Lillebælt Offshore Wind Farm

Underwater noise prognosis

Geophysical survey

NIRAS A/S

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Executive Summary

European Energy is planning geophysical survey activities in relation to the Lillebælt offshore wind farm (OWF), located in the Lillebælt Strait, Denmark. The investigation area covers the OWF site, as well as the export cable corridor (ECC). Geophysical survey activities generate underwater noise, some of which may affect marine fauna. NIRAS has been tasked with preparation of an underwater noise prognosis for these activities, to act as input for an impact assessment for marine mammals.

Ambient underwater noise levels

The ambient underwater noise levels for the project area and surroundings were examined based on available models and literature. This revealed underwater noise levels below $SPL_{rms} 90\ dB\ re. 1\mu Pa$, with the highest noise levels in the southeastern part of the project area. Compared to more open and trafficked waters, the ambient noise level is considered low. The primary sources for the ambient noise level are assumed to be shipping and fishing vessels, based on the vessel density map examined.

Underwater noise from geophysical activities

The potential for underwater noise impact was evaluated for the proposed geophysical survey activities:

1. Multibeam echosounder (MBES),
2. side scan sonar (SSS),
3. sub-bottom profiler (SBP),
4. sparker (3D UHRS),
5. Seismic refraction (SR) using a mini airgun,
6. Ultra Short Baseline (USBL) (positioning system),
7. Magnetometer.

The survey programme also includes gradiometer and drones, however those are considered without impact regarding underwater noise emission and are not considered further in this report. Underwater noise emission from the survey vessels was also evaluated.

The survey programme divides the equipment into 5 different survey types, within three sub-areas, see Table 1.1 and explanation in section 2.1.

Table 1.1: Overview of survey activities in the different sub-areas with identifiers for each combination to act as a reference for the impact ranges, where (1) Hydrographic surveys include MBES, SSS, SBP, MAG and USBL; (2) 3D UHRS surveys include sparkers, (3) UXO surveys include MAG and USBL, and (4) Refraction seismic includes mini airguns.

Site	**Survey type**			
	Hydrographic (1)	3D UHRS (2)	UXO survey (3)	Refraction seismic (4)
Offshore (A)	1A	2A	3A	
Near-to-offshore (B)	1B		3B	4B
Nearshore (C)	1C		3C	4C

The acoustic impact of the activities: MBES, SSS and magnetometer, was assessed based on available literature, while underwater sound propagation modelling was undertaken for the SBP, 3D UHRS, SR and USBL equipment types.

A 3D acoustic environmental model was created in QGIS and NIRAS TRANSMIT (NIRAS proprietary MATLAB toolbox), based on available online data sources, as well as client input, implementing environmental inputs for bathymetry, sediment, salinity, temperature, and sound speed.

Historical hydrographic conditions were examined for the months of April – August, corresponding to the intended survey window, and April was found to represent the worst-case scenario, in terms of lowest sound propagation loss over distance in all model positions.

Underwater sound propagation modelling was conducted for SBP, 3D UHRS, SR and USBL equipment types, in dBSea 2.4.12, using dBseaPE (for the SR source), and using dBSeaRay for all other sources. Both algorithms are Nx2D propagation models, using a 3D environmental model and respective source models as input. Sound propagation was calculated from four source positions (1 – 4) in a 25 x 0.5 m range-depth grid in 180 directions from each source position (2° resolution). Resulting sound propagation losses were processed in NIRAS SILENCE (NIRAS proprietary MATLAB toolbox) to determine impact ranges to relevant marine mammal threshold criteria.

For marine mammals, threshold criteria include hearing loss (threshold shift), resulting from cumulative underwater noise exposure, as well as instantaneous behavioural reaction resulting from a sudden change in the experienced noise level. A noise induced threshold shift is a temporary (TTS) or permanent (PTS) reduction in hearing sensitivity, following exposure to a high cumulative noise dose. The level of injury depends on both the intensity and duration of noise exposure. Small levels of TTS will disappear in a matter of minutes or hours, whereas more severe levels of TTS can last for days. At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a smaller or larger amount of PTS. An initial TTS of 40 dB or higher is generally considered to constitute a significantly increased risk of developing PTS (NOAA, 2018). Behavioural reaction on the other hand is linked to the instantaneous change in sound level, causing a reaction, such as avoidance or change in behaviour. Marine mammals included in the prognosis are harbour porpoise (*Phocoena phocoena*) and seal. For harbour porpoise, PTS, TTS, and behaviour criteria are included, while only PTS and TTS criteria are included for seal.

Impact ranges for harbour porpoise were studied for all combinations of equipment and positions, to investigate the impact on nearby Natura 2000 areas, for which harbour porpoise is appointed. For seal, which is not appointed at any of the Natura 2000 areas, representative worst-case calculations were conducted using a single source position per equipment type. The positions chosen for seal represent those with the strongest sound propagation, and thereby most conservative impact ranges.

Impact ranges for PTS and TTS describe the minimum distance from the source a marine mammal must at least be, prior to onset of survey activities, to avoid the respective impact. It therefore does not represent a constant distance the animals must maintain, but a safe starting distance, beyond which the threshold criteria are unlikely to be exceeded. For harbour porpoise and seal, fleeing behaviour of 1.5 ms^{-1} is included.

Impact ranges for behaviour, describes the specific distance, up to which, the behavioural threshold criterion is likely to be exceeded, when survey activities are operating at maximum intensity. It therefore acts as a constant deterrence throughout the survey activities.

The impact ranges for each of the relevant threshold criteria, are listed in Table 1.2 for harbour porpoise, and in Table 1.3 for seals.

Table 1.2: Impact ranges for very high-frequency cetaceans (harbour porpoise).

Activity and activity ID	Position	Impact range for harbour porpoise threshold criteria				
		Impulsive* criteria			Non-impulsive* criteria	
		$L_{E,cum,24h,1.5ms^{-1},VHF}$ $[dB\ re\ 1\mu Pa^2 s]$		$L_{p,rms,125ms,VHF}$ $[dB\ re\ 1\mu Pa]$	$L_{E,cum,24h,1.5ms^{-1},VHF}$ $[dB\ re\ 1\mu Pa^2 s]$	
		PTS 155 dB	TTS 140 dB	Behaviour# 103 dB	PTS 173 dB	TTS 153 dB
Sparker (2A) Model: Duraspark 400 Method: Numerical model Month: April Distances relative to towed equipment	1	60 - 200 m	300 - 950 m	0.95 - 1.3 km	-	-
	2	50 - 180 m	350 - 950 m	1.1 - 1.4 km	-	-
SBP (1A,1B,1C) Model: Innomar Medium 100 Method: Numerical model Month: April Distances relative to vessel	1	-	-	0.7 - 1.1 km	< 25 m	180 - 650 m
	2	-	-	0.9 - 1.1 km	< 25 m	180 - 550 m
	3	-	-	0.8 - 1.1 km	< 25 m	170 - 550 m
	4	-	-	450 - 800 m	25 - 50 m	120 - 450 m
USBL transceiver 1 (offshore) (1A,3A) Model: Kongsberg HiPaP 352P Method: Numerical model Month: April Distances relative to vessel and tow	1	-	-	1.7 - 2.5 km	25 - 70 m	300 - 850 m
	2	-	-	1.8 - 2.3 km	25 - 70 m	350 - 850 m
USBL transceiver 2 (nearshore) (1B,1C,3B,3C) Model: Easytrak Nexus 2 Method: Numerical model Month: April Distances relative to vessel and tow	3	-	-	1.6 - 2.2 km	25 - 110 m	350 - 900 m
	4	-	-	0.45 - 4.4 km	50 - 110 m	0.25 - 1.2 km
Seismic Refraction – mini airgun (4B,4C) Model: Mini G SODERA 20 cu. In. Method: Numerical model Month: April Distances relative to towed equipment	3	< 25 m	< 25 m	130 - 160 m	-	-
	4	< 25 m	< 25 m	90 - 180 m	-	-

*: Based on the equipment sound source characteristics, either impulsive or non-impulsive impact ranges are calculated.
#: Behaviour criterion is calculated for both impulsive and non-impulsive source types, however the threshold criterion is only supported in literature for impulsive source types and should therefore be considered with caution for non-impulsive sources.

The maximum Impact ranges for harbour porpoise behaviour threshold criterion is up to 4.4 km, however in a limited number of directions, when using the USBL system “Easytrak Nexus 2” at maximum source level. This equipment type is active in activities 1B, 1C, 3B and 3C (see section 2.1 for further explanation of activity ID). For activities 1A and 3A, a maximum impact range for the behavioural threshold is 2.5 km, also resulting from the use of USBL. For activity 2A, the sparker is the only active source, and results in a maximum impact range of 1.4 km. For activity 4B and 4C, the impact range is limited to 180 m, primarily due to the very low-frequent nature of the mini airgun used in this activity. It should be noted that the behaviour criterion is only considered valid for impulsive noise sources (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021), however, as no threshold criteria have been established by science for non-impulsive sources, the impulsive criterion is used as a conservative proxy.

Impact ranges for harbour porpoise PTS are limited to 200 m for the 3D UHRS survey (2A) and is below 200 m for all other survey activities, while TTS impact ranges extend to 1.2 km in the worst case, resulting from use of USBL in activities 1B, 1C, 3B and 3C. For activity 1A and 3A this is reduced to 850 m, also from using USBL. For the 3D UHRS survey (2A) a TTS impact range of up to 950 m is observed.

Table 1.3: Impact ranges for phocid carnivores (seals).

Activity	**Position**	**Impact range for seal threshold criteria**			
		Impulsive* criteria		Non-impulsive* criteria	
		$L_{E,cum,24h,1.5ms^{-1},PCW}$ $[dB\ re\ 1\mu Pa^2 s]$		$L_{E,cum,24h,1.5ms^{-1},PCW}$ $[dB\ re\ 1\mu Pa^2 s]$	
		PTS 185 dB	TTS 170 dB	PTS 201 dB	TTS 181 dB
Sparker (2A) Model: Duraspark 400 Method: Numerical model Month: April Distances relative to towed equipment	1	< 25 m	50 - 150 m	-	-
SBP (1A,1B,1C) Model: Innomar Medium 100 Method: Numerical model Month: April Distances relative to vessel	1	-	-	< 25 m	< 25 m
USBL transceiver 2 (nearshore) (1B,1C,3B,3C) Model: Easytrak Nexus 2 Method: Numerical model Month: April Distances relative to vessel and tow	4	-	-	< 25 m	< 25 m
Seismic Refraction – mini airgun (4B,4C) Model: Mini G SODERA 20 cu. In. Method: Numerical model Month: April Distances relative to towed equipment	4	< 25 m	< 25 m	-	-

*: Based on the equipment sound source characteristics, either impulsive or non-impulsive impact ranges are calculated. For “All sources active”, both impulsive and non-impulsive impact ranges are evaluated from the respective types of equipment.

The impact ranges for seal, are less than 25 m for all thresholds, except for TTS during the 3D UHRS survey, with a maximum impact range of 150 m. This is due to the sparker system which emits sound in the frequency range where seals are sensitive to sound.

Contents

List of abbreviations

Full name	Abbreviation	Symbol
Sound Exposure Level	SEL	$L_{E,p}$
Cumulative Sound Exposure Level	$SEL_{cum,t}$	$L_{E,cum,t}$
Sound Exposure Level - single pile strike	SEL_{SS}	L_{E100}
Sound Pressure Level	SPL	L_p
Source Level at 1 m	SL	L_S
Sound exposure source level at 1 m	ESL	$L_{S,E}$
Permanent Threshold Shift	PTS	
Temporary Threshold Shift	TTS	
National Oceanographic and Atmospheric Administration	NOAA	
Offshore Wind farm	OWF	
Low frequency	LF	
High frequency	HF	
Very High frequency	VHF	
Phocid Pinniped	PCW	
World Ocean Atlas 2023	WOA23	
Sound Exposure Propagation loss	EPL	
National Marine Fisheries Service	NMFS	
Maximum-over-depth	MOD	
Ultra-short Baseline	USBL	
Sub-bottom profiler	SBP	
MultiBeam Echosounder	MBES	
Side Scan Sonar	SSS	
Unexploded Ordnance	UXO	
Seismic refraction	SR	

1. Introduction and objectives

European Energy is planning geophysical survey activities in relation to the Lillebælt offshore wind farm (OWF), located in the Lillebælt Strait, Denmark. The investigation area covers the OWF site, as well as the export cable corridor (ECC). NIRAS has been tasked with preparation of an underwater noise prognosis for the geophysical survey activities, as input for an environmental impact assessment for marine mammals. The report also includes a description of the ambient underwater noise and vessel density based on available literature. The report is structured as outlined below.

Chapter	Content
2	Project description
3	Definitions: A brief introduction to terms and metrics used throughout the report
4	Marine mammal and fish threshold criteria for auditory impact
5	Ambient underwater noise study
6	Underwater noise prognosis for geophysical survey

2. Project description

Lillebælt OWF is in the Lillebælt Strait, Denmark, 3 km northeast of the island of Als. The survey area (Figure 2.1) covers approximately 23 km^2.

