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

Submitted to:
Laura Morse
Ørsted

Authors:
David Hannay
Mikhail Zykov

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JASCO Applied Sciences (USA) Inc
8630 Fenton Street, Suite 218
Silver Spring, MD 20910 USA
Tel: +1-301-565-3500
www.jasco.com

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Contents

1. Introduction

Ørsted's wind projects offshore Massachusetts and New Jersey may encounter unexploded ordnance (UXO) on the seabed in the wind farm lease areas and along electrical transmission 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 explosions of this type 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 takes will need to be accounted for in the project LOA or IHA. The study described in this report has applied acoustic source and sound propagation modeling 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.

Most of the underwater explosives acoustic assessment work in the US has been performed by or for the US Navy, who have worked closely with US National Marine Fisheries Service (NMFS) to choose and define appropriate criteria for effects based on best available science. These metrics and thresholds are discussed in this report. We have evaluated effects thresholds based on three key sound pressure metrics considered by the Navy and NMFS as indicators of injury and disturbance: peak pressure level (PK or L_{pk}), sound exposure level (SEL or L_E), 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 NOAA as an assessment criterion for sounds from explosive detonations. The names and symbols used for the above metrics follow the terminology of ISO 18405 (ISO 2017), except where tables and equations have been copied from previous regulatory documents. For each metric, the threshold limits depend on species and in some cases animal size and submersion depth. JASCO uses specialized acoustic models and empirical formulae to evaluate the distances from various sizes of charges that may be required to be removed by explosive detonation during Ørsted's construction activities. The theory underlying these models is provided in the technical discussion sections of this report.

This assessment considers acoustic effects on marine mammals, sea turtles and fish from five possible charge sizes at sites with four water depths near Ørsted's Revolution Wind project areas, but the results are also relevant for sites with similar depths at Ørsted's Ocean Wind 1 project off New Jersey. An unmitigated and mitigated scenario are considered at each site, with mitigation considering a 10 dB reduction to peak pressure, impulse and SEL, that might be obtained using an air bubble curtain or similar system. The results for unmitigated and mitigated UXO detonations are provided in Sections 9 and 10 respectively. Because of the large number of result tables, the Summary (Section 11) provides cross-references for effects assessment criteria to the relevant tables for both unmitigated and mitigated scenarios.

2. UXO Charge Sizes

The charge weights (characterized as equivalent TNT weight) to be assessed through acoustic modeling of charge weights, each representing a group of similar weapons (bins) that were defined by the US Navy, where each bin represents explosives/weapons having similar characteristics and charge weights. The final set of five bins has been modeled, with maximum charge sizes in each listed in Table 1. We note that the effect of the charges used to detonate the UXO have not been specifically included in this assessment.

Table 1. Navy "bins" and corresponding maximum charge weights (equivalent 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 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. Their influence is complex but can be predicted accurately by acoustic models.

Ørsted's recent projects in the US include the Revolution Wind project off Massachusetts, and the Ocean Wind 1 project on the Avalon Shoal off New Jersey. Both projects lie in relative shallow waters of 20-40 m depth, and both have sandy seabeds. The results of the present study are relevant for both 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, so results will be relevant for both project areas at sites with the same 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 cable route and two are inside the wind lease area of the Revolution Wind project. The locations sites are shown on the map of Figure 1. These modeling sites are as follows:

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.

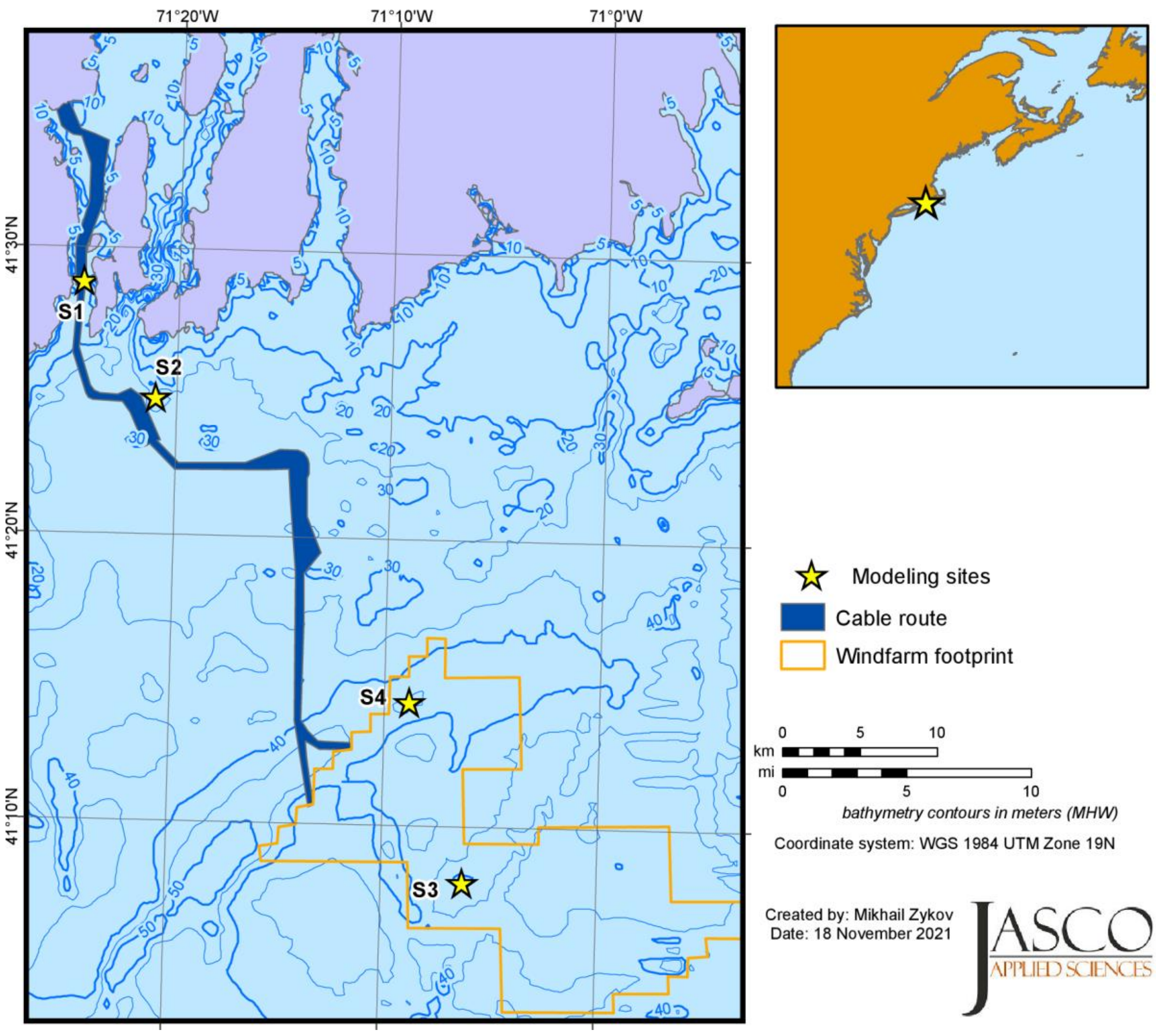

Figure 1. Map showing locations of the four modeling sites.

4. Blast Pressure Mitigation

Prediction of exceedance distances for effects to marine mammals were made 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. This amount of acoustic reduction is expected to be achievable by deploying an air bubble curtain 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 and SEL produced by underwater explosive detonations. One measurement of a small bubble curtain showed good performance for 1 kg charges, providing approximately 16 dB attenuation at all frequencies greater than 1 kHz using small diameter curtains of less than 11.5 m (Schmidke et al., 2009). The same study evaluated another relatively small bubble curtain (diameter 22 m in 20 m depth) surrounding 300 kg mines. That bubble curtain configuration produced smaller attenuations of approximately 2 dB at 100 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 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.

The spectral energy distribution of the shock pulse and the full 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 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 8.2.1. 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 SEL 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 be better. The minimum modern bubble curtain effectiveness for the bands dominating explosive detonation SEL in shallow waters is well above 10 dB. Therefore, the choice of 10 dB as a broadband SEL attenuation is expected to be conservative for SEL.

The very rapid onset of the shock pulse, within a few microseconds, 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 much greater than 10 dB.

5. Environmental Parameters

5.1. Seafloor Geoacoustic Parameters

Sound propagation in the shallow water environments of Ørsted's wind projects is influenced by the properties of the seafloor substrate. There is limited information on spatial variations of seafloor sediment compositions over the wind lease areas, so a general profile for the area has been used for all four modeling sites. The surficial sediments are believed to be primarily sand as described by DWSF (Denes et al. 2018). Table 2 shows the sediment layer geoacoustic property profile used for acoustic modeling of SEL in this study. These properties are based on the sediment type and generic porosity-depth profile using a sediment grain-shearing model (Buckingham 2005). This profile should be relevant for sites throughout the 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.

<table>
<tr><th>Depth below seafloor (m)</th><th>Material</th><th>Density (g/cm³)</th><th>P-wave speed (m/s)</th><th>P-wave attenuation (dB/λ)</th><th>S-wave speed (m/s)</th><th>S-wave attenuation (dB/λ)</th></tr>
<tr><td>0–5</td><td rowspan="4">Sand</td><td>1.87</td><td>1,650–1,690</td><td>0.74–1.0</td><td rowspan="4">300</td><td rowspan="4">3.65</td></tr>
<tr><td>5–10</td><td>1.87–2.04</td><td>1,690–1,830</td><td>1.0</td></tr>
<tr><td>10–100</td><td rowspan="2">2.04</td><td>1,830–2,140</td><td>1.0–1.67</td></tr>
<tr><td>>100</td><td>2,140</td><td>1.67</td></tr>
</table>

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 summer months when the UXO removal is expected to occur.

