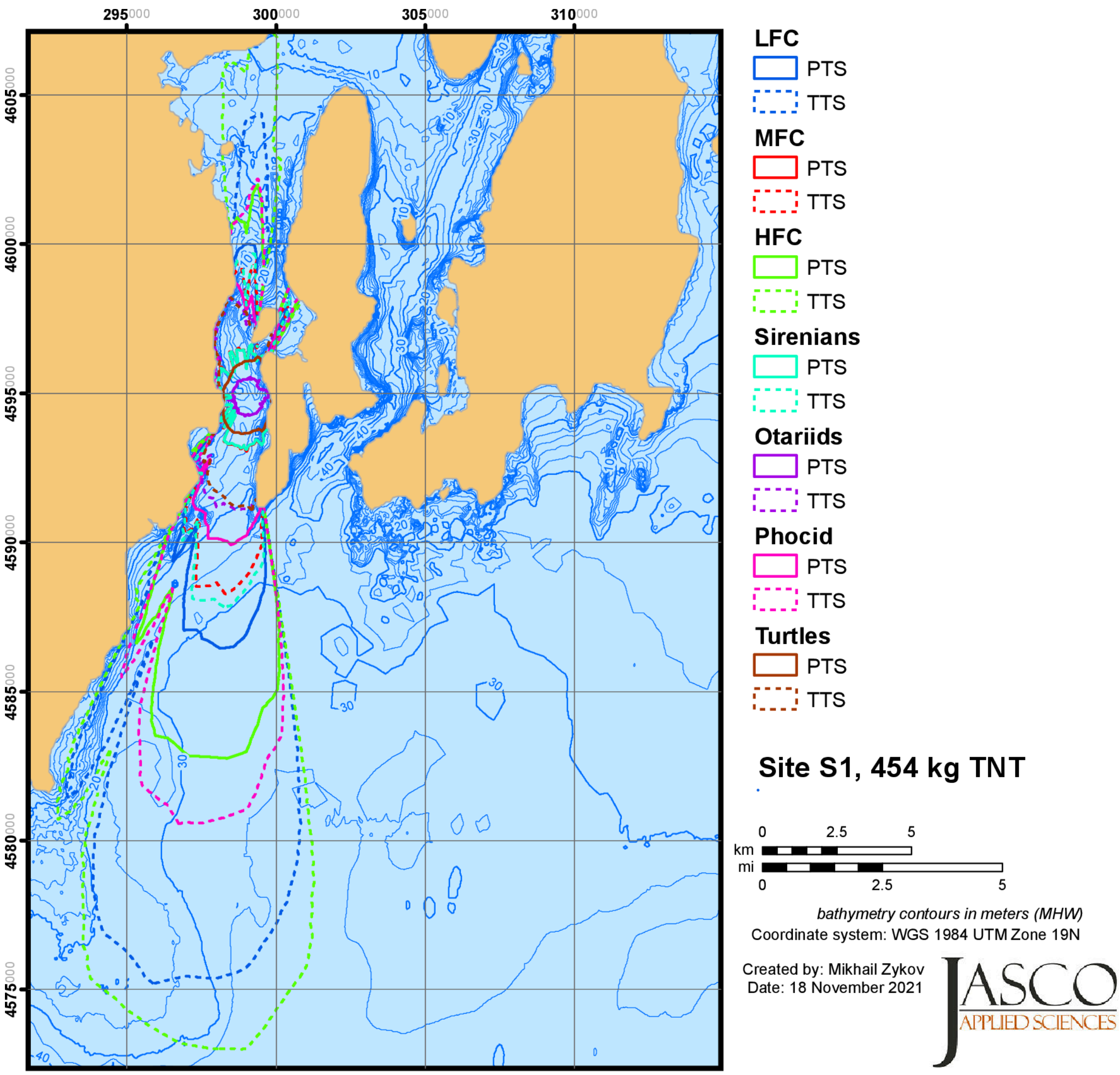

Figure A-2. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S1.