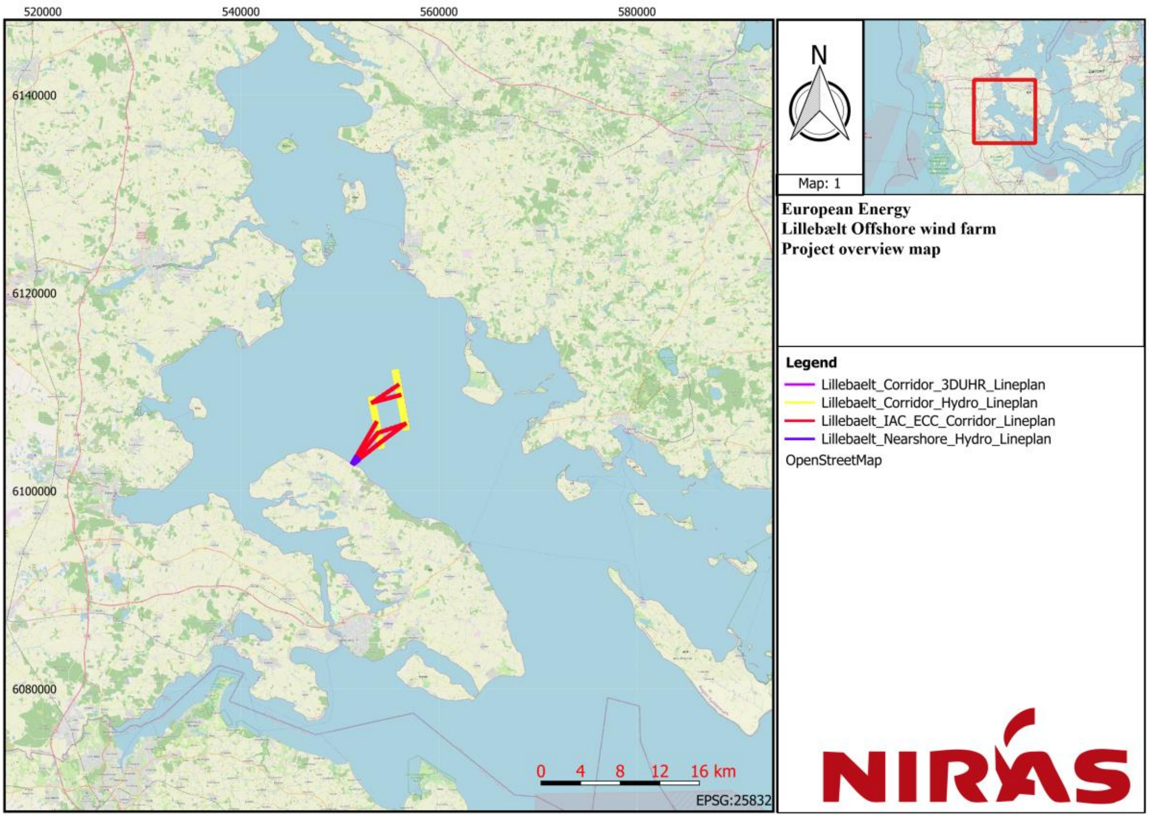

Figure 2.1: Overview of the Lillebælt OWF survey area. Note that the purple lines are not visible as they fully overlap with the yellow lines.

2.1. Description of Activities

Underwater noise emission is expected to occur because of the geophysical survey activities, where the physical properties of the seabed within the OWF site, as well as the inter array cable (IAC) corridor and in the export cable corridor (ECC) are investigated.

Geophysical investigations are typically characterised by non-invasive acoustic techniques. By analysing the reflections of sound waves emitted towards the seafloor and sediment layers, the sediment layer composition, as well as pockets of natural resources, can be determined. Investigations that map the bathymetry and objects on or imbedded in the seabed, such as unexploded ordnance (UXO), are also considered part of the geophysical investigations.

The investigation programme consists of five different survey types:

1. Hydrographic survey, including the use of:
    a. sub-bottom profilers (SBP),
    b. multi beam echosounders (MBES),
    c. side scan sonars (SSS)
    d. magnetometers (MAG)
    e. ultra short baseline (USBL) - positioning system used for towed objects.
2. 3D UHRS survey, including the use of:
    a. Sparkers
3. UXO survey, including the use of:
    a. Magnetometers (MAG)
    b. USBL
4. Refraction seismic survey, including the use of:
    a. Mini airgun
5. Drones
    a. No underwater acoustic emission

The survey area is divided into three different sub-areas:

A. The offshore area covering the wind turbine generators (WTG), see yellow lines in Figure 2.1
B. The near-to-offshore area covering the ECC and shallow WTGs, see red lines west of the WTG area in Figure 2.1
C. The nearshore area shown in purple in Figure 2.1

In Table 2.1, the acoustic survey types (1 – 4) planned for each area are shown for the different sub-areas (A-C).

Table 2.1: Overview of survey activities in the different sub-areas with identifiers for each combination to act as a reference for the impact ranges, where (1) Hydrographic surveys include MBES, SSS, SBP, MAG and USBL; (2) 3D UHRS surveys include sparkers, (3) UXO surveys include MAG and USBL, and (4) Refraction seismic includes mini airguns.

Site	**Survey type**			
	Hydrographic (1)	3D UHRS (2)	UXO survey (3)	Refraction seismic (4)
Offshore (A)	1A	2A	3A	
Near-to-offshore (B)	1B		3B	4B
Nearshore (C)	1C		3C	4C

3. Definitions

Acoustic metrics and relevant terms used in the report are defined in this chapter. Terminology follows ISO standard 18405 (DS/ISO 18405, 2017), however with a few exceptions as outlined in the following.

3.1. Frequency weighting functions

In underwater noise assessments, frequency weighting is often used to reflect the underwater noise impact more accurately on specific marine mammals.

Humans are most sensitive to frequencies in the range of 2 kHz - 5 kHz and for frequencies outside this range, the sensitivity decreases. This frequency-dependent sensitivity correlates to a weighting function, for the human auditory system it is called A-weighting. For marine mammals the same principle applies through the weighting function, W(f), defined through Equation 1 (NOAA, 2018).

$$W(f) = C + 10 * \log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right) \text{[dB]} \qquad \text{Equation 1}$$

Where:

- **a** is describing how much the weighting function amplitude is decreasing for the lower frequencies.
- **b** is describing how much the weighting function amplitude is decreasing for the higher frequencies.
- $\mathbf{f_1}$ is the frequency at which the weighting function amplitude begins to decrease at the lower frequencies [kHz]
- $\mathbf{f_2}$ is the frequency at which the weighting function amplitude begins to decrease at the higher frequencies [kHz]
- **C** is the function gain [dB].

For an illustration of the parameters see Figure 3.1.

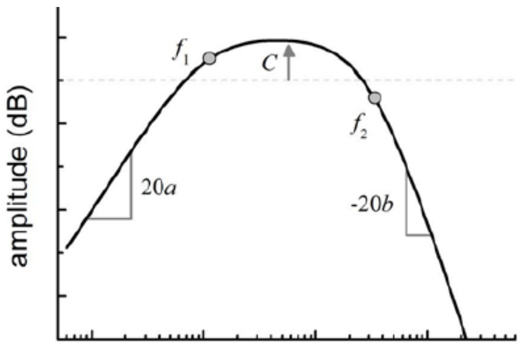

Figure 3.1: Illustration of the 5 parameters in the weighting function (NOAA, 2018).

Marine mammals are divided into four hearing groups, in regard to their frequency specific hearing sensitivities: 1) Low-frequency (**LF**) cetaceans, 2) High-frequency (**HF**) cetaceans, 3) Very High-frequency (**VHF**) cetaceans, 4) and Phocid Carnivores in Water (**PCW**) (NOAA, 2018; Southall, et al., 2019). The parameters in *Equation 1* are defined for the hearing groups and the values are presented in Table 3.1.

Table 3.1: Parameters for the weighting function for the relevant hearing groups (NOAA, 2018).

Hearing Group	a	b	f_1 [kHz]	f_2 [kHz]	C [dB]
Low frequency (LF) Cetaceans	1.0	2	0.2	19	0.13
High frequency (HF) Cetaceans	1.6	2	8.8	110	1.20
Very high frequency (VHF) Cetaceans	1.8	2	12	140	1.36
Phocid Carnivores in Water (PCW)	1.0	2	1.9	30	0.75

The weighting function amplitude for the four hearing groups is achieved by inserting the values from Table 3.1 into Equation 1. The resulting spectra for the four hearing groups are shown in Figure 3.2.

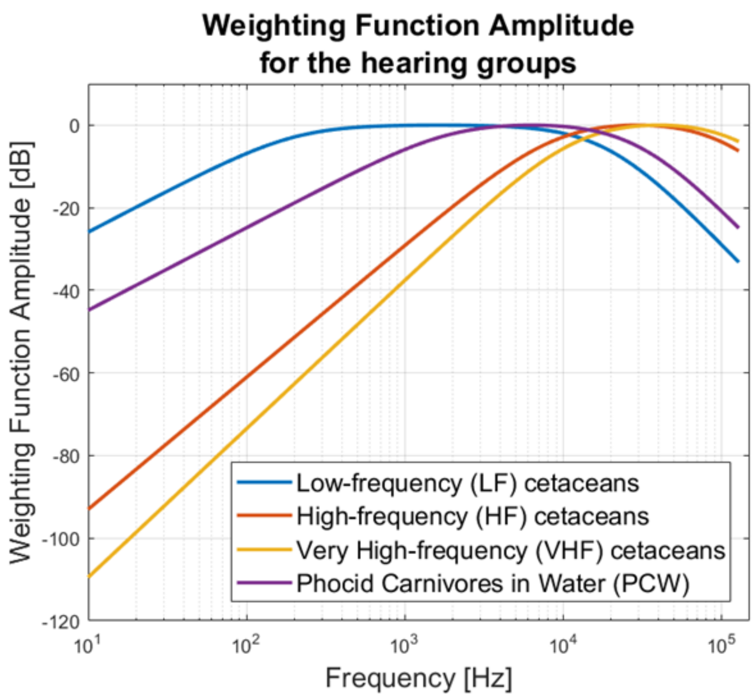

Figure 3.2: The weighting functions for the different hearing groups.

For this project, relevant species only include harbour porpoise (classified as a Very High Frequency Cetacean (VHF)) and seals (PCW).

3.2. Sound Pressure Level

The Sound Pressure Level (SPL), L_p, is used to describe the noise level. The definition for SPL is shown in Equation 2 (Erbe, 2011):

$$L_p = 20 * \log_{10}\left(\sqrt{\left(\frac{1}{T}\right)\int_0^T p(t)^2}\right) \quad [\text{dB re. } 1\mu\text{Pa}]$$ Equation 2

Where p is the acoustic pressure of the noise signal during the time of interest, and T is the total time. L_p is the average unweighted SPL over a measured period.

For ambient underwater noise and for operational underwater noise, L_p is the preferred metric.

To evaluate the behavioural response of the marine mammal a time window is needed. Often, a fixed time window of 125 ms. is used due to the integration time of the ear of mammals (Tougaard & Beedholm, Practical implementation of auditory time and frequency weighting in marine bioacoustics, 2018). The metric is then referred to as $L_{p,125ms}$ and the definition is shown in Equation 3 (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021).

$$L_{p,125ms} = L_{E,p} - 10 * \log_{10}(0.125) = L_{E,p} + 9 \text{ dB} \quad [\text{dB re. } 1\mu\text{Pa}]$$ Equation 3

Where $L_{E,p}$ is the sound exposure level, which are explained in the next section. When considering the threshold for specific marine mammal species, the terminology is $L_{p,125ms,w}$, where "w" denotes the species-specific weighting.

3.3. Sound Exposure Level

The Sound Exposure Level (SEL), $L_{E,p}$, describes the total energy of a noise event (Jacobsen & Juhl, 2013). A noise event can for instance be the duration of an entire survey from start to end, or it can be a single noise event like an airgun pulse. The SEL is normalized to 1 second and is defined in (Martin, Morris, & O'Neill, 2019) through Equation 4.

$$L_{E,p} = 10 * \log_{10}\left(\frac{1}{T_0 p_0^2} \int_0^T p^2(t)\right) \quad [\text{dB re. } 1\mu\text{Pa}^2\text{s}]$$ Equation 4

Where T_0 is 1 second, 0 is the starting time and T is end time of the noise event, p is the pressure, and p_0 is the reference sound pressure which is 1 μPa.

The relationship between SPL, Equation 2, and SEL, *Equation 4*, is given by *Equation 5* (Erbe, 2011).

$$L_{E,p} = L_p + 10 * \log_{10}(T)$$ Equation 5

When SEL is used to describe the sum of noise from more than a single event/pulse, the term Cumulative SEL, $(SEL_{cum,t})$, $L_{E,cum,t}$, is used, while the SEL for a single event/pulse, is the single-strike SEL (SEL_{SS}), L_{E100}. The SEL_{SS} is calculated on the base of 100% pulse energy over the pulse duration.

Marine mammals can incur hearing loss, either temporarily or permanently because of exposure to high noise levels. The level of injury depends on both the intensity and duration of noise exposure. SEL is therefore a commonly used metric to assess the risk of hearing impairment because of noisy activities (Martin, Morris, & O'Neill, 2019).