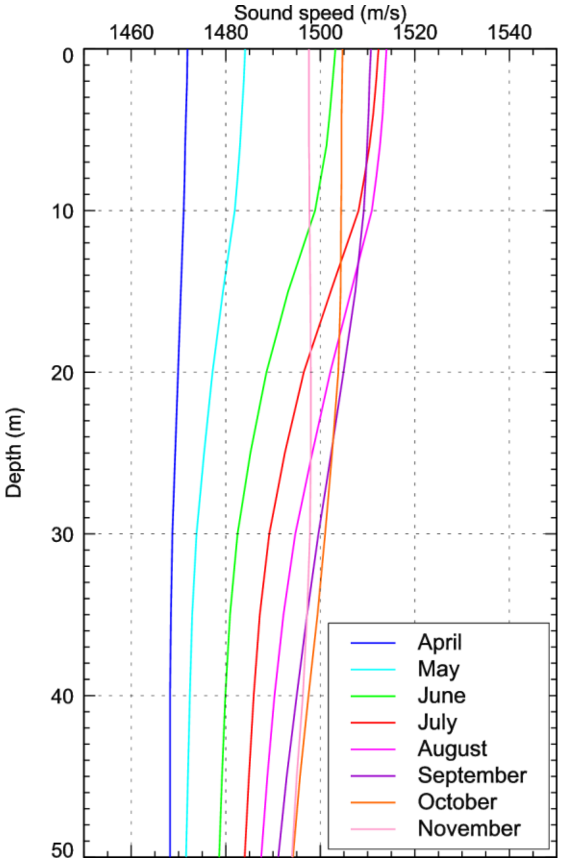

Figure 2. Monthly average sound speed profiles in proposed construction area (excluding winter season) (source: GDEM (NAVO 2003)).

6. Acoustic Thresholds for Mitigation Zones and Takes

6.1. Marine Mammals and Sea Turtles: Auditory Injury

The injury zones surrounding explosives detonations are of key importance for developing mitigations to minimize takes. Two injury mechanisms are assessed: auditory injury and non-auditory injury. We follow the US Navy approach for assessing both types. Auditory injury (onset of permanent threshold shift (PTS)) is assessed using a dual criteria of peak pressure level (PK) and frequency-weighted SEL ($L_{E,w}$), where the frequency weighting functions are dependent on the species group. The Navy has published a table containing PK and $L_{E,w}$ thresholds for onsets of PTS and temporary threshold shift (TTS – not an injury) that will be used here for marine mammals and sea turtles (Table 3). Note the TTS thresholds also listed in that table are used for Level-B take assessments (see Section 6.3).

Table 3. US Navy peak (2017) pressure and frequency-weighted sound exposure thresholds for onset of PTS and TTS. The Group column represents species groups from top to bottom: low-frequency cetaceans, mid-frequency cetaceans, high-frequency cetaceans, sirenians, otariids in water, pinnipeds in water, turtles, otariids in air, and pinnipeds in air. Note: the term “peak SPL” used in column 6 represents the peak pressure level (PK) metric as defined in ISO 18405. PK is not truly an SPL, as SPL is defined as a root-mean-square pressure level.

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

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

Non-auditory injury mitigation zones are calculated using metrics representing slight injury from lung and gastrointestinal tract compression injuries. The relevant metrics are PK and acoustic impulse (J_p) of the blast shock pulse. The impulse calculation involves integrating pressure through time, with the integration period limited by the smaller of the arrival time difference between direct and surface-reflected paths, and 20% of the animal’s lung oscillation period. These times are straightforward to calculate using the Goertner formulas (Goertner 1982). The Navy’s impulse criteria for slight injury is based on measurements of blast effects on mammals (Yelverton 1973). The Navy has published two sets of equations for these thresholds that depend on animal mass and submersion depth. The first set of equations is usually intended for estimating numbers of animals that may be affected (Table 4), while the second set of equations is more conservative and normally used for defining mitigation zones (Table 5). NMFS has asked that the more conservative values also be used for take assessments for Ørsted’s projects. The approach requires choosing a set of representative animal masses to assess. Masses for smaller and larger animals in several species categories for marine mammals and sea turtles were defined for that purpose (see Section 7.1).

Table 4. US Navy impulse and peak pressure threshold equations for estimating numbers of marine mammals and turtles that may experience mortality or injury due to explosives (Department of the Navy 2017).

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 5. US Navy impulse and peak pressure threshold equations for estimating distances to onset of potential effect for marine mammal and turtle mortality and slight lung injury due to explosives (Department of the Navy 2017). These thresholds are relevant for mitigation planning.

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).

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

The acoustic criteria relevant for Level-B takes include PK and SEL 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 they are below the onset of TTS thresholds for frequency-weighted SEL and peak pressure level (Table 3). When multiple blast events occur within a 24-hour period, the US Navy approach applies a disturbance threshold of TTS SEL minus 5 dB. Thus, the effective Level-B take threshold for single events in each 24-hour period is the TTS onset, and for multiple events it is the $L_{E,w}$ for TTS – 5 dB.

The calculation of TTS and behaviour (TTS – 5 dB) effects thresholds is more difficult for multiple blasts within a 24-hour period because marine mammals and turtles could receive partial doses of SEL from more than one of the charges detonated. The individual event doses depend on the charge sizes, relative detonation timing, marine mammal locations, and geoacoustic environment parameters along paths between the detonation and the exposed marine mammals, most of which are not known in advance of the UXO removals. If the parameters other than animal locations were known, then animal movement models could be used to provide exposure and take estimates. However, since Ørsted plans on only one charge detonation per day, a simpler single event SEL modeling is sufficient to calculate an SEL map around each charge, and the TTS zones can be evaluated using the TTS criteria from Table 3.

Note: The authors of the Navy assessment protocols suggest calculating (but not applying) SPL-based disturbance threshold for turtles of L_p = 175 dB re 1 µPa^2, but that is not currently required by BOEM or NMFS. Modeling of SPL requires using full wave source and propagation models that are not required for

SEL assessments. That has not been done for this initial assessment, but it can 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 peak pressure limits for onset of mortality or injury leading to mortality due to explosives, as recommended by the ANSI expert working group (Popper et al. 2014) and provided in Table 6. The injurious effects thresholds for all fish species groups are the same: PK = 229–234 dB re 1 µPa. The present assessment has applied the lower threshold value of PK = 229 dB re 1 µPa for potential mortal injury and mortality.

Table 6. 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 6) are qualitative and vague on that subject; for fish with swim bladders used for hearing they indicate high likelihood of TTS and recoverable injury at near (N) and intermediate (I) distances, where near refers to within a few tens of meters and intermediate refers to a few hundreds of meters. For fish 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 at far (F) distances of a few kilometers.

7. Species and Animal Sizes

This assessment considers behavior and injury effects of UXO removal blasts on marine mammals, sea turtles and fish that may occur in or near the wind lease and cable route operations areas. The SEL-based PTS and TTS effects thresholds are dependent on the marine mammal species-group. The Impulse-based PTS thresholds depend on the mass of the animal and its submersion depth (Table 5). We list here the species groups of concern and provide representative animal sizes considered for this assessment. In all cases we consider possible submersion depths from the sea surface to the seafloor.

7.1. Marine Mammals and Turtles

The impulse thresholds for mortality and slight lung injury (1% of animals) relevant for marine mammals and turtles depend on the animal lung volume, which is dependent on animal mass and depth (see equations in Table 5). The low and high mass estimates for representative animals of several species or species groups are provided in Table 7. The corresponding impulse thresholds for each of the animal masses is provided in Table 8. Impulse thresholds increase with animal depth due to compression of the lung, which makes it less susceptible to damage. An important aspect of this type of assessment is that impulse level is also depth dependent. This leads to the complex situation that the location of threshold exceedance most distant from the charge may not occur near the surface even thought the impulse threshold is lowest there. The depth-dependence of impulse is also affected by the animal's lung volume at depth and the time delay between the direct and surface reflected acoustic paths, as discussed in Section 8.1.3. The approach taken here has been to calculate depth-dependent thresholds in 1 meter depth increments, and impulse exposures on a 1 m × 1 m range-depth scale. The maximum distance of threshold exceedance is then defined by the maximum impulse exceedance range at any depth.

Table 7. Representative low and high mass estimates for the species groups and species considered in this assessment.

Species or species group	Low mass estimate (kg)	High mass estimate (kg)
Low frequency cetaceans and sperm whales	100,000	150,000
Pilot and minke whales	3000	5000
Midfrequency cetaceans	200	500
Pinnipeds (in water)	200	350
High frequency cetaceans and turtles	100	150

Table 8. Impulse thresholds in Pa·s for Onset Injury Impulse (see Table 5) for all animal masses in Table 7, and for selected submersion depths between 1 and 60 m.