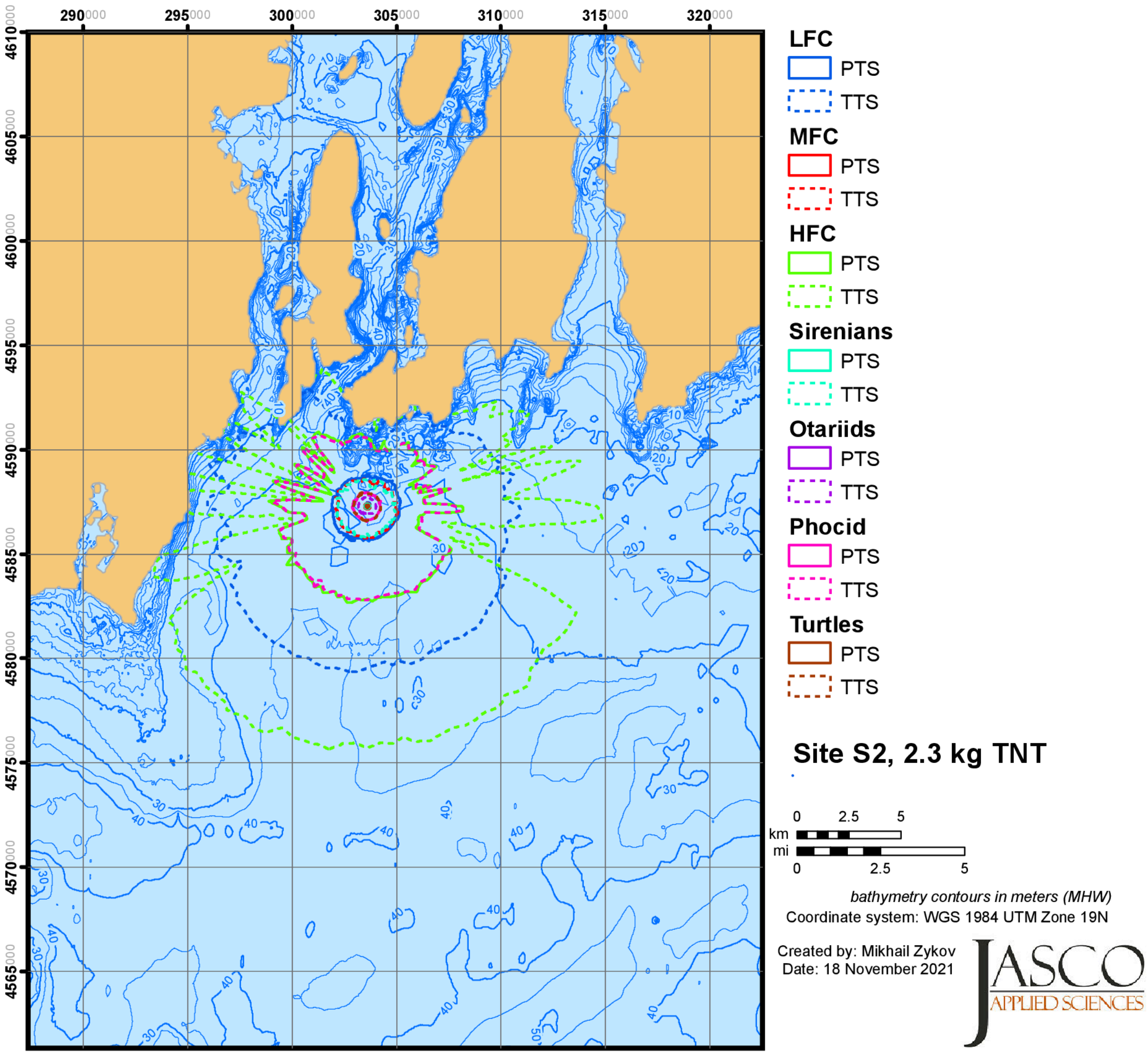

Figure A-3. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S2.