3.4. Cumulative Sound Exposure level

For moving sources in combination with moving receivers, the $L_{E,cum,t}$ is calculated using the approach presented in (Tougaard, Input to revision of guidelines regarding underwater noise from oil and gas activities - effects on marine mammals and mitigation measures., 2016). The survey vessel speed, and its direction relative to a moving receiver is used to calculate the $L_{E,cum,t}$ for a given receiver. In Equation 6, the distance between the source and receiver at the i^{th} pulse, r_i, is given for a specific piece of survey equipment. This is based on a starting position of the marine mammal relative to the source, defined by the on-axis distance, l_0, corresponding to the transect line, and the off-axis distance, d_0, corresponding to the perpendicular distance from the transect line. Δt_i is the time in seconds between the first pulse and the i^{th} while v_{ship} and $v_{receiver}$ is the ship and receiver moving speed respectively, in m/s.

$$r_i = \sqrt{\left(l_0 - ((i-1) \cdot \Delta t_i) \cdot v_{ship}\right)^2 + (d_0 + ((i-1) \cdot \Delta t_i) \cdot v_{receiver})^2}$$ Equation 6

By summing the pulses from the entire survey, within a 24h window, given the propagation loss for the survey area, Equation 7 gives the resulting $L_{E,cum,24h}$.

$$L_{E,cum,24h} = 10 * \log_{10}\left(\sum_{i=1}^{N} 10^{\left(\frac{L_{S,E} - X*\log_{10}(r_i) - A*(r_i)}{10}\right)}\right) \qquad \text{Equation 7}$$

Where N is the total number of pulses for that piece of survey equipment, $L_{S,E}$ is the source level at 1 m distance, X and A describe the sound exposure propagation losses (EPL), $N_{PL,E}$, for the specific project site. For surveys using multiple equipment types, the contribution from each source is first normalized into 1 sec. SEL based on firing frequency, and then added.

To differentiate between different marine species, and differences in swim speed, the species specific received cumulative SEL in this report is denoted $L_{E,cum,t,v_f,w}$ where "w" is the frequency weighting, currently only relevant for marine mammals, see section 3.1.

The parameters used in Equation 6 and Equation 7, related to the source level, firing frequency, movement speed and source direction must be based on best available knowledge. The EPL parameters (X and A) must be determined through advanced sound propagation modelling, in which all relevant site-specific environmental parameters are considered.

3.5. Source level

Two representations for the acoustic output of a sound emitting source are used in this report, namely Source Level (SL), L_S, and the sound exposure source level (ESL), $L_{S,E}$.

SL is defined for a continuous source as the SPL_{rms} at 1 m from the source with a reference value of $1\ \mu Pa \cdot m$. The metric is used primarily for non-impulsive source types, such as vessels.

ESL is used to describe a transient sound source and is defined as the SEL at 1 m from the source with a reference value of $1\ \mu Pa^2\ m^2\ s$. This is the standard metric used to describe the source level of impulsive noise sources.

4. Underwater Noise Threshold Criteria

In Denmark, underwater noise from geophysical survey activities is handled by the authorities on a project-by-project basis. In order to provide a prognosis of impact, absent official threshold criteria, best available scientific knowledge from (NOAA, 2018), (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021), (Energistyrelsen, 2023) is used in this prognosis.

Two sets of threshold criteria are typically considered in evaluating the impact of underwater noise, based on the impulsiveness of the noise source. Following the definition of impulsive vs. non-impulsive noise sources in (NOAA, 2018), the terms are considered as follows:

- Impulsive: Sounds that are typically transient, brief (duration < 1 s), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay.
- Non-impulsive: Sounds that are broadband, narrowband, or tonal, brief, or prolonged, continuous, or intermittent, and typically do not have a high peak sound pressure with rapid rise nor decay time.

For geophysical survey activities, it is not always clear if a source behaviour is impulsive or non-impulsive. While equipment types, such as airguns and explosives are unquestionably impulsive in nature, other types of equipment are non-impulsive, and for some types of equipment, it is not clear whether impulsive or non-impulsive criteria should apply.

The impulsiveness of individual activities is reflected upon in the evaluation of each activity. For cumulative assessment, when all survey equipment is active simultaneously, it is considered likely that non-impulsive threshold criteria are more suitable than impulsive threshold criteria, which may be overly conservative. If, however, the combined noise emission is dominated heavily by an activity which is clearly defined as impulsive, it would however stand to reason that impulsive threshold criteria might be more appropriate.

4.1. Threshold criteria for marine mammals

Based on the newest scientific literature, species specific frequency weighted $\mathrm{L}_{\mathrm{E,cum,24h},v_f,w}$ threshold values (NOAA, 2018), (Southall, et al., 2019) for TTS and PTS are used, Table 4.1. For avoidance behaviour, $\mathrm{L}_{\mathrm{p,125ms,VHF}} = 103\ \mathrm{dB\ re.\,1\ \mu Pa}$ (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021) is used for harbour porpoise.

Table 4.1: Threshold criteria for marine mammals. PTS and TTS criteria (NOAA, 2018), behaviour criteria (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021) for hearing group classifications in (Southall, et al., 2019). "w" notation refers to species specific weighted levels.

Species (w)	**Swim speed (v_f) [ms^{-1}]**	**Threshold criteria**				
		$L_{E,cum,24h,v_f,w}$ [$dB\ re.1\ \mu Pa^2 s$]				$L_{p,125ms,w}$ [$dB\ re.1\ \mu Pa$]
		PTS		TTS		Behaviour
		Non-impulsive	impulsive	Non-impulsive	Impulsive	
Harbour porpoise (VHF)	1.5 ms^{-1}	173 dB	155 dB	153 dB	140 dB	103 dB
Seals (PCW)	1.5 ms^{-1}	201 dB	185 dB	181 dB	170 dB	-

5. Ambient Underwater Noise Study

Ambient underwater noise soundscapes are rich and complex, shaped by both natural and anthropogenic sources. Naturally occurring sounds include the calls of marine animals, such as porpoise, as well as the sounds of waves, currents, and geological activities like underwater volcanoes and earthquakes. These elements create a dynamic acoustic environment that is essential for communication and navigation among marine species.

On the other hand, anthropogenic sources have increasingly impacted these soundscapes. Shipping traffic, industrial activities, and underwater construction contribute significant noise pollution, often drowning out natural sounds. Understanding these soundscapes is crucial for marine conservation efforts and the health of marine ecosystems. A non-exhaustive overview of ambient underwater noise sources is shown in Figure 5.1.

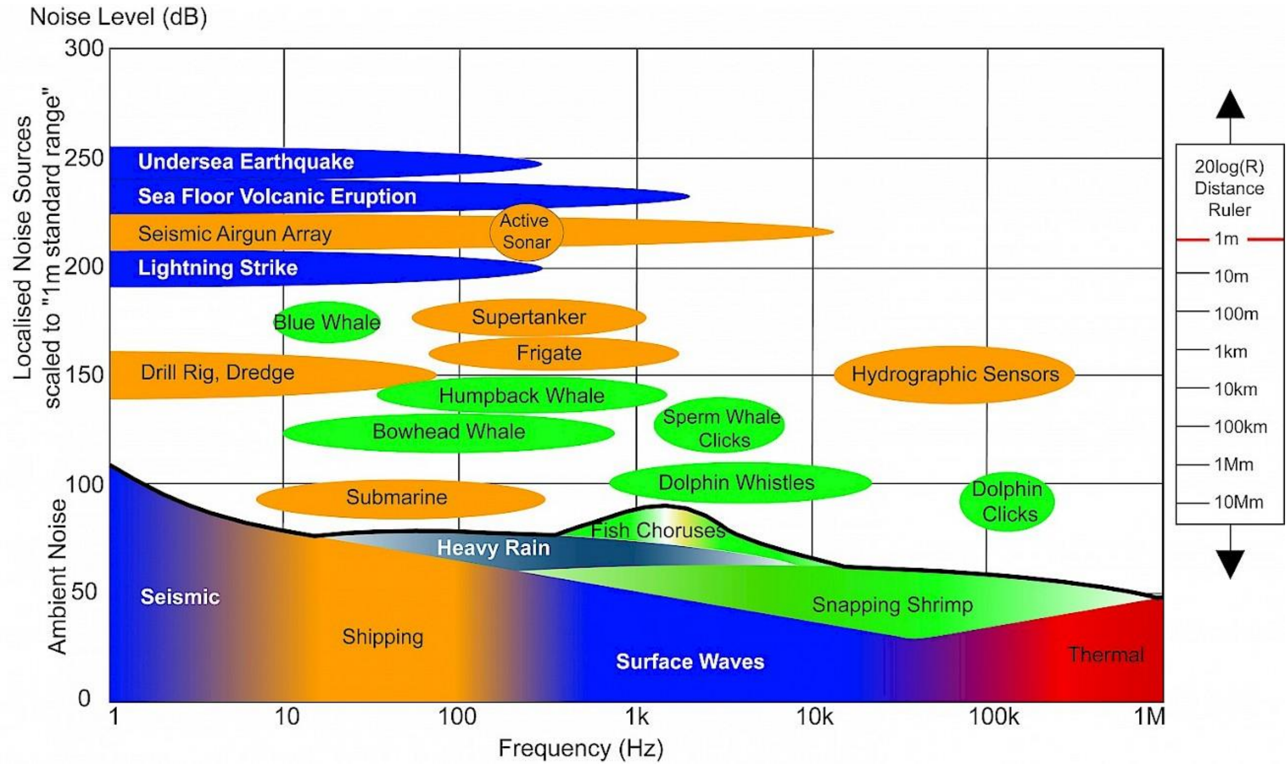

Figure 5.1: Sources of underwater noise in the sea. Source: (OSPAR, 2022).

5.1. Ambient noise level

For the Lillebælt Strait, the ICES continuous underwater noise dataset (ICES, 2018), presents the underwater noise levels in the Baltic Sea as an average for each quarter of 2018 (Q1 – Q4). The noise maps represent a simplified modelled ambient noise level consisting of underwater noise from wind speed and vessel noise (based on AIS data). Noise levels are presented for individual 1/3 octave frequency bands as the median ambient noise level (SPL_{rms}) over all water depths for the quarter.

The available noise levels are limited to three frequency bands of 63, 125 and 500 Hz. The two one-third octave band acoustic measurements centred at 63 and 125 Hz are used as international (European Union Marine Strategy Framework Directive) indicators for underwater ambient noise levels driven by shipping activity (EC Decision 2017/848, 2017). Noise maps for the project area and surroundings are shown in Figure 5.2 - Figure 5.4, for the frequency bands 63 Hz, 125 Hz and 500 Hz respectively. In addition to the 2018 ICES data set, the data portal also features a 2014 data set (ICES, 2014) including a modelled noise map for the frequency band 2 kHz, see Figure 5.5.

The ICES maps show that the ambient noise levels vary with season, and with frequency. The levels at 63 Hz and 125 Hz are higher than those at 500 Hz and 2 kHz. Noise levels also vary by season, with a tendency of higher levels in the colder months/seasons.

the EMODnet vessel density map (EMODnet, CLS, 2022), is shown in Figure 5.6 for the project area and surroundings for the months of February, May, August and November (as representative months for Q1 – Q4). There is no observable correlation between the vessel traffic and ambient noise levels.

It should be noted that the ambient noise level is only modelled for four frequency bands and in averages for the four quarters, making it difficult to compare the impacts on marine life, especially for species with a high frequency hearing like harbour porpoise.

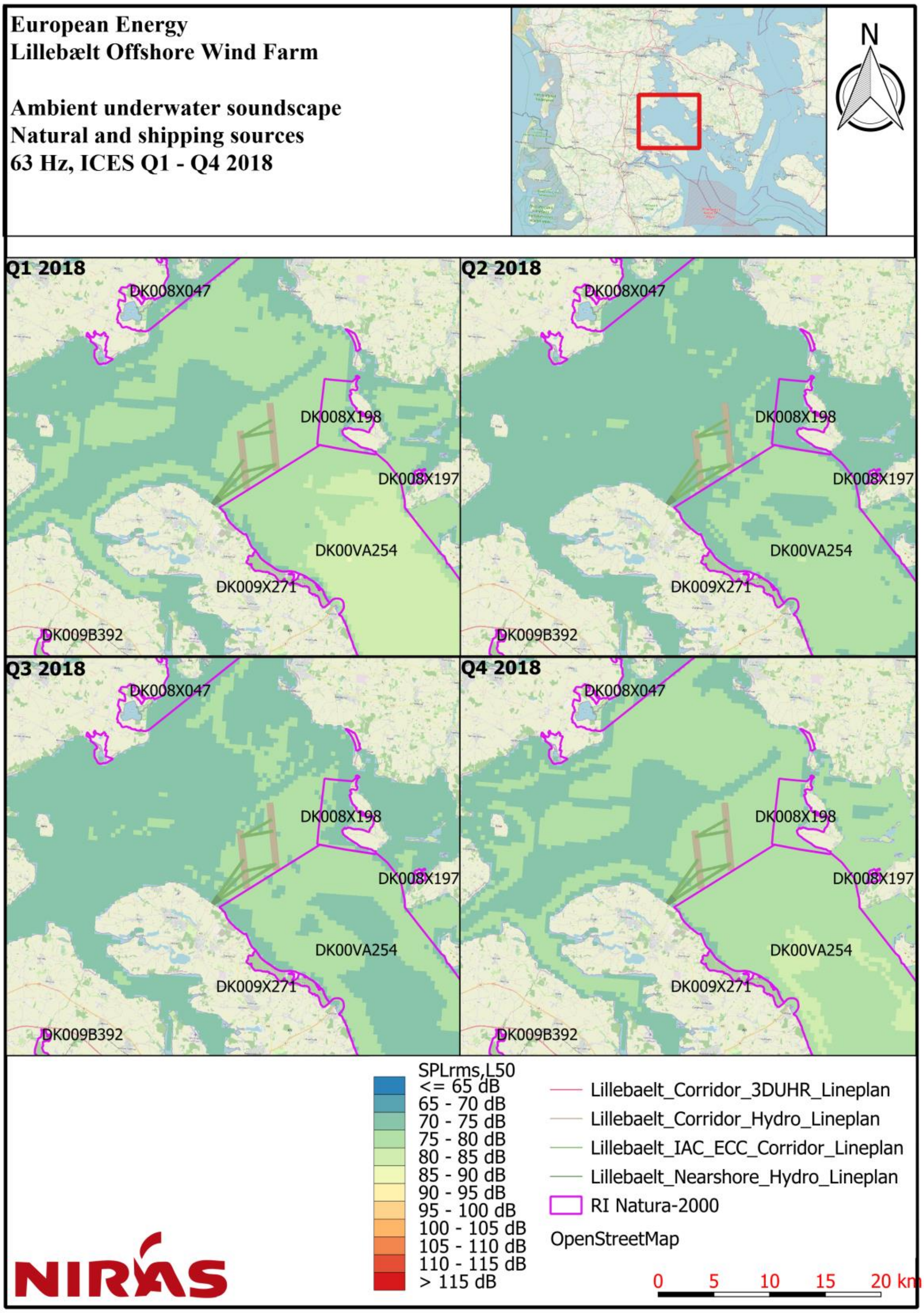

Figure 5.2: ICES soundscape map for 63 Hz, Q1-Q4 2018, 50th percentile $SPL_{rms,63Hz}$ $[dB\ re.1\mu Pa^2]$.