Depth (m)	Animal mass								
	100 kg	150 kg	200 kg	350 kg	500 kg	3000 kg	5000 kg	100,000 kg	150,000 kg
1	224	256.4	282.2	340.1	383	695.9	825.1	2239.7	2563.8
10	247.3	283.1	311.5	375.4	422.8	768.3	911	2472.7	2830.5
20	264.5	302.8	333.2	401.6	452.3	821.8	974.4	2644.9	3027.6
30	277.4	317.6	349.5	421.2	474.4	862.1	1022.1	2774.4	3175.9
40	287.9	329.6	362.8	437.2	492.3	894.7	1060.7	2879.3	3295.9
50	296.8	339.7	373.9	450.6	507.5	922.2	1093.4	2967.9	3397.4
60	304.5	348.6	383.7	462.3	520.7	946.2	1121.8	3045	3485.7

7.2. Fish

The three fish groups identified by Popper et al. (2014) are: fish with no swim bladder, fish with swim bladder not involved in hearing, and fish with swim bladder involved in hearing. All three groups are assigned the same peak pressure threshold interval for mortality or mortal injury, as discussed in Section 6.4. This assessment applies the lower threshold limit: 229 dB re 1 µPa.

8. Acoustic Modeling

8.1. PK and Impulse

8.1.1. 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 PK and impulse (J_p) metrics is calculated with empirical 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. This behavior imparts an initial pressure "shock pulse" into the water that is represented well by an abrupt 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 peak pressure. Arons and Yennie (1949) made measurements of the detonations of a range of charge sizes in Vineyard Sound, coincidentally just a few miles from Ørsted'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 the SI (MKS) system units in the formulae presented here.

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

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

8.1.2. 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, that depends on charge weight, 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 peak pressure and time constant are obtained by modified formulae (Rogers 1977):

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

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

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 that transitions to spherical spreading and the time constant 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.

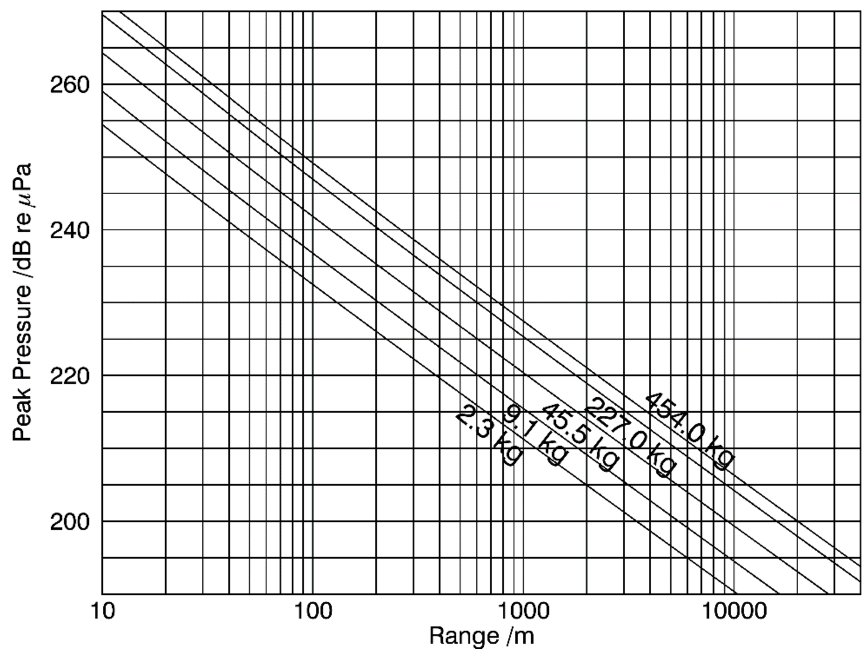

Figure 3. Peak pressures versus distance from detonations of the charge weights listed in Table 1, calculated with Eqs. 2 and 4.

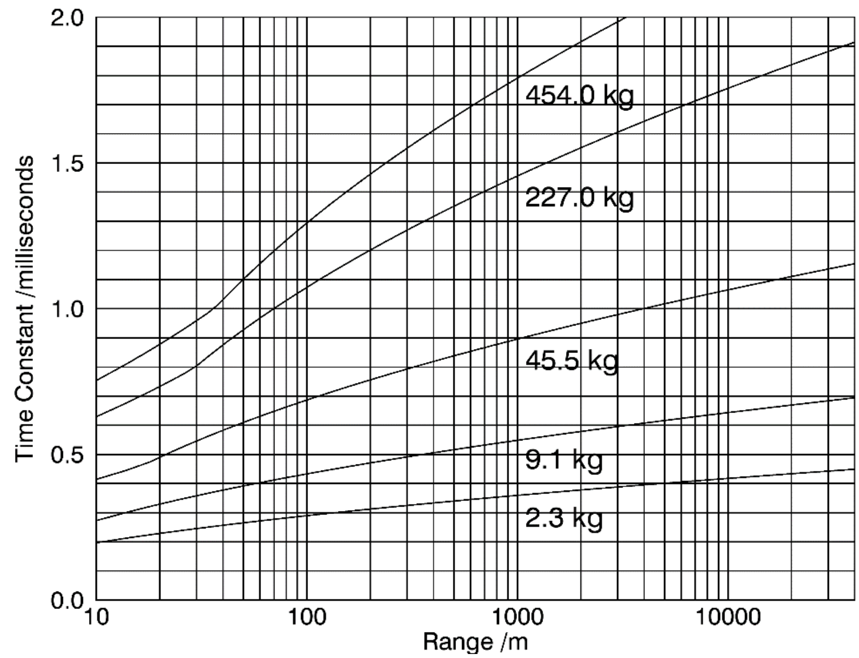

Figure 4. Time constants calculated with Eqs. 3 and 5 and converted to milliseconds for the exponential decay approximation of the shock pulse, for each of the charge weights listed in Table 1.

8.1.3. 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 is considered as ending at $t = T$, the impulse is given by:

$$J_p = \int_0^T P(t)\, dt \qquad 6$$

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:

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

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:

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

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:

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

$$t_{osc} = 97.1\, (V 4\pi/3)^{\frac{1}{3}} / \sqrt{\rho_0 g z_r + p_{atm}} \quad \mathrm{s} \qquad 10$$

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.

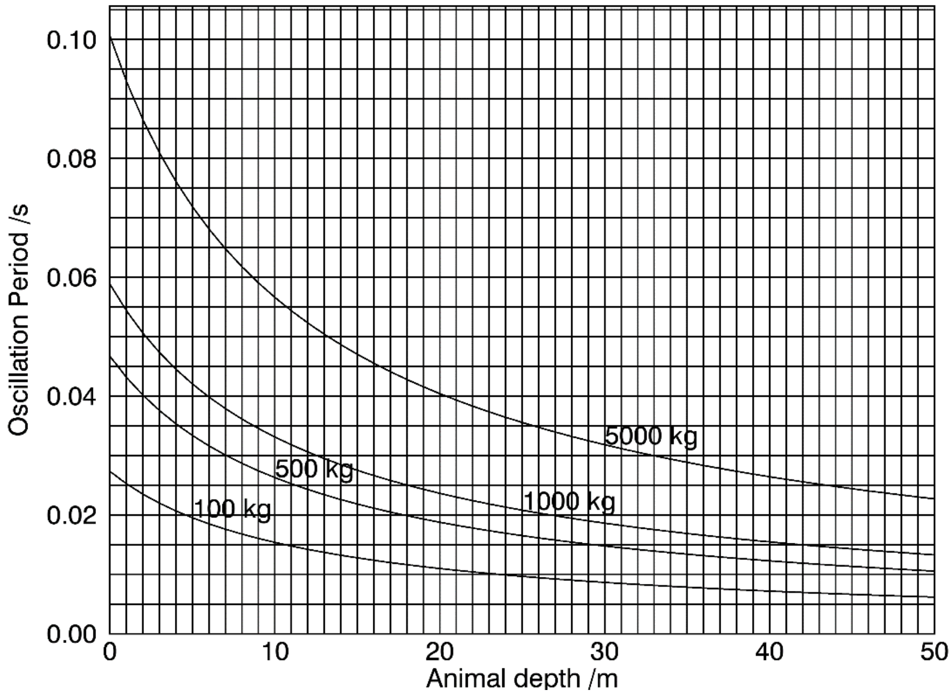

Figure 5. Lung oscillation periods for animal masses of 100 kg, 500 kg, 1000 kg and 5000 kg versus submersion depth, calculated using Eq. 10.

8.2. Sound Exposure Level Model

SEL and SPL calculations are dependent on the entire pressure waveform, including the initial shock pulse (as described above) and the subsequent oscillation of the explosive product gas bubble. This leads to a series of alternating negative and positive pressure phases trailing the initial positive pressure shock pulse. The shape of this full 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 bubble pulses. 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.

The SEL thresholds for injury and disturbance occur at distances of many water depths in the relatively shallow waters of Ørsted's Ocean Wind and Revolution Wind's wind farm environments. The sound field at distances of several water depths 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 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 SEL with distance from the detonation varies in a complex way with sound frequency. The modeling of SEL performed here was carried out in decidecade frequency bands using the marine operations noise model (MONM, JASCO Applied Sciences). This model applies a parabolic equation approach for frequencies below 4 kHz, and a Gaussian beam ray trace model at higher frequencies.

8.2.1. 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 its 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 6) 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):

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

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:

$$\Delta\text{ESL} = 13.3 \log W. \tag{12}$$

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 6) 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.