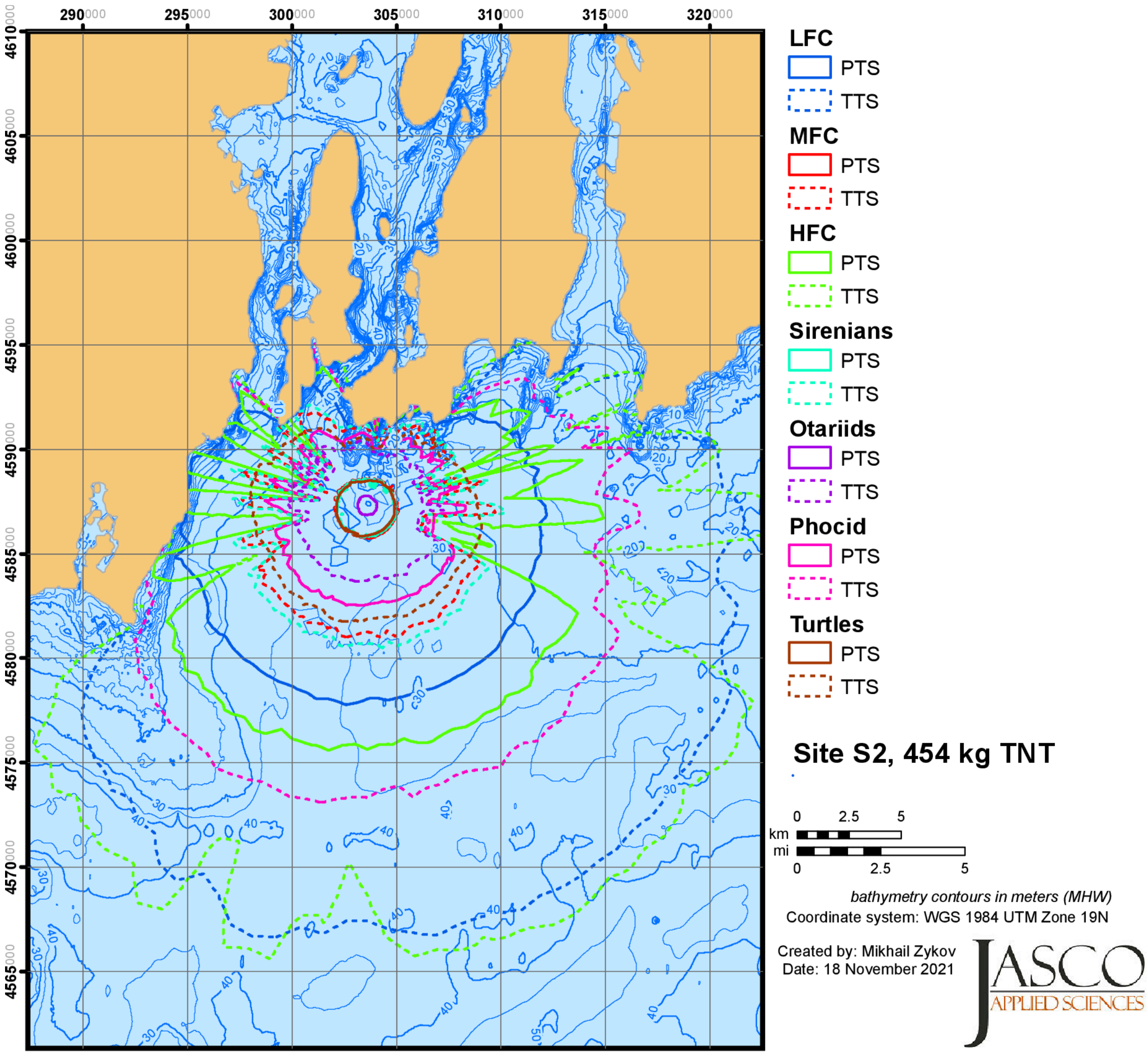

Figure A-4. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S2.