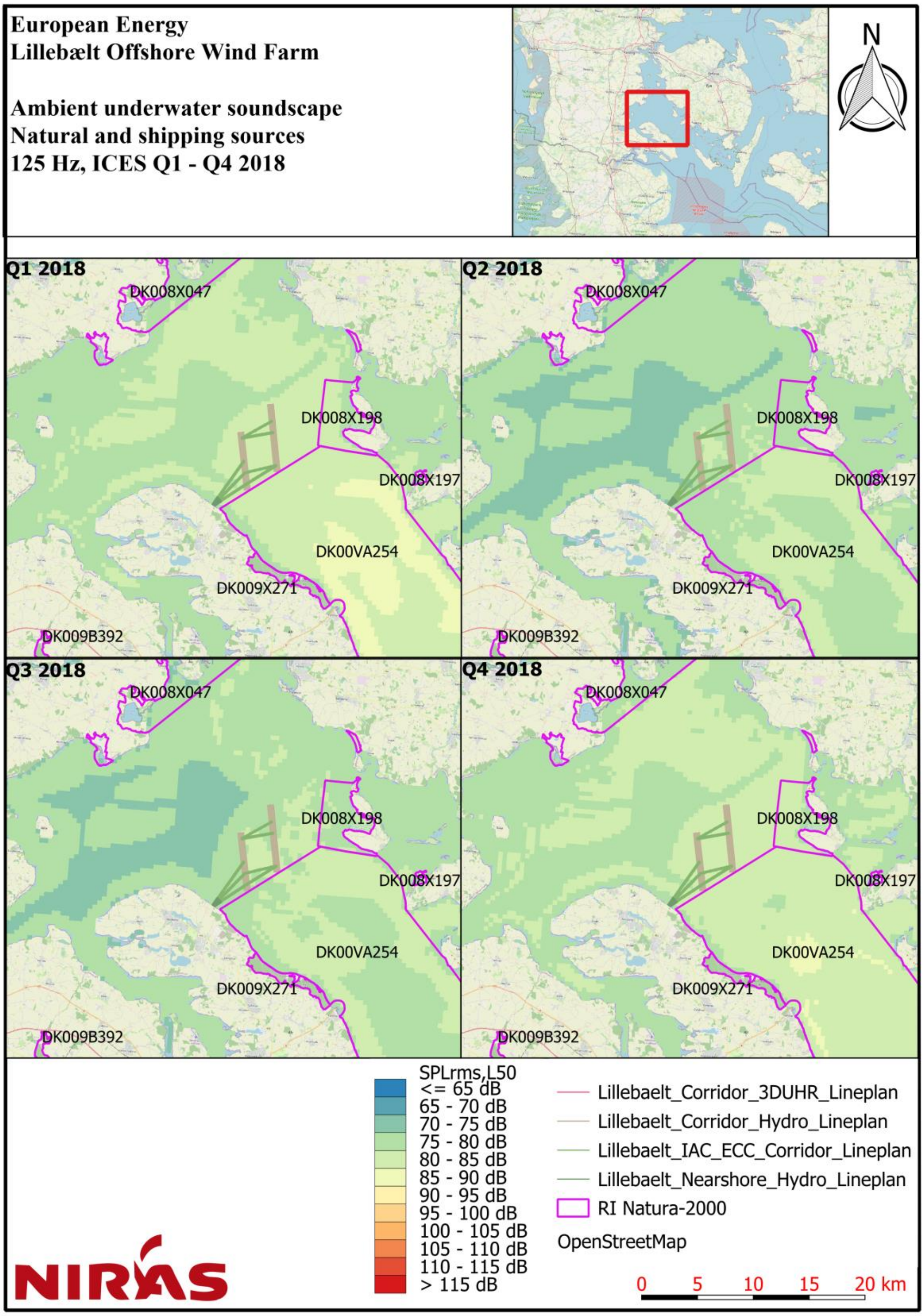

Figure 5.3: ICES soundscape map for 125 Hz, Q1-Q4 2018, 50th percentile $SPL_{rms,125Hz}$ $[dB\ re.1\mu Pa^2]$.

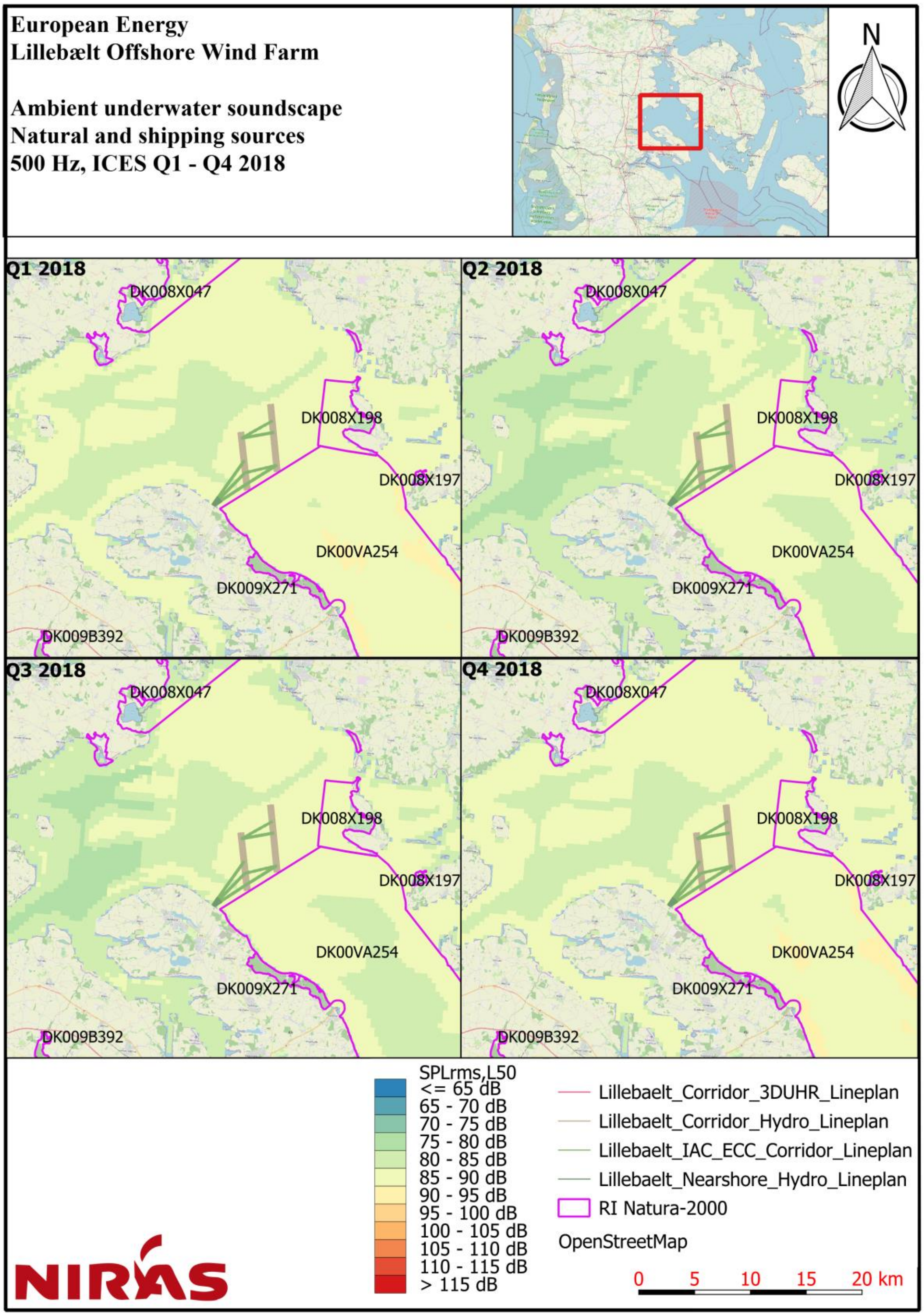

Figure 5.4: ICES soundscape map for 500 Hz, Q1-Q4 2018, 50th percentile $SPL_{rms,500Hz}$ $[dB\ re. 1\mu Pa^2]$.

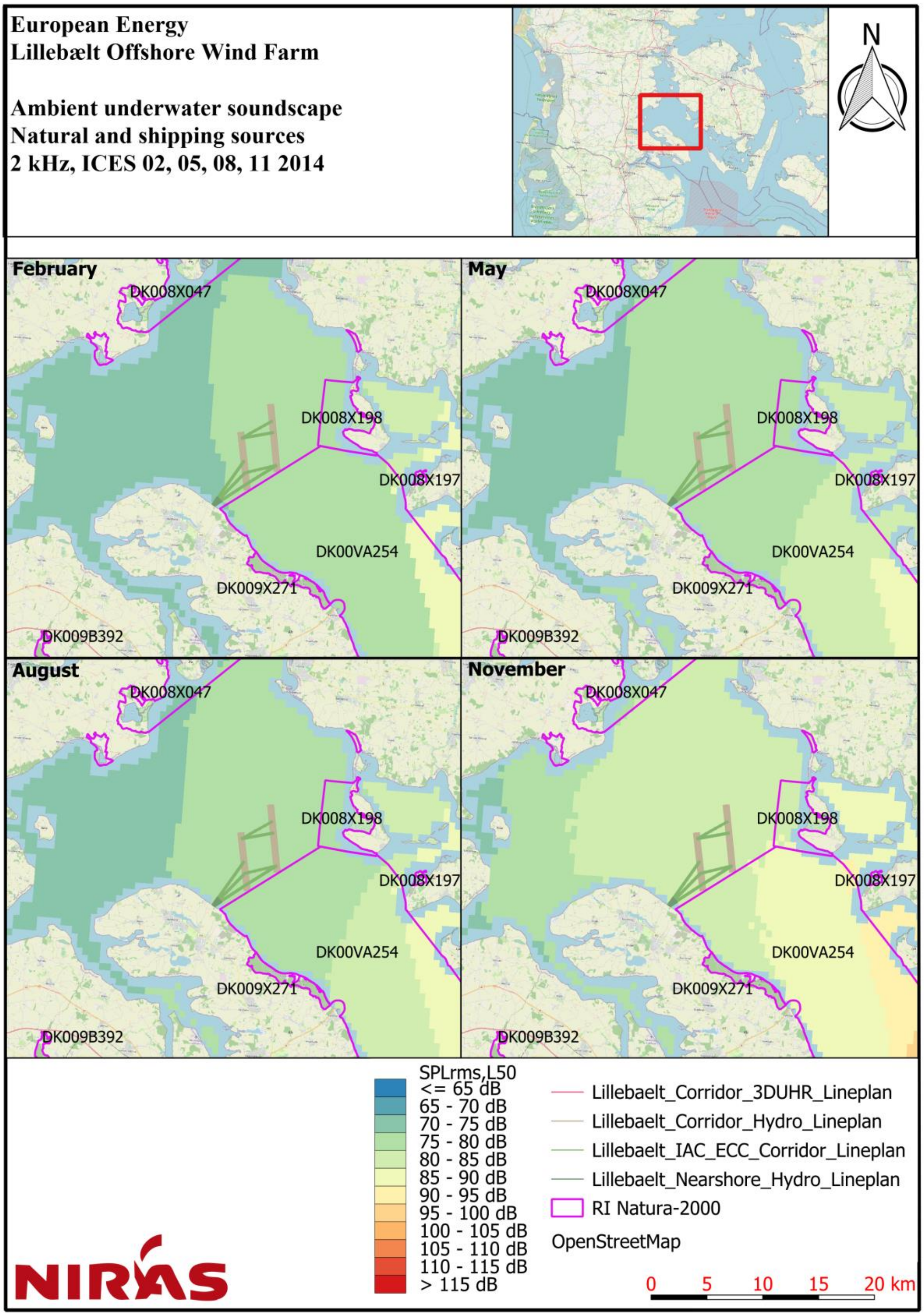

Figure 5.5: ICES soundscape map for 2 kHz, Feb, May, Aug, Nov 2014, 50th percentile $SPL_{rms,2kHz}$ $[dB\ re.1\mu Pa^2]$.