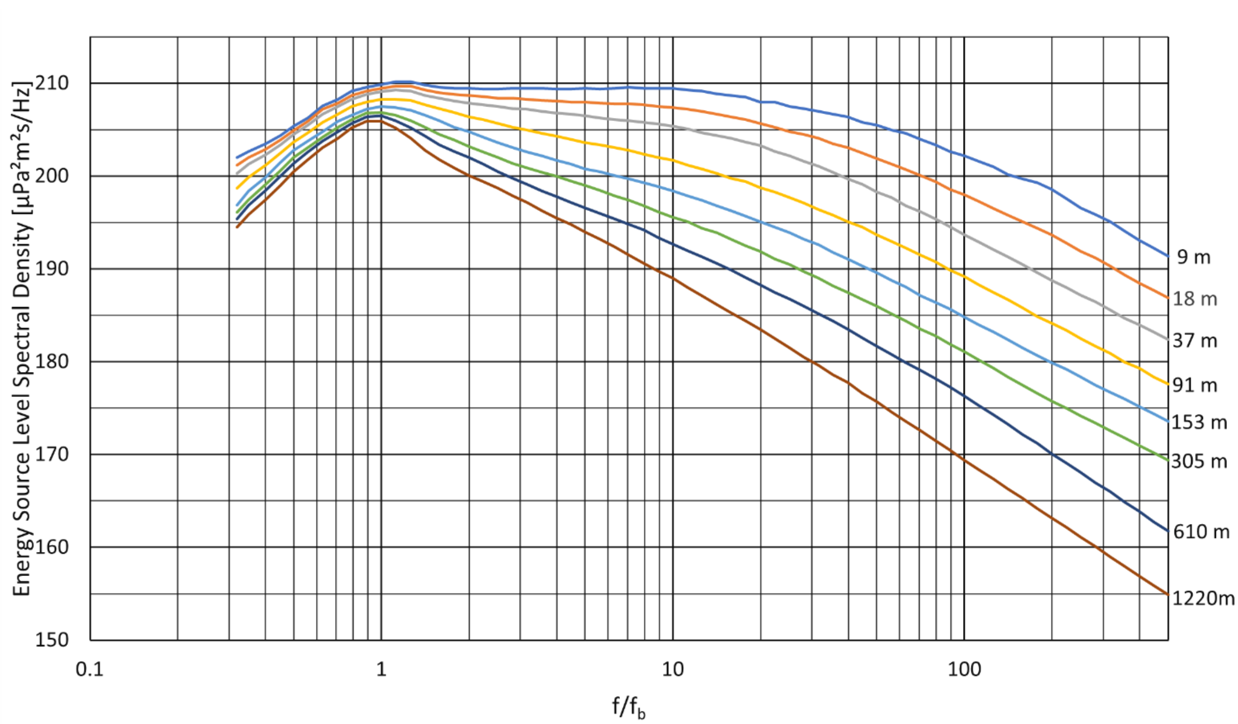

Figure 6. Energy source level spectral density curves for underwater explosion events at various depths expressed in normalized frequency, relative to the frequency f_{b1} of the first bubble pulse (after Urick 1983).

9. Exceedance Distance Results (Unmitigated)

9.1. Marine Mammals and Sea Turtles TTS and PTS Exceedance Distances for Peak Pressure

Peak pressure exceedance distances are not dependent on water depth or seabed properties, so Table 9 is relevant for all sites in the wind farm area.

Table 9. Marine mammals, turtles and fish PTS and TTS maximum exceedance distances for peak pressure for various UXO charge sizes 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	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

9.2. Marine Mammals and Sea Turtles Onset of Injury Threshold Exceedance Distances for Impulse

Impulse levels and thresholds are depth-dependent, so maximum exceedance distances could vary between sites with different depths.

Table 10. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S1 (12 m water depth) for various UXO charge sizes. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size		Animal size		Animal size		Animal size		Animal size	
	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	30	26	82	74	106	98
Pilot and minke whales	<10	<10	34	30	98	86	182	166	222	198
Mid-frequency cetaceans	38	26	90	66	198	158	310	258	358	306
Pinnipeds	38	30	90	78	198	174	310	278	358	326
High frequency cetaceans and sea turtles	46	42	114	102	230	210	350	326	406	378

Table 11. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S2 (20 m water depth) for various UXO charge sizes. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	26	22	90	78	134	118
Pilot and minke whales	<10	<10	34	26	106	90	250	218	318	286
Mid-frequency cetaceans	34	22	94	70	246	186	454	374	546	458
Pinnipeds	34	26	94	78	246	210	454	406	546	490
High frequency cetaceans and sea turtles	46	38	118	102	298	270	522	482	618	574

Table 12. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S3 (30 m water depth) for various UXO charge sizes. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	26	22	90	78	138	122
Pilot and minke whales	<10	<10	30	26	106	90	282	242	398	346
Mid-frequency cetaceans	30	22	94	66	258	194	582	466	730	602
Pinnipeds	30	26	94	78	258	218	582	510	730	650
High frequency cetaceans and sea turtles	42	34	122	106	322	286	674	622	838	774

Table 13. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S4 (45 m water depth) for various UXO charge sizes. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large	Animal size Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	22	22	86	74	142	122
Pilot and minke whales	<10	<10	30	22	106	86	294	250	438	374
Mid-frequency cetaceans	30	22	90	58	270	198	630	502	842	694
Pinnipeds	30	22	90	70	270	222	630	550	842	750
High frequency cetaceans and sea turtles	38	34	118	102	334	294	734	674	958	890

9.3. Fish Onset of Injury by Peak Pressure

Table 14. 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 from Popper et al. (2014).

Fish Hearing Group	Onset Injury PK (dB re 1 µPa)	All sites: Maximum distance to 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

9.4. Marine Mammals and Sea Turtles: PTS Distances for SEL

The methods discussed in Section 8.2 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 were extracted over depth to create noise maps of the type shown in Figure 7. Similar maps for all sites for the 2.3 kg and 454 kg charge sizes are provided in Appendix A.

Exceedance distances to each of the marine mammal, 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 15 to 18 are maxima over depth.

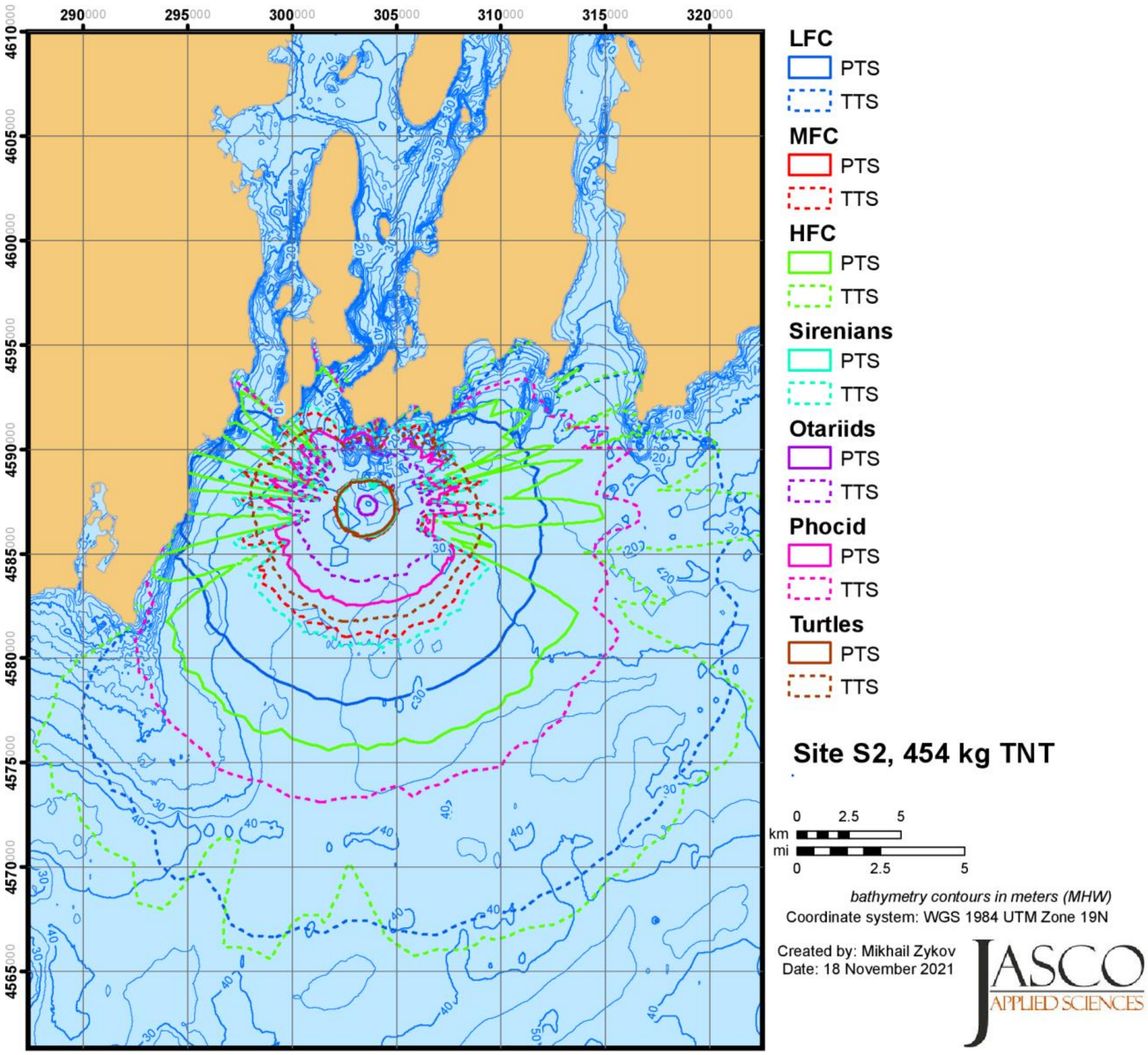

Figure 7. Frequency-weighted SEL PTS and TTS exceedance zone maps for the 454 kg charge size at Site S2, for each species group.