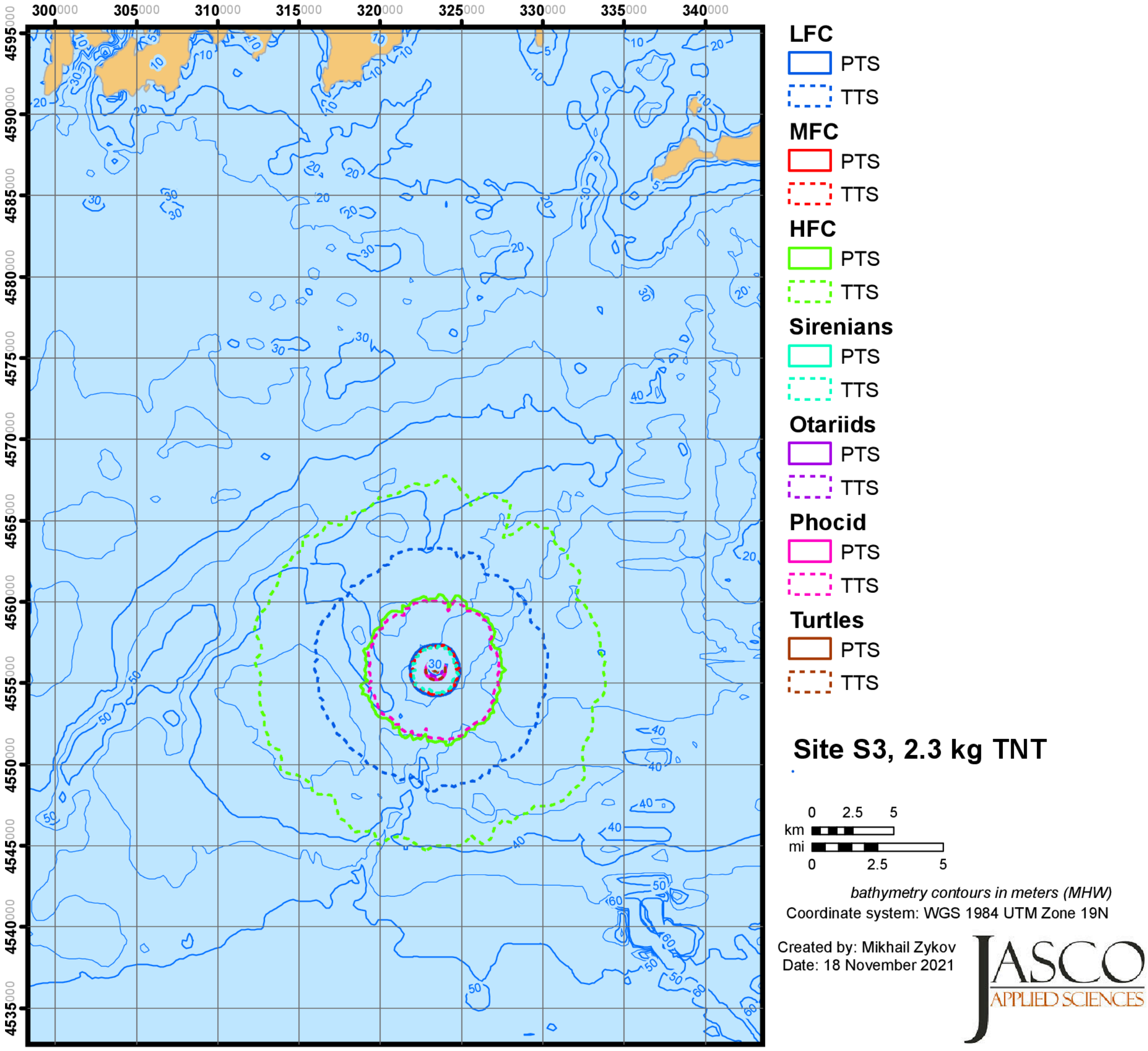

Figure A-5. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S3.