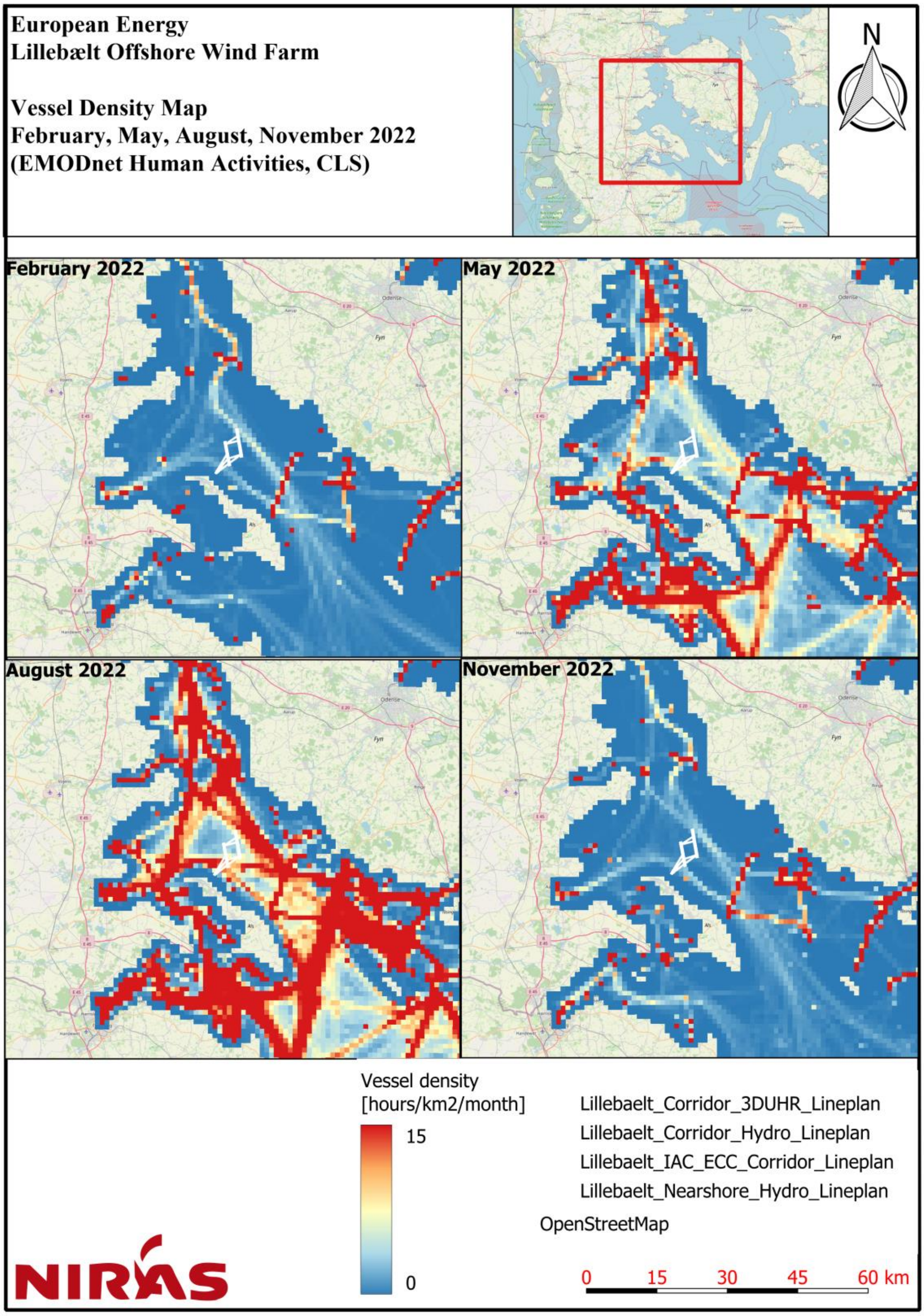

Figure 5.6: Vessel density map from 2022, from EMODnet (EMODnet, CLS, 2022) based on AIS data from CLS.

6. Underwater noise prognosis for geophysical survey

Geophysical survey activities have the potential to cause avoidance response, TTS, and PTS in marine mammals (Madsen, Wahlberg, Tougaard, Lucke, & Tyack, 2006).

Proposed survey equipment is first evaluated for its potential to have adverse effects on marine mammals (section 6.1). For equipment where direct evaluation of impact ranges is not possible or suitable, sound propagation modelling is conducted using:

- A source model, charactering the noise source, and the emission of noise into the water column (section 6.2).
- An environmental model, charactering the marine environment and its acoustic properties (section 6.3).
- A sound propagation model, through which the source and environmental model is used to determine the sound propagation (section 6.4).

Results are reported as impact ranges for marine mammals, in both numerical and graphical form in section 6.5.

6.1. Equipment evaluation

European Energy has specified equipment models to be used (see Table 6.1). Proxies for equipment specific acoustic characteristics are used where information was unavailable.

Table 6.1: Geophysical survey equipment models and operational parameters. Conservative proxy equipment and parameter values are used where [client] has not supplied information. Proxies are indicated using italic font.

Type	Equipment model	Source Level, L_S [dB re 1 µPa · m]	Primary Frequency Range (kHz)	Pulse Length	Beam Width	Sound exposure source level, $L_{S,E}$ (omnidirectional point source) [dB re 1 $\mu Pa^2 m^2 s$]	Duty cycle over a 24-hour period
Sub-bottom profiler (SBP)	Innomar Medium 100	247 dB (5.5 kW)	1-150	*0.07 – 2 ms*	*2°*	*172.8 dB*	*40 Hz*
	Silas EBP10*	- (900 W)	3.5-1000	-	-	-	-
Sparker (UHRS)	3x DuraSpark 400	226 dB	0.1-1.2	*2 ms*	-	*188 dB*	*4 Hz*
Airgun	SODERA Mini G 20 in^3	225 dB	*0-0.5*	*3.6 ms*	Omni	*189 dB*	*0.1 Hz*
Multi-beam echosounder (MBES)	Kongsberg EM2040-04 Dual head	*190 - 220 dB*	300-400	*0.3 - 10 ms*	*2° @ 200 kHz 1° @ 400 kHz*	-	-
	R2Sonic 2024 Single head	-	400	-	-	-	-
	Edgetech 6205 S2	-	520/850	-	-	-	-
Side scan sonar (SSS)	Edgetech 4200	*210 dB*	300+600 300+900	*<12 ms (300kHz) <5 ms (600kHz) <3 ms (900kHz)*	*0.50° (300 kHz) 0.26° (600 kHz) 0.20° (900 kHz)*	*191 dB (300 kHz) 187 dB (600 kHz) 185 dB (900 kHz)*	*15 Hz*
Ultrashort Baseline (USBL) Transceiver	Kongsberg HiPAP 352P	191 dB	21 - 31	20 ms	Omni	174 dB	1 Hz
	Easytrak Nexus 2 USBL, Model 2692	192 dB	18 – 32	20 ms	Omni	175 dB	1 Hz
USBL transponder	Kongsberg cNODE 30-180 (used with Kongsberg HiPAP352P)	190 dB	21-31	20 ms	Omni	173 dB	1 Hz
	Applied Acoustics 1119	*188 dB*	*21-31*	-	*Omni*	*171 dB*	*1 Hz*
Magnetometer#	Geometrics G882	-	-	-	-	-	-

**: Limited source information available, but based on input power (Watt), it is considered to have lower acoustic source level than the Innomar Medium 100.*

#: The source type has no source level, but typically requires the use of USBL to track the equipment position.

6.1.1. Sub-bottom profiler (Innomar Medium 100 and Silas EBP10)

The Innomar Medium 100 and the Silas EBP both create detailed profiles of the uppermost part of the seabed, typically the uppermost 20 m below the seabed.

The Innomar Medium 100 emits two high frequency pulses, called the primary frequencies, with both pulses typically in the frequency range of 100 – 120 kHz. The frequency separation between the two pulses dictates the secondary frequency, created inside the water column as the difference between the two primary frequencies: $f_{sec} = f_{pri2} - f_{pri1}\ [Hz]$. The source level of the Innomar Medium 100 is listed as $SL\ =\ 247\ dB\ re.1\mu Pa\ @1m$. It is a complex sound source as the sound emission is focused towards the seabed. The horizontal emission of underwater noise is therefore significantly lower than the source level would indicate, compared to the emission directly downward into the seabed.

The source characteristics of the Silas EBP10 are sparse, with no information available on source level, pulse rate or directionality. Based solely on the input power rating of 900 W (compared to 5500 W for the Innomar Medium 100) it is assessed that it is a significantly less noisy equipment type than the Innomar.

In a sound source verification study for geophysical survey activities in the Danish North Sea (Pace, Robinson, Lumsden, & Martin, 2021), acoustic measurements were conducted for the Innomar Medium 100. In the study, the sound level was measured in the horizontal direction at distances ranging from tens of meters to 750 m. In Figure 6.1, all measured data points in the horizontal direction are presented as the individual pulse SEL, along with a logarithmic curve fit. The trend indicates a source level of 193 dB and a rapid decay of approximately 37 dB/decade in the horizontal direction.

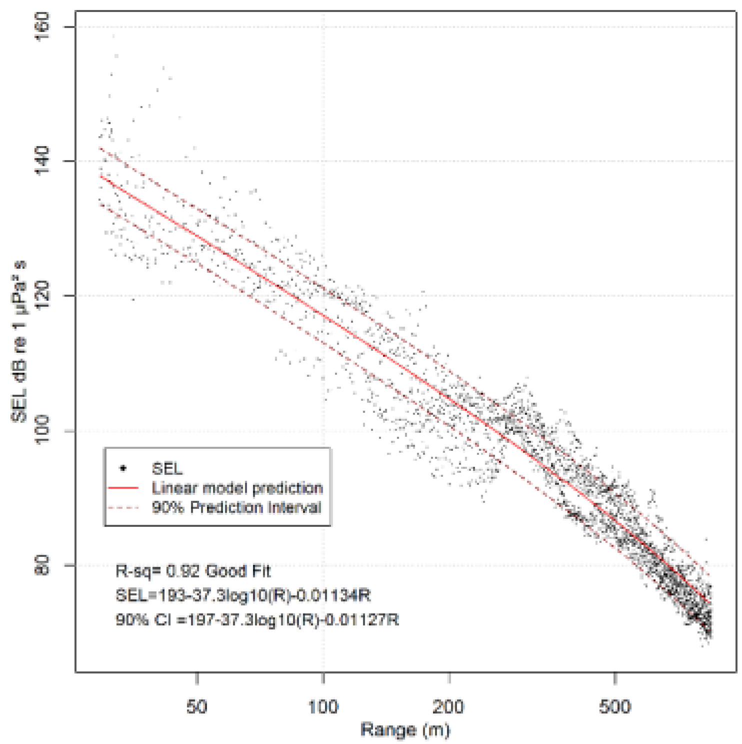

Figure 6.1: Sound Exposure Level measurements and curve fit for Innomar Medium 100, during a sound source verification study in the North Sea (Pace, Robinson, Lumsden, & Martin, 2021).

The curve fit obtained from these measurements, should however be considered with a degree of caution, and should not be considered generally applicable. The environmental conditions affect the sound propagation. To use the measurement data in a different setting or environment, it is necessary to compensate for the environment where it was obtained, and to develop an equivalent source model that, given the same environment, performs in line with the measurements. NIRAS constructed a 3D acoustic model in dBSea, representing the actual survey environment, based on the information supplied in the report along with best available knowledge. In this model, an equivalent omnidirectional point source was designed, mimicking the measured data. The equivalent model can then be used in other marine environments, however recognizing that the model approximates the equipment behaviour, more so than an actual source model. It is therefore also recognized that this introduces an uncertainty into the sound propagation model. It is however considered the best-possible approach given the lack of an actual source model, which would require detailed source level and frequency measurements, as well as detailed frequency specific directivity measurements.

Due to the Innomar Medium 100s high frequency content, and thereby the strong impact of hydrography on impact ranges, this equipment should be evaluated through sound propagation modelling.

Due to the lack of information for the Silas EBP10 system, the Innomar Medium 100, is for this prognosis, considered a conservative proxy, and impact ranges from the modelling of the Innomar, will be used instead.

6.1.2. Sparker (Duraspark 400)

The Duraspark 400, is a multi-tip electrode sparker, discharging energy through electrodes arranged in a uniformly spaced planar grid, creating a downward focused acoustic pulse. The directivity at primary frequencies, where most of the source energy is located, is provided in Table 6.1.

The dominant frequency content for the emitted acoustic signals is between 100 Hz to 1.2 kHz. Although being downward focused, the directivity is limited, and significant sound energy will be emitted in the horizontal direction. Thus, the noise source has the potential to cause long impact ranges. For this survey, three sparkers are used side by side, in a rotating firing sequence, with a total of four pulses being emitted every second. Instead of considering three sparker units, it is considered equivalent to consider the acoustic output based on the firing frequency (4 Hz) and assuming a single unit.