Table 15. 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 16. 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 17. 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 18. 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

9.5. Marine Mammals and Sea Turtles: TTS Distances for SEL

The SEL distances thresholds are not dependent on animal depth, but the SEL exposure levels are. The TTS threshold exceedance distances provided in Tables 19 to 22 are maxima over depth.

Table 19. 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 20. 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 21. 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 22. 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

10. 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).

10.1. Marine Mammals and Sea Turtles TTS and PTS Exceedance Distances for Peak Pressure with 10 dB mitigation

Peak pressure exceedance distances are not dependent on water depth or seabed properties, so Table 23 is relevant for all sites in the wind farm area.

Table 23. Marine mammals, turtles and fish 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

10.2. Marine Mammals and Sea Turtles Onset of Injury Threshold Exceedance 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.

Table 24. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S1 (12 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size		Animal size		Animal size		Animal size		Animal size	
	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	<10	<10	26	22	41	36
Pilot and minke whales	<10	<10	<10	<10	32	26	84	73	110	98
Mid-frequency cetaceans	<10	<10	28	19	81	60	158	130	192	161
Pinnipeds	<10	<10	28	22	81	67	158	141	192	173
High frequency cetaceans and sea turtles	13	11	36	31	99	88	183	168	220	203

Table 25. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S2 (20 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size		Animal size		Animal size		Animal size		Animal size	
	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	<10	<10	24	21	41	35
Pilot and minke whales	<10	<10	<10	<10	30	24	92	77	137	117
Mid-frequency cetaceans	<10	<10	26	18	83	61	208	161	272	220
Pinnipeds	<10	<10	26	21	83	69	208	179	272	239
High frequency cetaceans and sea turtles	12	<10	34	29	105	92	248	224	316	290

Table 26. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S3 (30 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size		Animal size		Animal size		Animal size		Animal size	
	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	<10	<10	23	20	38	32
Pilot and minke whales	<10	<10	<10	<10	28	23	93	78	144	121
Mid-frequency cetaceans	<10	<10	24	17	83	58	222	169	311	247
Pinnipeds	<10	<10	24	20	83	67	222	189	311	270
High frequency cetaceans and sea turtles	12	<10	31	27	106	92	264	239	361	329

Table 27. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse (non-auditory) at Site S4 (45 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are animal mass and submersion-depth dependent and provided in Table 8.

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)	
	Animal size		Animal size		Animal size		Animal size		Animal size	
	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
Low-frequency cetaceans	<10	<10	<10	<10	<10	<10	21	18	35	30
Pilot and minke whales	<10	<10	<10	<10	26	21	91	73	146	122
Mid-frequency cetaceans	<10	<10	23	16	79	51	231	173	330	259
Pinnipeds	<10	<10	23	18	79	61	231	194	330	286
High frequency cetaceans and sea turtles	11	<10	29	25	105	89	280	250	388	352

10.3. Fish Onset of Injury by Peak Pressure with 10 dB mitigation

Table 28. 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 PK (dB re 1 µPa)	All sites: Maximum distance to 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

10.4. Marine Mammals and Sea Turtles: PTS distances for 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 29 to 32 are maxima over depth.

Table 29. 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 30. 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 31. 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 32. 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

10.5. Marine Mammals and Sea Turtles: TTS distances for 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 33 to 36 are maxima over depth.

Table 33. 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 34. 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 35. 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 36. 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

11. 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, charge sizes, and detonation locations (Sites S1–S4). While these specific sites were chosen inside Ørsted's Revolution Wind project area, the model results are equally valid for sites inside the Ocean Wind 1 project area having the same water depths. The threshold distances modeled here are all necessary to address NMFS's assessment requirements for species-dependent effects criteria for assessing Level-A and 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: peak pressure level (PK), acoustic impulse (J_p), and sound exposure level (SEL). The SEL levels are dependent on species group while the impulse levels are dependent on animal mass and submersion depth. All three metrics have species- or animal size-dependent thresholds. The SEL and impulse levels depend on water depth. 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.

11.1. Unmitigated Take Distances

11.1.1. 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:

- Peak pressure: Table 9 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.
- Impulse: Tables 10 to 13 contain onset of non-auditory injury (1% of animals) distances for Sites S1 to S4, respectively. Note for each species group there are separate distances for small and large animals representative of the group, and smaller animals in each group have lower thresholds leading to larger exceedance distances. The deeper sites generally have larger exceedance distances than shallower sites. The greatest distance for onset of lung injury is 958 m from the 454 kg charge for smaller high-frequency cetaceans and sea turtles.
- SEL (species-group weighted): Tables 15 to 18 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 9.4. The greatest distance is 11 300 m for high-frequency cetaceans at Site S1.
- SEL and peak pressure injury zones are always larger than the Impulse 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.

11.1.2. Unmitigated Level-B Takes

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

- Peak pressure: Table 9 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 19 to 22 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. We did not assess TTS zones for multiple blasts.

11.1.3. Unmitigated Effects on Fish

- Peak pressure: Table 14 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.

11.2. 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 10 and discussed here.

11.2.1. Mitigated Level-A Takes

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

- Peak pressure: Table 23 contains mitigated PTS (auditory injury) exceedance distances valid for all sites. The greatest PTS distance is 5369 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 1000 m.
- Impulse: Tables 24 to 27 contain onset of non-auditory injury (1% of animals) exceedance distances for Sites S1 to S4, respectively. The greatest distance for onset of mitigated non-auditory injury is 388 m from the 454 kg charge at Site S4, for smaller high-frequency cetaceans and sea turtles (note these injury thresholds are dependent on animal mass).
- SEL (species-group weighted): Tables 29 to 32 contain PTS threshold exceedance distances at Sites S1 to S4, respectively. The greatest $R_{95\%}$ distance is 6200 m for high-frequency cetaceans at Site 1.

11.2.2. Mitigated Level-B Takes

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

- Peak pressure: Table 23 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 33 to 36 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.

11.2.3. Mitigated Effects on Fish

- Peak pressure: Table 28 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.

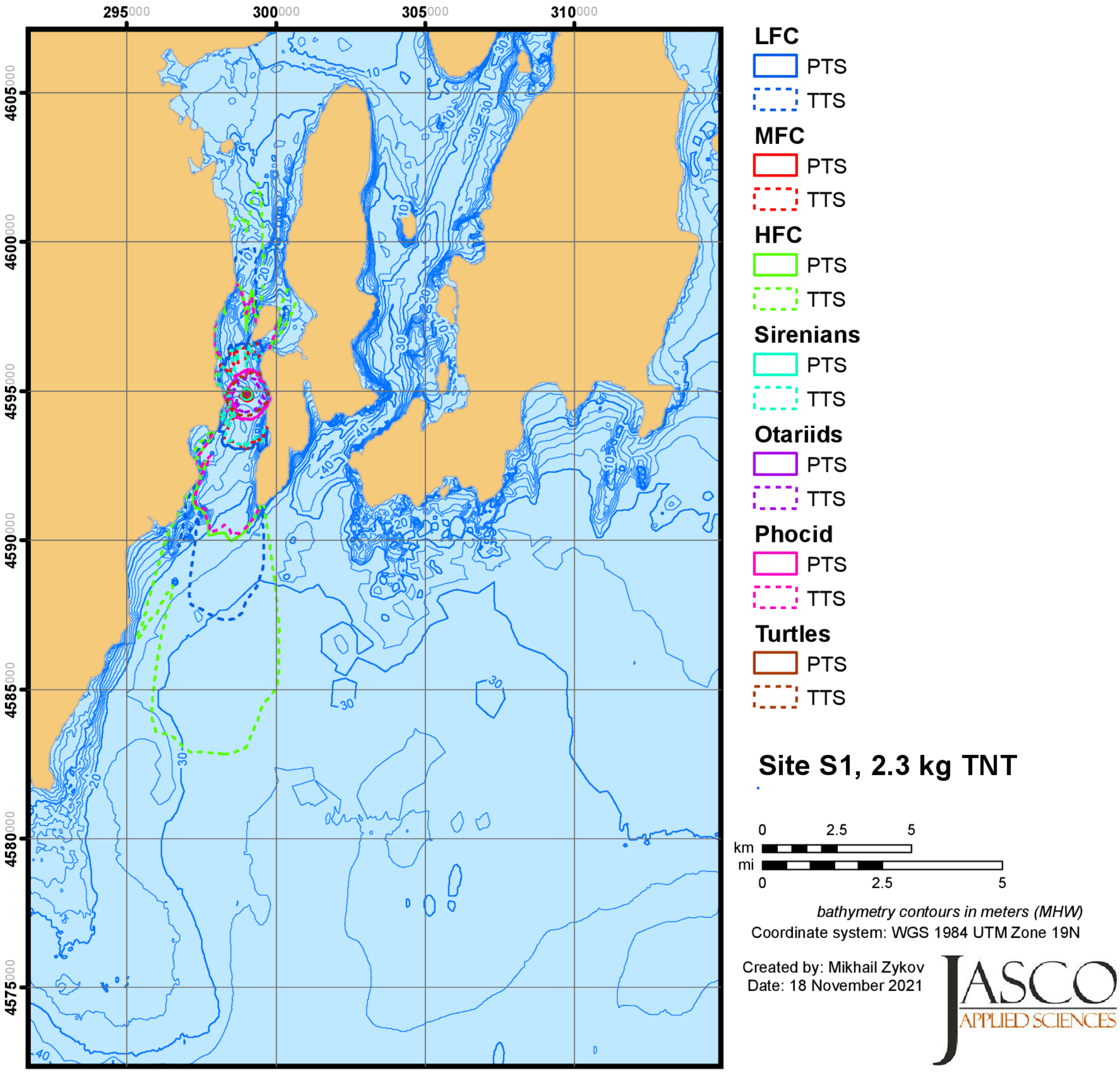

Figure A-1. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S1.