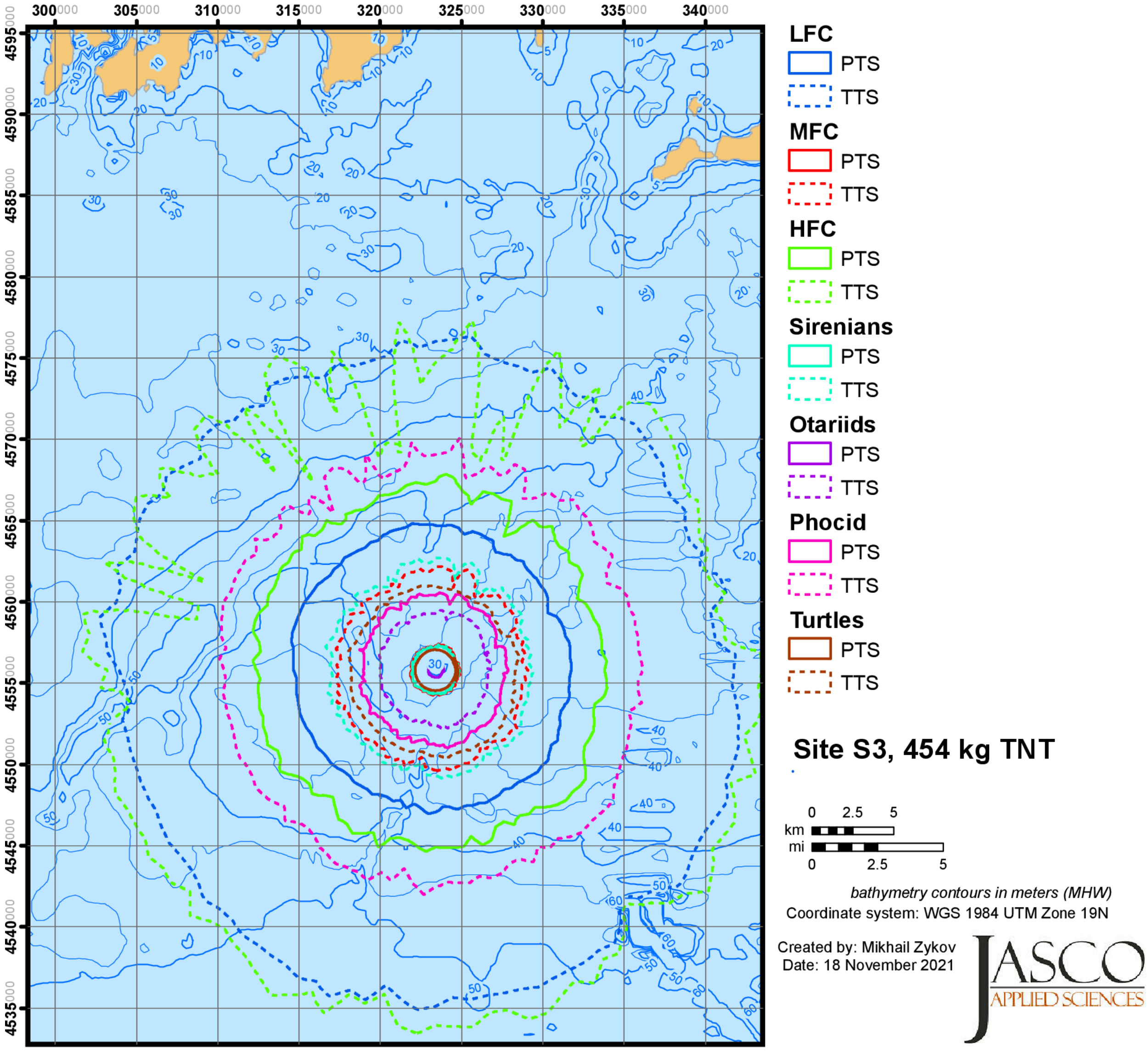

Figure A-6. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S3.