In a sound source verification study for geophysical survey activities in the Danish North Sea (Pace, Robinson, Lumsden, & Martin, 2021), acoustic measurements were carried out for a 360 tip sparker system (assessed to be equivalent in functionality to the proposed Duraspark 400. In the study, the sound level was recorded in the horizontal direction at distances ranging from tens of meters to 2 km. In Figure 6.2, all measured data points in the horizontal direction are presented as the individual pulse SEL, along with a logarithmic curve fit. The trend indicates a source level $L_{S,E} = 168\ dB$ and a decay of approximately 14.5 dB/decade in the horizontal direction.

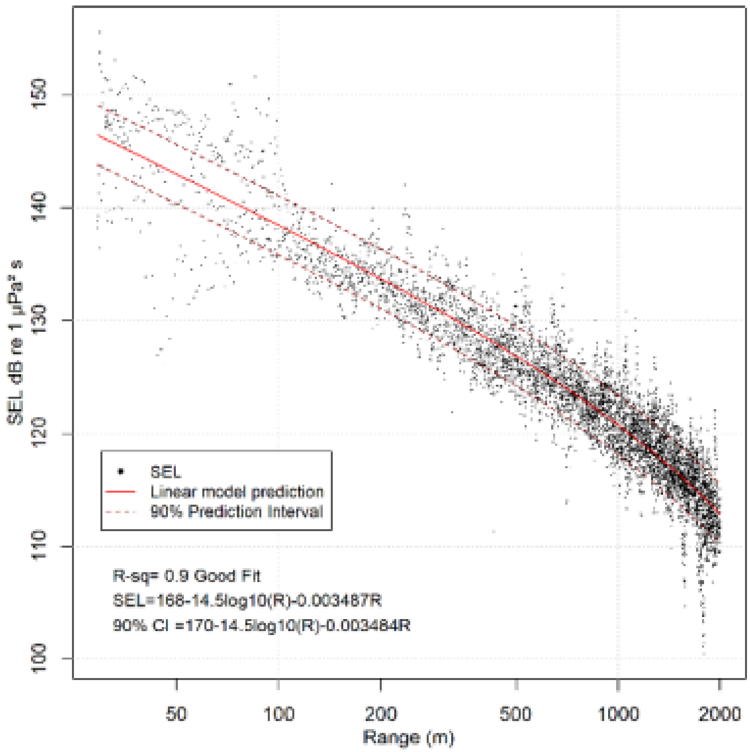

Figure 6.2: Sound Exposure Level measurements and curve fit for 360 tip sparker, during a sound source verification study in the North Sea (Pace, Robinson, Lumsden, & Martin, 2021).

The curve fit obtained from these measurements, should however be considered with a degree of caution, and should not be considered generally applicable. As for the Innomar Medium 100, NIRAS developed an equivalent sound source model to represent the Duraspark 400 sparker, in the same way as described in section 6.1.1.

The Duraspark 400 sparker has an impulsive nature and due to its low frequency characteristic, its sound propagation is likely to be affected by the bathymetry of the project area and surroundings. This equipment should therefore be evaluated through sound propagation modelling.

6.1.3. Airgun (SODERA Mini G 20 cu. inch)

A mini airgun of the model, SODERA Mini G 20 cu. inch, is used to investigate the sub-bottom layers of the seabed structure.

Airguns work by rapidly releasing compressed air, causing a release of a focused pressure pulse. A single-airgun configuration is omnidirectional and thereby emits underwater noise equally in all directions. Most of the energy from an airgun is in the low frequency range, with the primary frequency content between 10 Hz – 1 kHz, and the highest energy level around 20 – 40 Hz. It is therefore below the primary hearing frequency range of harbour porpoise and seal. The low frequency nature of the source allows the sound to propagate with low propagation loss (PL) over distance, and combined with the impulsive nature of the source, and its high source level it still has the potential to cause adverse effects on marine life. As an omnidirectional point source, it can be implemented directly into an underwater sound propagation model.

The SODERA Mini G 20 cu. inch airgun has an impulsive nature and due to its low frequency characteristic, its sound propagation is likely to be affected by the bathymetry of the project area and surroundings. This equipment should therefore be evaluated through sound propagation modelling.

6.1.4. Ultra-Short Baseline: (Kongsberg HiPaP 352P + cNode; Easytrak Nexus 2 + AA 1119)

The Ultra Short Baseline (USBL) system is used to determine the relative position of an underwater object, relative to a known reference point. It consists of a USBL transceiver mounted at a known reference point, and a transponder unit mounted on the object whose relative position is of interest. For applications such as seabed surveys, the USBL transceiver would typically be mounted on the vessel. The absolute position of the vessel is registered by a GPS, thereby creating a fixed reference point for the USBL. A transponder unit is then attached to the towed equipment, such as a Side Scan Sonar (SSS), a magnetometer, ROV, etc.

It can be operated in one of two ways as outlined below, the choice between which typically relies on available equipment and project specific conditions:

A. Transponder mode (acoustic), whereby the USBL transceiver on the vessel emits a loud acoustic pulse acting as a "trigger". When the "trigger" pulse is registered by the transponder unit on the towed equipment, it sends out an acoustic "response" pulse. A hydrophone array on the USBL transceiver, records the "response" pulse and the relative distance and bearing of the transponder, relative to the vessel is registered. In this way the relative geographical position of the towed equipment is determined with high precision.

B. Responder mode (cabled), where the "trigger" pulse is not sent acoustically through the water, but instead as an electrical impulse through a cable between the vessel and the transponder unit. On receiving the trigger pulse, the transponder unit will still emit its response pulse acoustically.

The directivity of USBL transceivers and transponders can be either directional (narrow beam) or omnidirectional. For this study, only omnidirectional types are considered.

European Energy has announced that two different USBL setups were proposed as options to use for the different survey activities:

- Configuration 1 consists of:
    - A Kongsberg HiPAP 352P transceiver ($SL = 192\ dB\ re.1\ \mu Pa$), and
    - A Kongsberg cNODE transponder ($SL = 190\ dB\ re.1\ \mu Pa$).
- Configuration 2 consists of:
    - An Easytrak Nexus 2, model 2692 transceiver ($SL = 191\ dB\ re.1\ \mu Pa$).
    - Information on the transponder model has not been provided, however the most likely choice is an Applied Acoustics 1119 transponder ($SL = 188\ dB\ re.1\ \mu Pa$) or equivalent.

For all USBL equipment, the operational frequency has been assumed to be centred around the 25 kHz 1/3 octave band. Transponder mode is assumed, meaning both USBL transceiver and transponder will actively emit acoustic pulses. If responder mode is used, the acoustic emission from the transceiver is removed, and impact ranges will decrease. It is however unclear if this is an option for the planned activities.

Due to USBLs high frequency content, and thereby the strong impact of hydrography on impact ranges, this equipment is evaluated through sound propagation modelling. Only the two transceiver source levels (being the highest of transceiver and transponder) is calculated, however for cumulative noise dose calculations, transponder contributions are also considered.

6.1.5. Multi-beam Echosounder (Kongsberg EM2040; R2Sonic 2024; Edgetech 6205 S2)

All three proposed MBES are hydroacoustic devices used for mapping the seafloor and collecting bathymetric data in marine environments. They employ the principles of sonar to measure the depth of the seabed and generate high-resolution bathymetric maps.

The transducer array is the primary component of the MBES. It consists of multiple individual transducers arranged in a fan-shaped or circular array. Each transducer emits a narrow beam of sound pulses in a downward direction and receives the echo reflected from the seafloor.

The frequencies emitted by all three MBES systems are higher than 200 kHz, and thereby beyond the hearing ability of any marine mammals. Coupled with the strong downward directivity, this equipment type is unlikely to have any negative auditory effects on marine mammals. It is therefore not considered for underwater noise modelling.

6.1.6. Side scan sonar (Edgetech 4200)

The Edgetech 4200 side scan sonar is an underwater imaging system used for high-resolution imaging and mapping of the seafloor. Unlike multibeam echosounders (MBES) that primarily measure bathymetry, side scan sonars are designed to provide detailed visual representations of the seafloor surface and protruding features.

The transducer array in an SSS is responsible for transmitting and receiving acoustic signals. It typically consists of one or more transducers arranged in a line or an array configuration. Each transducer emits a narrow beam of sound waves perpendicular to the seafloor, covering a wide swath on either side of the sonar system.

The frequencies emitted by the SSS are typically at least 300 kHz, which is outside the hearing ability of any marine mammals or fish. While the Edgetech 4200 also comes with the option of a 100 kHz frequency, European Energy will not use this setting. Coupled with the strong downward directivity, and restricting the use of frequencies below 200 kHz, this equipment type is unlikely to have any negative auditory effect on marine mammals. It is therefore not considered for underwater noise modelling.

6.1.7. Magnetometer (Geometrics G882)

Marine magnetometers used in geophysical surveys for detecting buried objects such as UXOs are designed to identify variations in the magnetic field caused by the presence of ferromagnetic materials. These materials, including metallic objects like munitions, generate localized disturbances in the Earth's magnetic field, which can be detected and analysed by the magnetometer system.

The magnetometer sensor is typically mounted on a specialized instrument platform, such as a towfish or a remotely operated vehicle (ROV). The platform is then towed at a constant altitude above the seafloor, typically a few meters, ensuring consistent proximity to the target area.

The magnetometer does not rely on acoustic output to function, and it therefore has no underwater noise emission, and underwater noise modelling is therefore not undertaken for this equipment. Depending on the tow setup, it can however be necessary to use a USBL system to track the location of the magnetometer.

6.1.8. Noise from survey vessels

In addition to the noise from the individual activities, the survey vessel is also likely to be a source of underwater noise during the survey execution. In (Pace, Robinson, Lumsden, & Martin, 2021), the survey vessel underwater noise emission was measured, and reported in 1/3-octave levels at 5 different distances from the vessel, with and without marine mammal frequency weighting applied, see Figure 6.3.

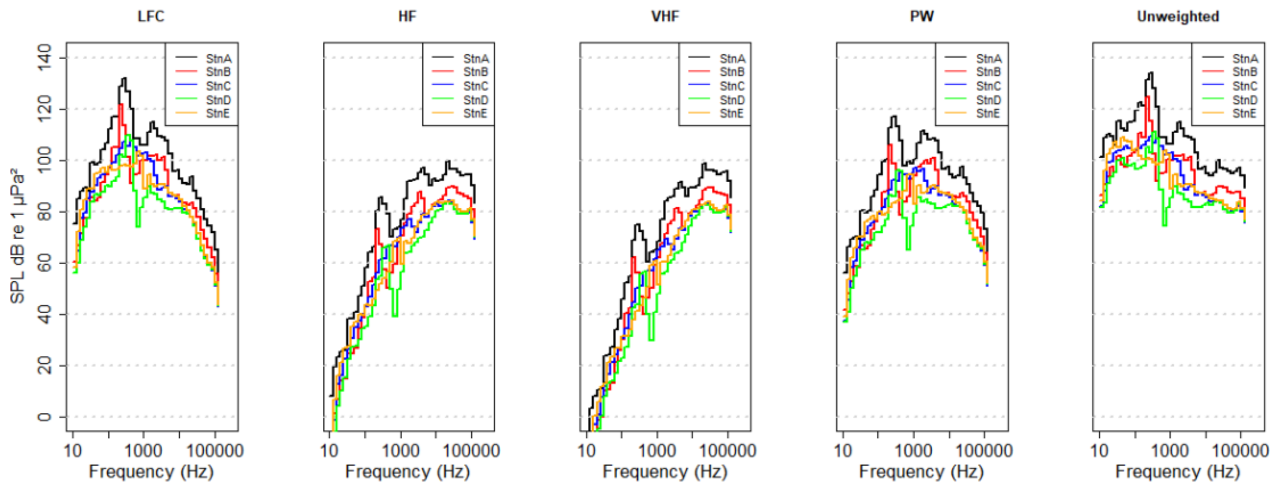

Figure 6.3: Weighted and unweighted 1/3 octave sound pressure level (SPL) measured at 5 different hydrophone distances (stnA is directly underneath the vessel path, stnB at 150 m distance, stnC at 540 m, stnD at 780 m and stnE at 2040 m). (Pace, Robinson, Lumsden, & Martin, 2021).

From Figure 6.3, noise levels are observed to be primarily low frequent, with most of the acoustic energy below a few hundred Hz. For harbour porpoise (VHF-weighting), the measurements at station B (150 m distance) show 1/3-octave band levels below 90 dB in all bands, with broadband level below the threshold criteria for behaviour reaction, $L_{p,125ms,VHF} = 103 \text{ dB re. } 1 \text{ µPa}$.

Vessel noise is a continuous noise type and is therefore evaluated by comparison with the non-impulsive TTS and PTS criteria. In Table 6.2, distances to PTS and TTS for each of the relevant species are provided, based on the measurement data in Figure 6.3, and assuming a 24-hour survey duration.

Table 6.2: PTS and TTS impact ranges from geophysical survey vessel noise.

Species	Swim speed [ms^{-1}]	Impact range [m]		
		PTS	TTS	Behaviour
		Non-impulsive	Non-impulsive	
Harbour porpoise (VHF)	1.5	< 10 m	< 100 m	< 150 m
Seal (PCW)	1.5	< 10 m	< 100 m	-

From this evaluation, it is not considered necessary to conduct underwater noise modelling.