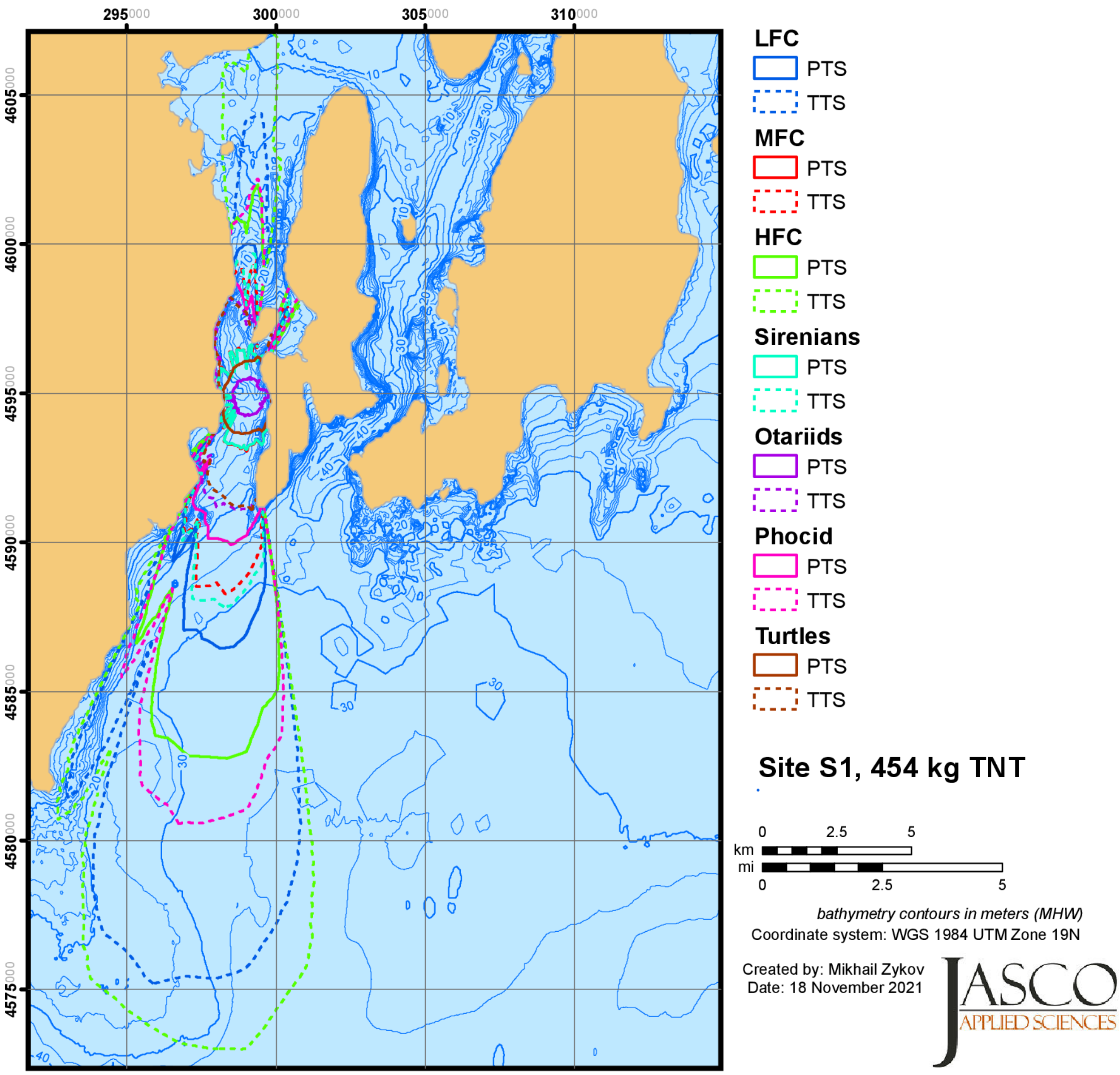

Figure A-2. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S1.

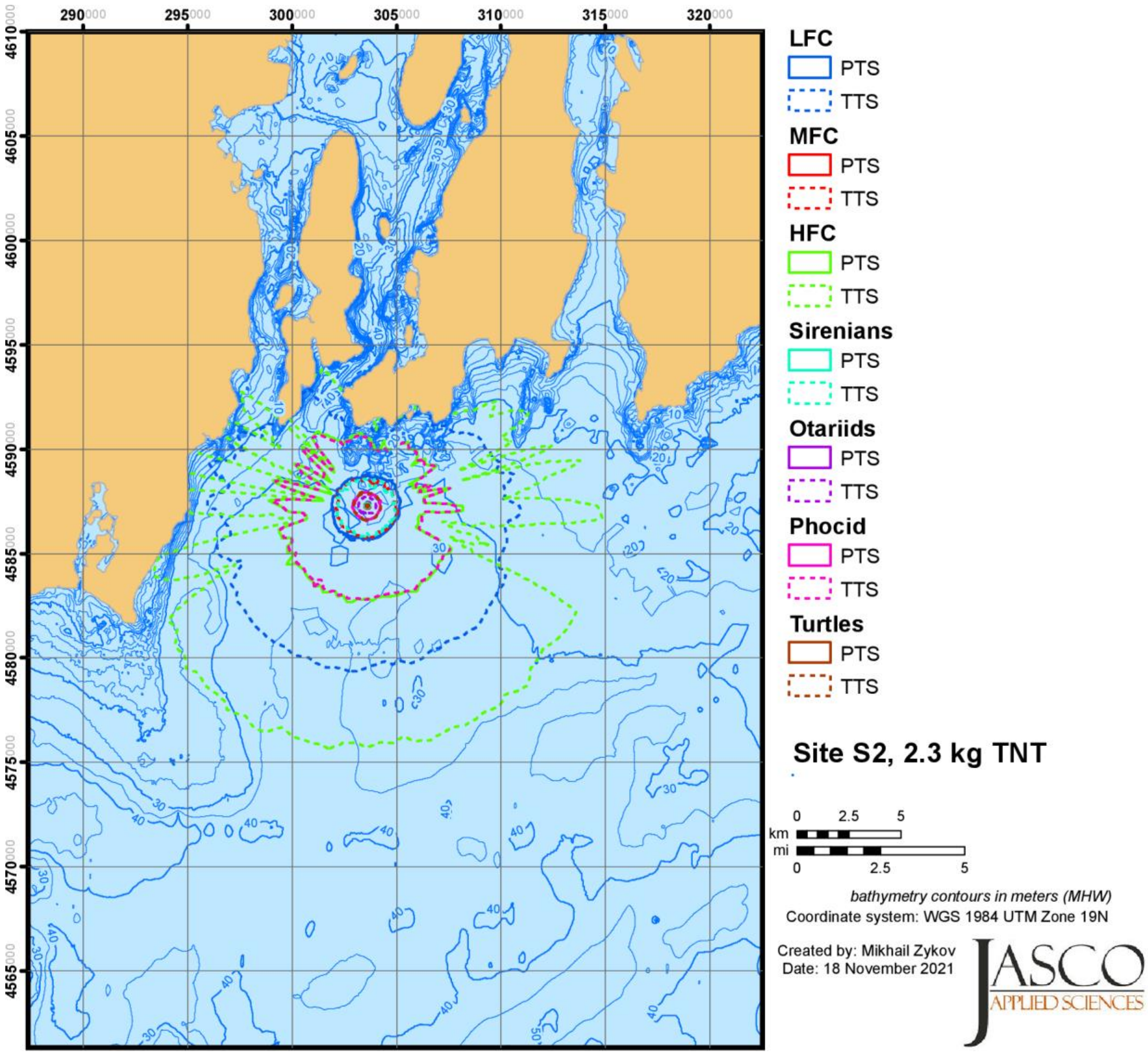

Figure A-3. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S2.