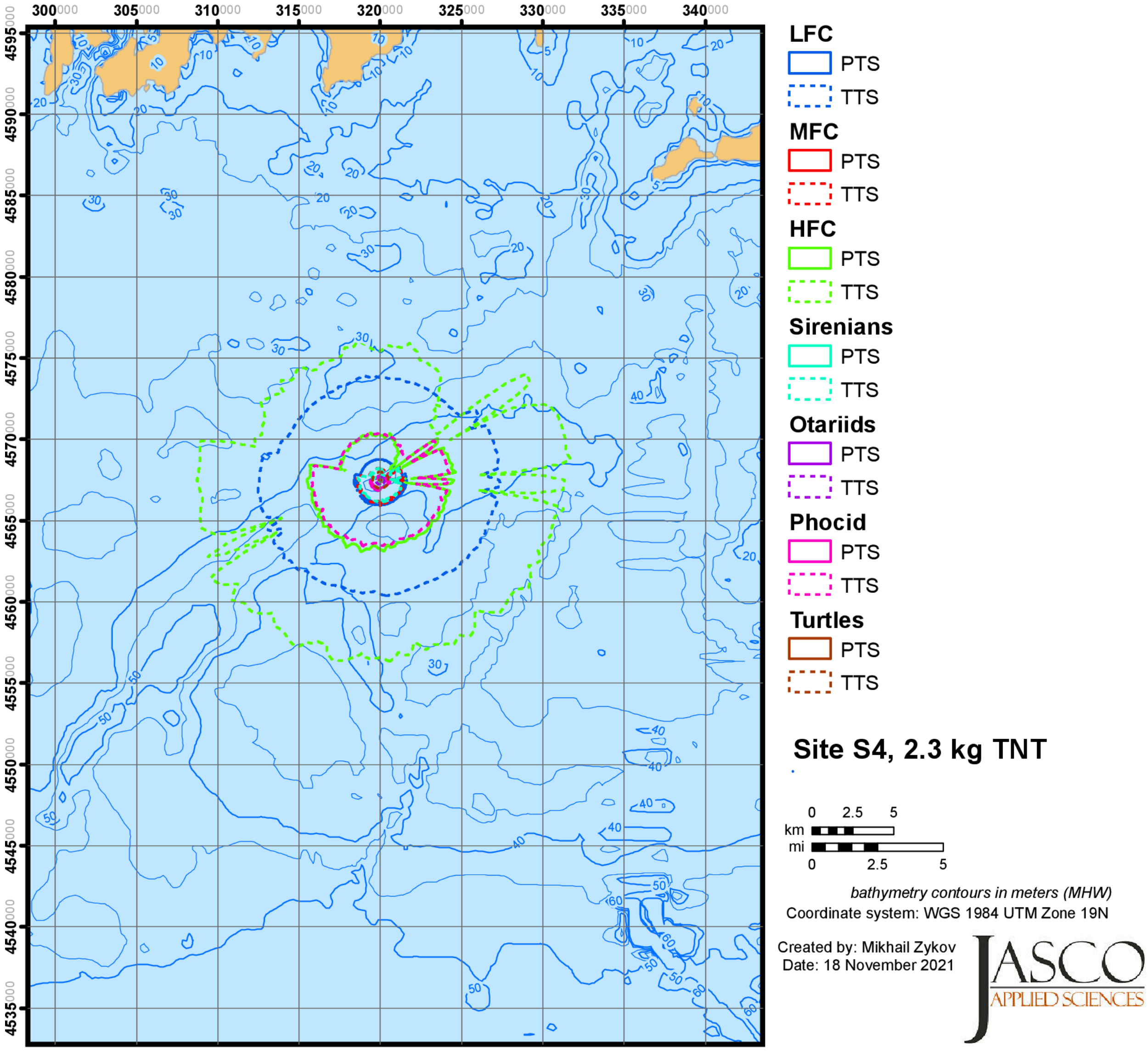

Figure A-7. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S4.