6.1.9. Summary of equipment evaluation

All proposed equipment types were evaluated for their potential to emit harmful levels of underwater noise, and the following methods are used:

- MBES, SSS, magnetometer and vessel are not considered suitable/necessary to carry out underwater noise modelling for due to negligible/insignificant acoustic impact.
- The parametric SBP (Innomar Medium 100), Duraspark 400 sparker, SODERA 20 cu in. airgun and both USBL transceivers are evaluated through sound propagation modelling, as they have significant frequency content within the audible range of harbour porpoise.

6.2. Source model

6.2.1. Parametric SBP (Innomar Medium 100) implementation

The Innomar Medium 100 source model is based on the approach described in section 6.1.1, using an omnidirectional equivalent point source. Source characteristics are shown in Figure 6.4, as both unweighted (blue) and VHF weighted (green). It is reiterated that this is an equivalent point source model from a horizontal propagation perspective, and not an accurate representation of the sound source characteristics. It is therefore only to be used as a conservative model for calculating horizontal impact ranges for marine mammals.

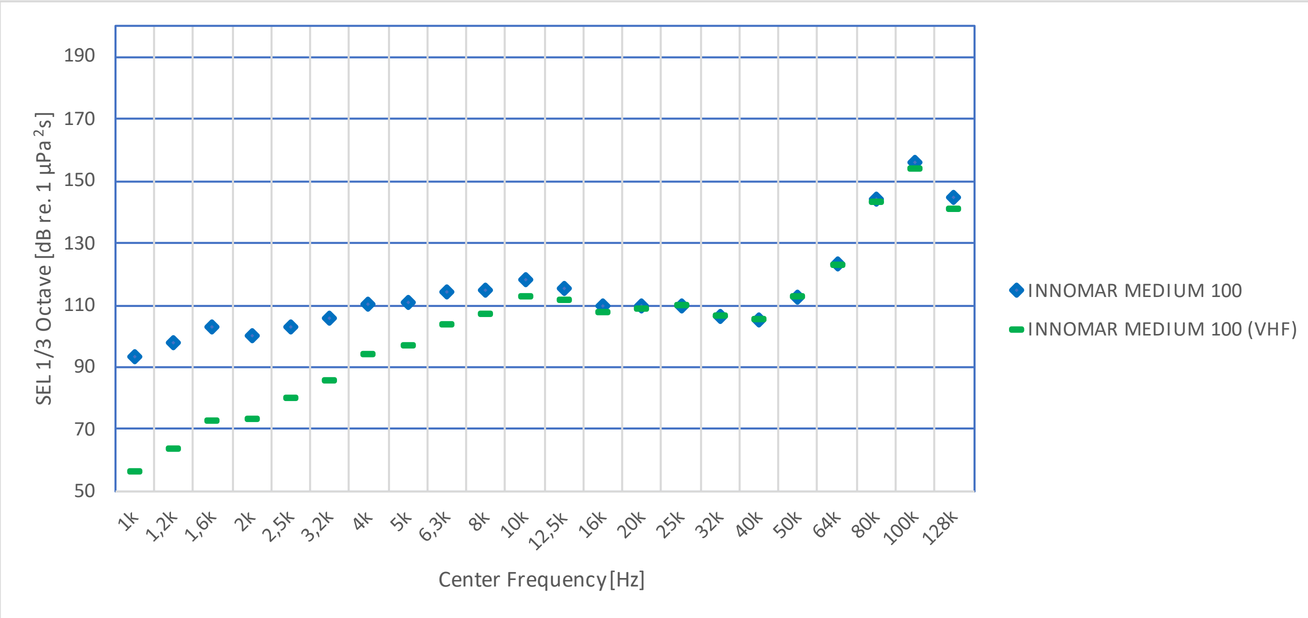

Figure 6.4: Equivalent omnidirectional point source model frequency spectrum for the Innomar Medium 100 parametric SBP. The source model is calibrated to fit measurement results from (Pace, Robinson, Lumsden, & Martin, 2021).

The Innomar Medium 100 is mounted on the vessel and is operated at a 40 Hz pulse rate, while the vessel sails at 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The Innomar Medium 100 is considered a non-impulsive source type, and impact range calculation is therefore based on the non-impulsive threshold criteria.

6.2.2. Sparker (Duraspark 400) implementation

The Duraspark 400 source model is based on the approach described in section 6.1.2, using an omnidirectional equivalent point source. Source characteristics are shown in Figure 6.5, as both unweighted (blue) and VHF weighted (green). It is reiterated that this is an equivalent point source model from a horizontal propagation perspective, and not an accurate representation of the sound source. It is therefore only to be used as a conservative model for calculating horizontal impact ranges for marine mammals.

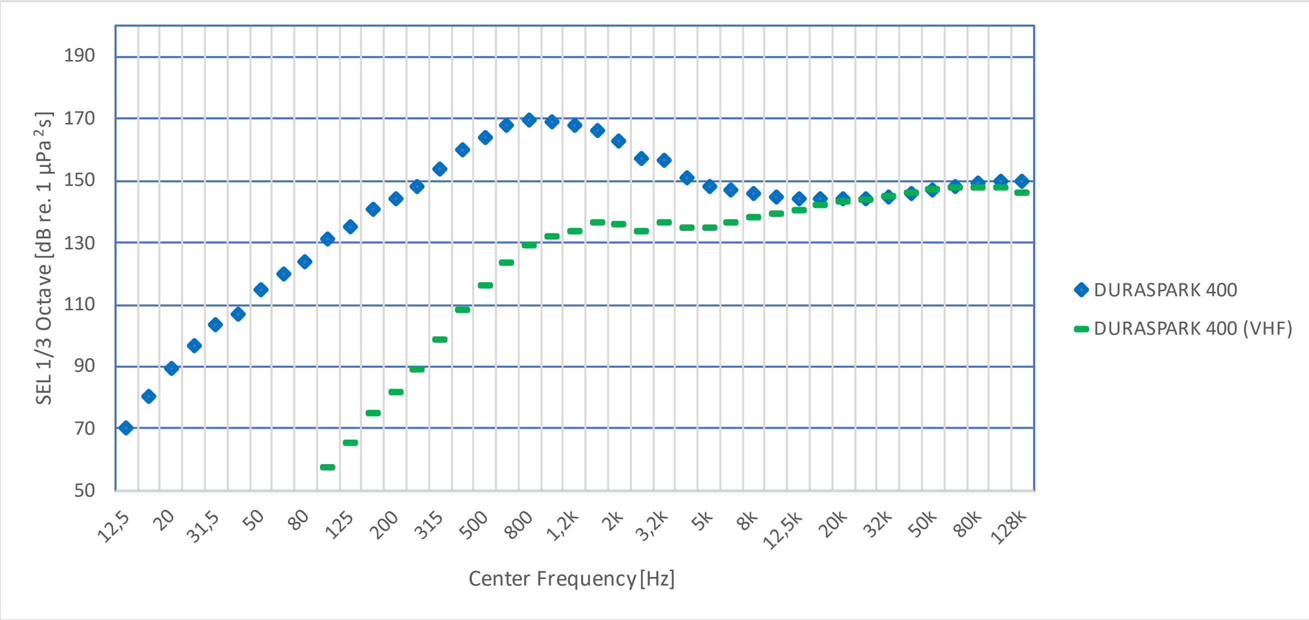

Figure 6.5: Equivalent omnidirectional point source model frequency spectrum for the Duraspark 400 sparker. The source model is calibrated to fit measurement results from (Pace, Robinson, Lumsden, & Martin, 2021), but adjusted in source level to represent information from client.

While three Duraspark 400 units are used, the model is simplified to use a single Duraspark 400 unit towed behind the survey vessel. European Energy has detailed, that the firing frequency of the three sparkers combined is 4 Hz, meaning the individual sparker firing rate is 1.33 Hz, while the vessel sails at 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The Duraspark 400 is considered an impulsive source type, and impact range calculation is therefore based on the impulsive threshold criteria.

6.2.3. Airgun (SODERA Mini G 20 cu. inch) implementation

The SODERA Mini G 20 cu. inch source model is based on the approach described in section 6.1.3, using an omnidirectional point source. Source characteristics are shown in Figure 6.6, as both unweighted (blue) and VHF weighted (green).

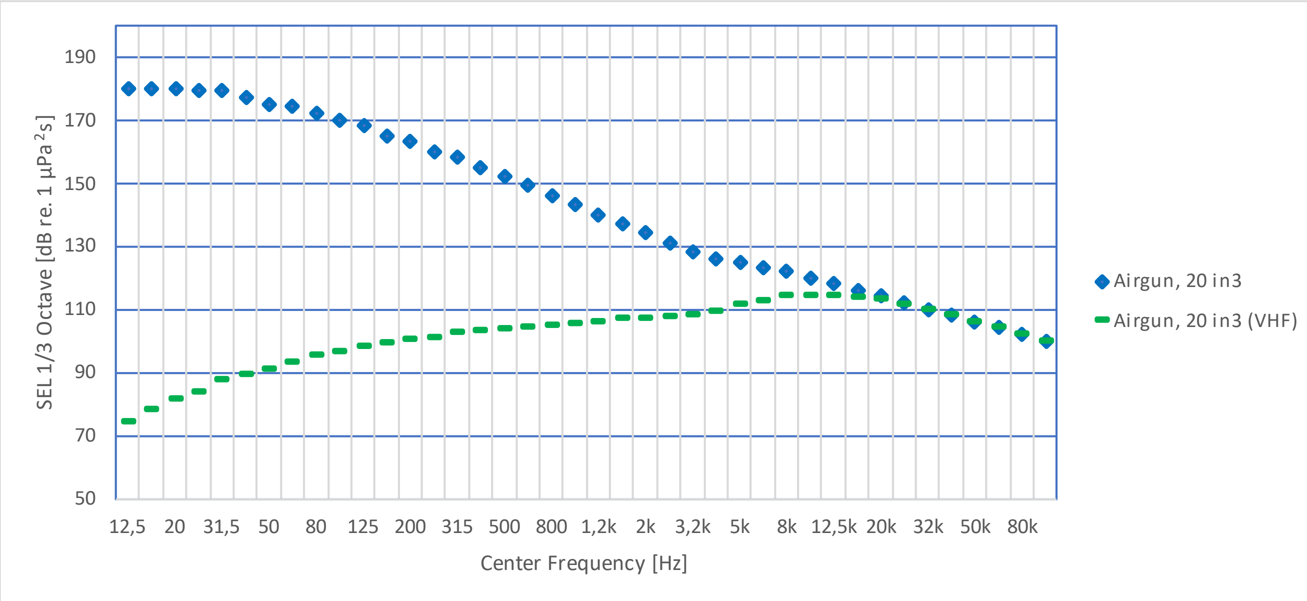

Figure 6.6: Equivalent omnidirectional point source model frequency spectrum for the Mini G 20 cu. inch airgun.

The Mini G 20 cu. inch is towed behind the survey vessel and is assumed operated at a 0.1 Hz pulse rate, while the vessel sails at 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The Mini G 20 cu. inch is considered an impulsive source type, and impact range calculation is therefore based on the impulsive threshold criteria.

6.2.4. USBL (Kongsberg HiPaP 352P + cNode; Easytrak Nexus 2 + AA 1119) implementation

The Kongsberg HiPaP 352P + cNode; Easytrak Nexus 2 + AA 1119 source models are based on the approach described in section 6.1.4, using an omnidirectional single-frequency point source with all energy located in the 25 kHz, 1/3 octave band. Source levels used are:

- USBL system 1: Kongsberg:
  - Transceiver (Kongsberg HiPaP 352P): $SL = 191\ dB\ re.1\ \mu Pa$
  - Transponder (Kongsberg cNODE): $SL = 190\ dB\ re.1\ \mu Pa$
- USBL system 2: Easytrak:
  - Transceiver (Easytrak Nexus 2, 2692): $SL = 192\ dB\ re.1\ \mu Pa$
  - Transponder (AA 1119): $SL = 188\ dB\ re.1\ \mu Pa$

The USBL transceiver is mounted on the vessel, while the transponder unit is mounted on the tow, and both are assumed operated at a 1 Hz pulse rate, while the vessel speed is 4 knots. The activity is assumed ongoing for 24 hours continuously, and it is assumed that it is not turned off during line turns. The USBL is treated as a non-impulsive source type, due to its narrowband frequency content, pulsed characteristic and with no rapid rise nor decay. Only the transceivers of each USBL system are modelled and used to evaluate behavioural impact range, however for PTS and TTS impact range calculations, the transponders are included, based on the same propagation models but with adjusted source level.

6.2.5. Source positions

It was agreed with European Energy to select four representative positions throughout the investigation area, so different sound propagation scenarios are covered. Areas where sound propagation results in the longest impact ranges are identified, considering nearby marine mammal protection areas. Position 1 was chosen as the closest point from the offshore surveys to the Natura 2000 areas "Maden på Helnæs og havet vest for" and "Bredgrund". Position 2 was chosen as the closest point to the Natura 2000 area "Lillebælt". Position 3 was chosen as representative worst case for the near-to-offshore surveys, and position 4 as representative for the near-shore survey activities. The source positions are listed in Table 6.3, along with coordinates, and distances to relevant areas of interest. The positions are also shown in Figure 6.7.

Table 6.3: Source positions used for sound propagation modelling of underwater noise during geophysical surveys.