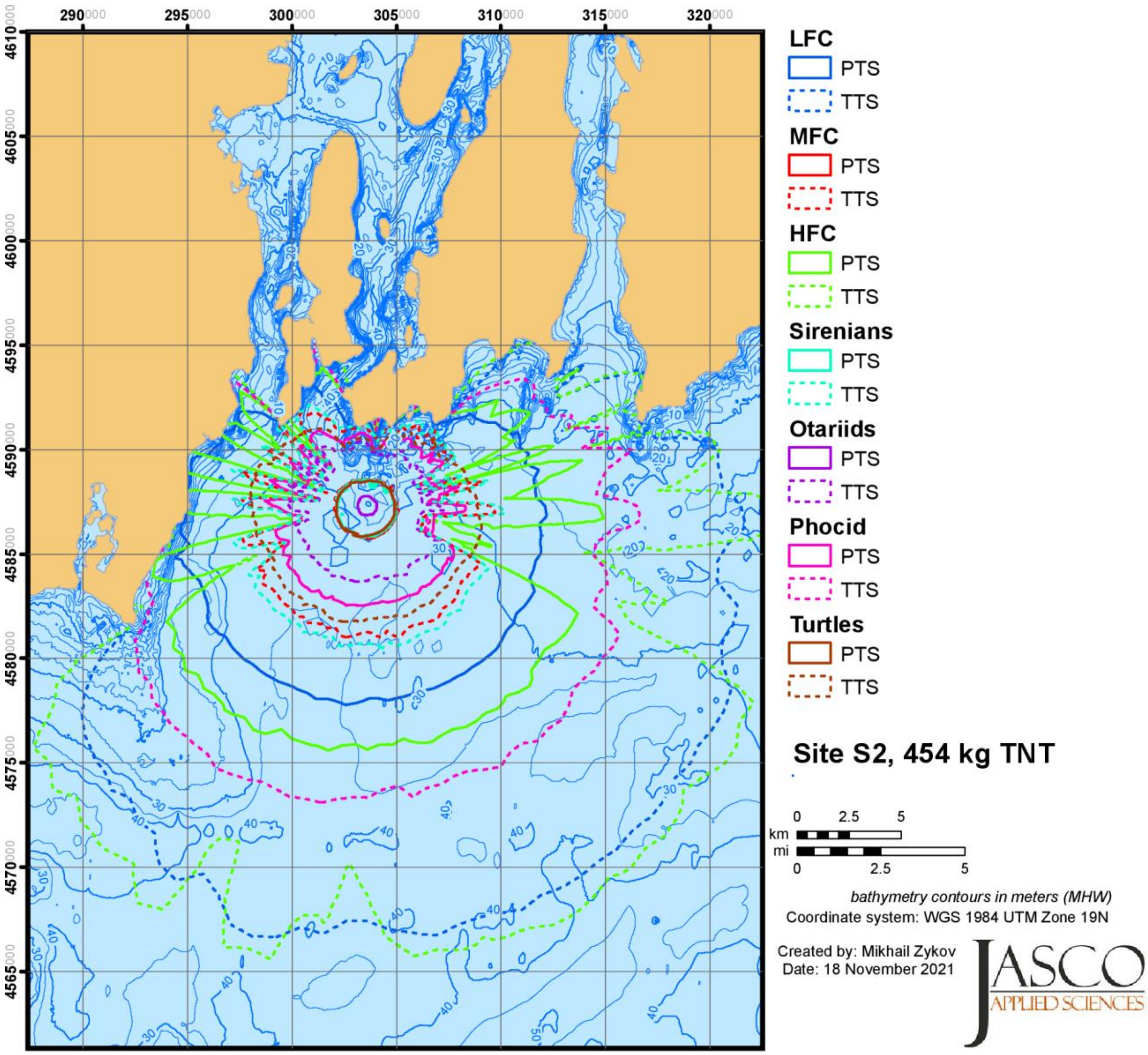

Figure A-4. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S2.

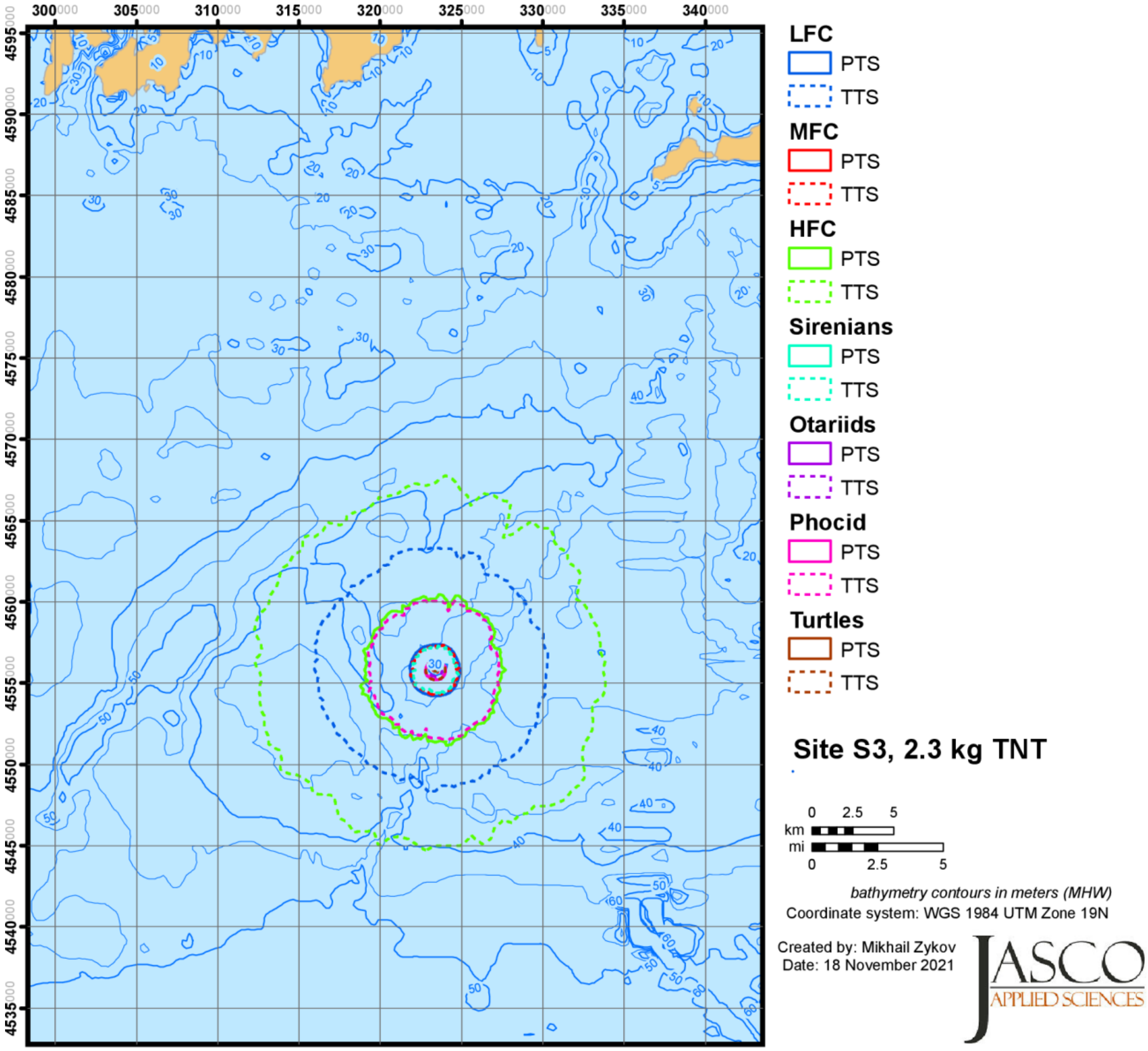

Figure A-5. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S3.