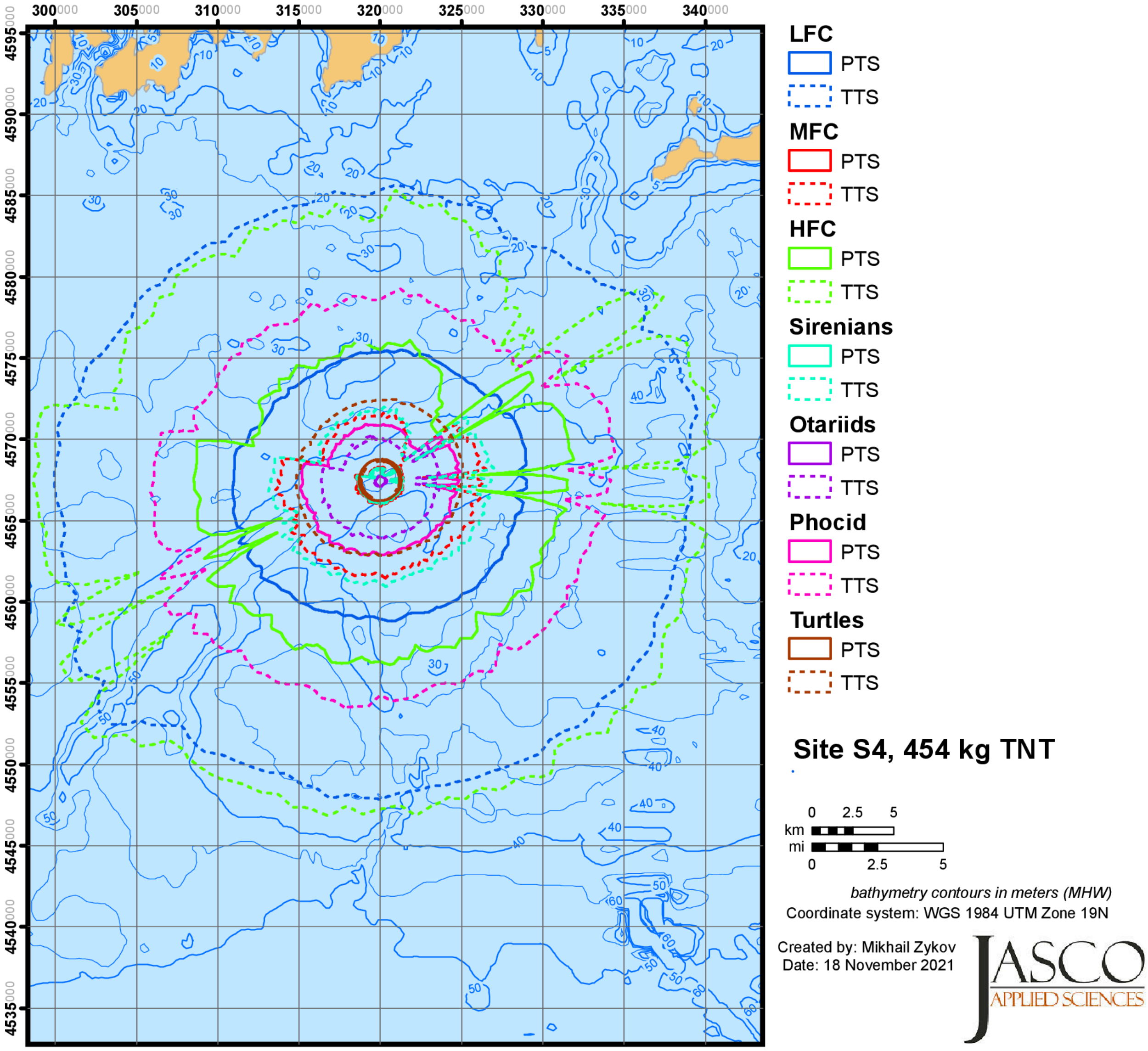

Figure A-8. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S4.