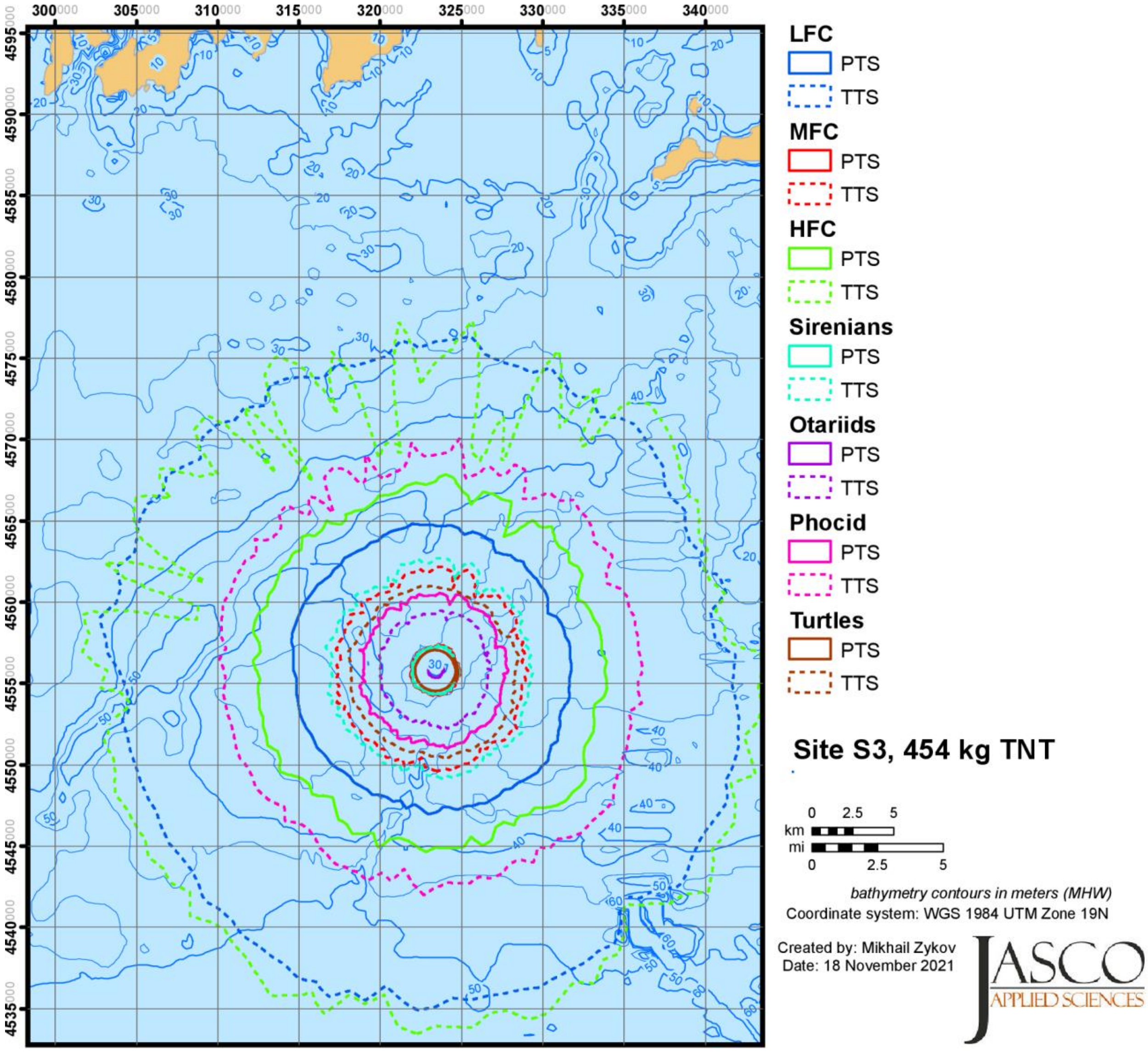

Figure A-6. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S3.

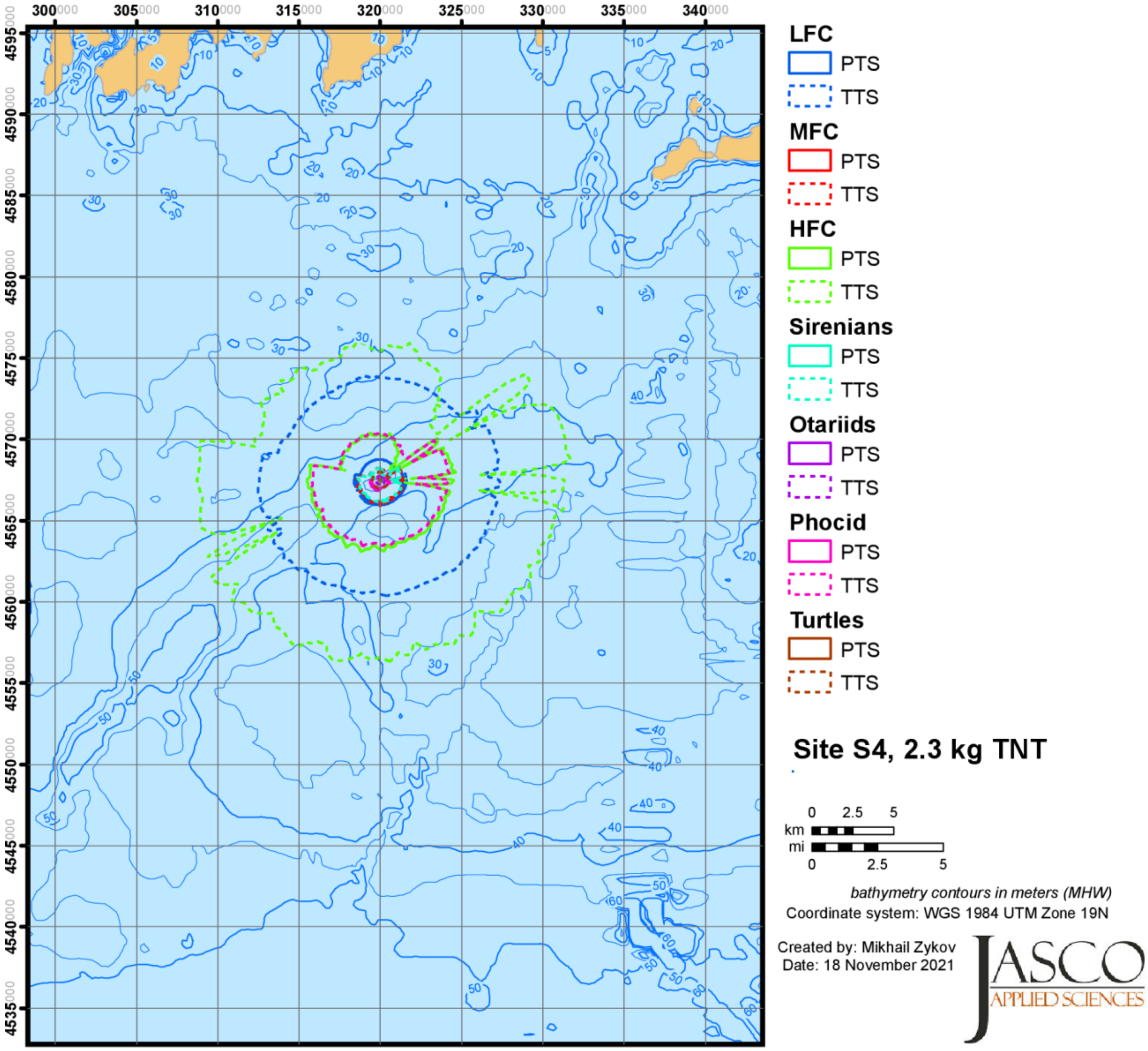

Figure A-7. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S4.

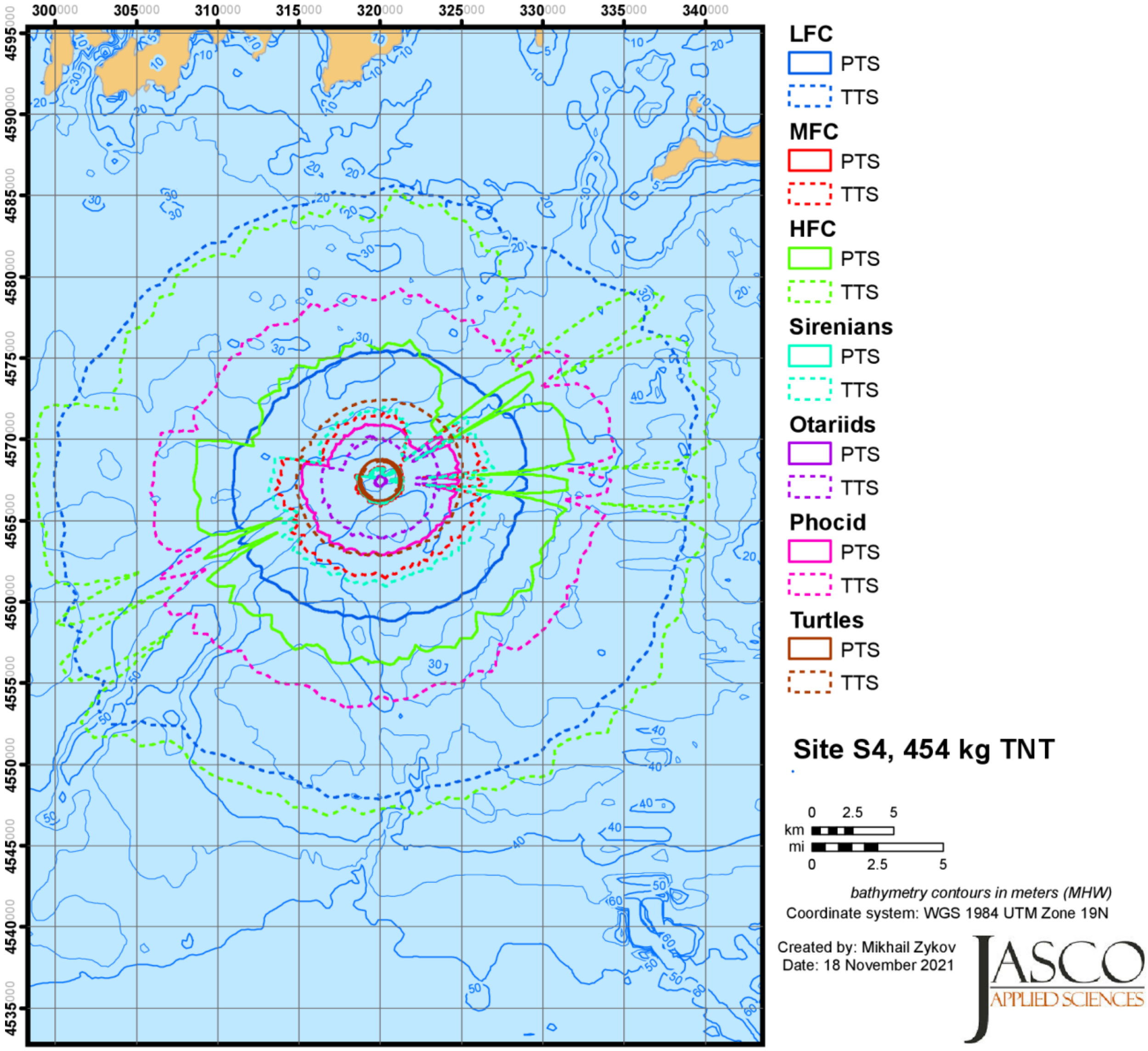

Figure A-8. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S4.