Position ID	Easting	Northing	EPSG	Nearby areas of interest
1	556844	6106485	25832	Nat2000 area "Bredgrund": 250 m distance Nat2000 area "Maden på Helnæs og havet vest for": 4.1 km distance Nat2000 area "Lillebælt": 16.8 km distance
2	553031	6109247	25832	Nat2000 area "Bredgrund": 4.7 km distance Nat2000 area "Maden på Helnæs og havet vest for": 7.1 km distance Nat2000 area "Lillebælt": 12.3 km distance
3	553077	6104088	25832	Nat2000 area "Bredgrund": 550 m distance Nat2000 area "Maden på Helnæs og havet vest for": 8.7 km distance Nat2000 area "Lillebælt": 16.4 km distance
4	551623	6103113	25832	Nat2000 area "Bredgrund": 600 m distance Nat2000 area "Maden på Helnæs og havet vest for": 10.5 km distance Nat2000 area "Lillebælt": 16.5 km distance

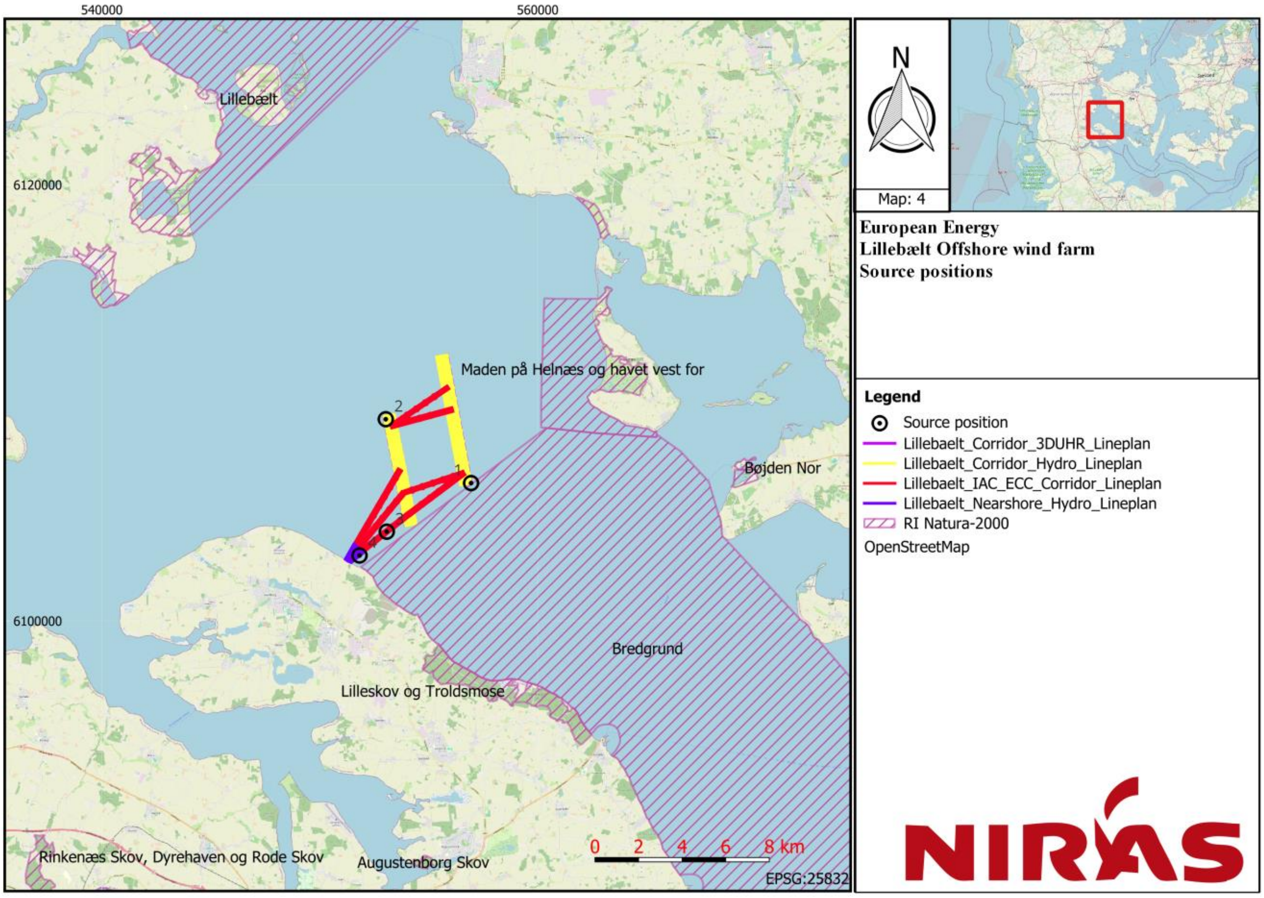

Figure 6.7: Source positions chosen for sound propagation modelling as well as nearby relevant Natura 2000 areas.

6.3. Environmental model

Sound travels faster and farther in water than in air because water is denser and more efficient at transmitting sound waves. However, the aquatic environment is complex and heterogeneous, and sound propagation is influenced by environmental parameters:

- Bathymetry,
- seabed sediments,
- temperature, salinity, and sound speed,
- sea surface roughness, and
- volume attenuation.

These factors can cause sound to refract, reflect, scatter, and attenuate as the sound waves propagate through water, making it challenging to predict its behavior. These factors, and their implementation for sound propagation modelling, are described in the following sections.

6.3.1. Bathymetry

The shape and composition of the seafloor plays a critical role in the propagation of sound waves through the water. The seafloor can function as a barrier or a reflector for sound waves, depending on its composition and shape. A smooth, flat seafloor can reflect sound waves back towards the surface, whereas a rough, irregular seafloor can scatter sound waves in different directions, causing them to lose intensity and become weaker over distance.

Additionally, underwater ridges, canyons, and other geological features can function as waveguides, trapping and focusing sound waves in specific depths or regions.

Overall, bathymetry affects underwater sound propagation by influencing the speed, direction, and intensity of sound waves as they travel through the water. A detailed understanding of the bathymetry is necessary for predicting and modelling the nature of underwater sound propagation in a real-world scenario.

The bathymetry for the project area and surroundings consists of information from the sources listed in Table 6.4. A visualisation of the bathymetry model for the project area and surroundings is shown in Figure 6.8. In areas with large variations in the bathymetry, sharp increases/decreases to the water depth can occur between neighbouring depth points. This is not an accurate representation of the real environment, but a result of the bathymetric model resolution, which for the chosen source is 115 m x 50 m. A more realistic case would be a smooth change of water depth between the grid points. To remedy this, NIRAS uses a moving average function to smooth the bathymetry.

Table 6.4: Bathymetry model data sources.

Data source	Reference
Bathymetry	(EMODnet, EMODnet bathymetry portal, 2022)

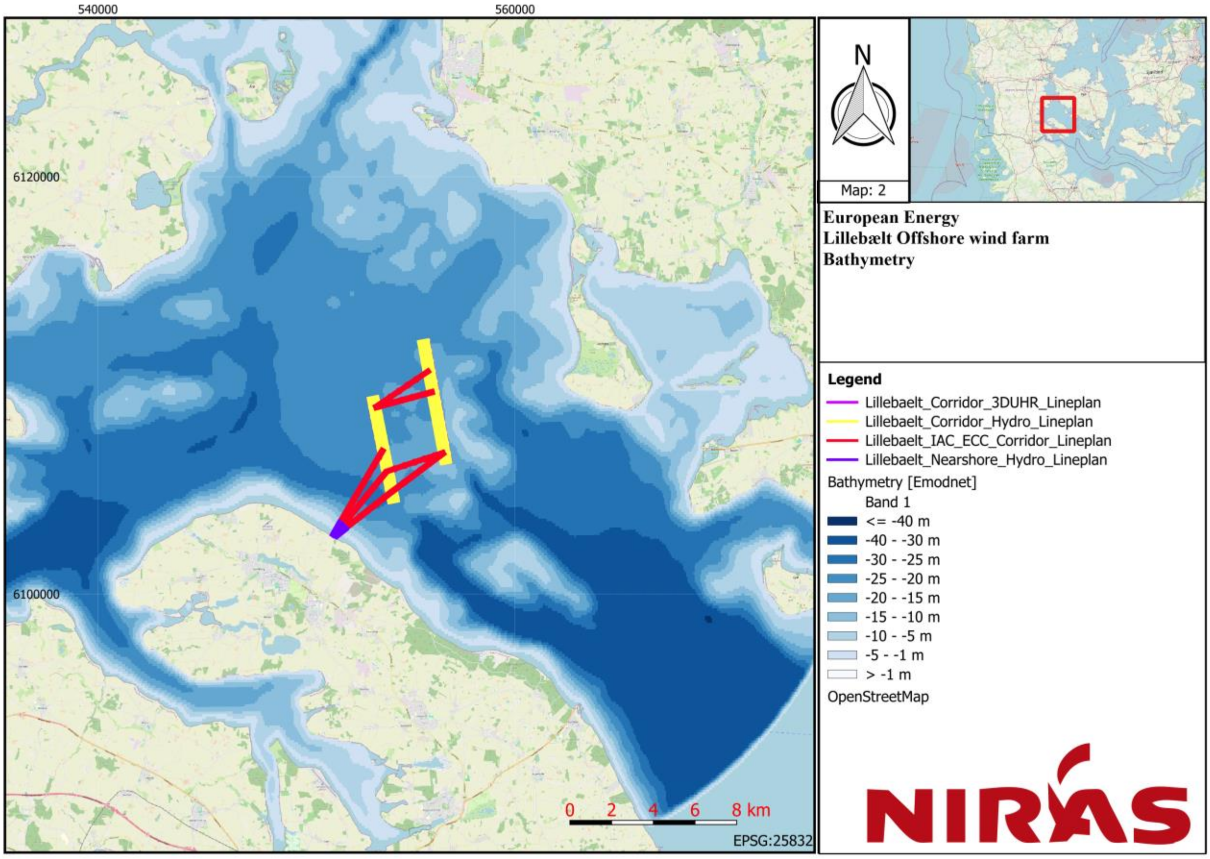

Figure 6.8: Bathymetry for the project area and surroundings, sources as listed in Table 6.4.

6.3.2. Seabed sediment

Seabed sediment layers can have a significant effect on the propagation of sound waves through the water. The acoustic properties of sediment layers are influenced by several factors, including the composition, density, porosity, and grain size distribution of the sediments. Sediments with larger grain sizes and lower porosity have higher acoustic velocities and can transmit sound waves more efficiently than finer grained and more porous sediments.

The properties of sediment layers can also affect the reflection, refraction, and attenuation of sound waves. For example, a layer of fine-grained, soft sediment can absorb and scatter sound waves, causing them to lose intensity and become weaker over distance. Conversely, a layer of hard, compacted sediment can reflect sound waves, resulting in increased sound intensity in certain areas.

The thickness of sediment layers can also play a role in underwater sound propagation. Thicker sediment layers can absorb and scatter sound waves more effectively, while shallower sediment layers can reflect and refract sound waves more strongly.

The thickness and acoustic properties of each seabed layer, from seabed to bedrock, is obtained through site specific literature research in combination with available site-specific survey findings.

From the available sediment data sources, a discretized and simplified version is created, whereby the layer thicknesses and sediment types are defined in a number of points. Depending on the project, a conservative approach (worst case sediment profile for the entire model area), or a detailed approach (multiple sediment profiles representing local differences) might be appropriate. The higher the number of sediment profiles, the greater the potential to reflect actual conditions, however this requires significantly more detailed information about the sediment structure throughout the project area. A simplified profile on the other hand using a worst-case profile, requires less information, but will also likely overestimate impact ranges.

For each point in the model, the sediment layer types are translated into geoacoustic parameters, in accordance with Table 6.5, utilizing information from (Jensen, Kuperman, Porter, & Schmidt, 2011; Hamilton, 1980).

Table 6.5: Geoacoustic properties of sediment layers used in the environmental model. Sources: (Jensen, Kuperman, Porter, & Schmidt, 2011; Hamilton, 1980). Note, mixed sediment is based on a mix of sand, silt, and gravel. Moraine boulders is similarly a mix of primarily moraine with boulders.

Sediment	Sound Speed [m/s]	Density [kg/m^3]	Attenuation factor [dB/λ]
Clay	1500	1500	0.2
Silt	1575	1700	1.0
Mud (clay-silt)	1550	1500	1.0
Sandy mud	1600	1550	1.0
Sand	1650	1900	0.8
Muddy sand	1600	1850	0.8
Coarse substrate	1800	2000	0.6
Gravel	1800	2000	0.6
Mixed sediment	1700	1900	0.7
Moraine	1950	2100	0.4
Moraine Boulders	2200	2200	0.3
Rock and boulders	5000	2700	0.1
Chalk	2400	2000	0.2

It was chosen to use a conservative single point approach whereby a single conservative sediment profile is used throughout the area. As mentioned above, it is recognized that this might result in overly conservative impact ranges. The sediment profile consists of 40 m of mixed sediment overlaying 40 m moraine on top of the chalk layer. This was based on the database sources for topsoil sediment and for the chalk layer, see Table 6.6. Acoustic parameters for the three layers are shown in Table 6.5.

Table 6.6: Sediment model data sources.

Data source	Reference
Seabed substrate (topsoil) map	(EMODnet, EMODnet-Geology portal, Seabed Substrate layer, 2021)
Chalk layer top depth	(Danmarks Geologiske Undersøgelse (DGU), 1994)
Acoustic parameter model for sediment types	Table 6.5

6.3.3. Temperature, salinity, and sound speed profile

The combined effects of temperature and salinity on seawater density can create complex sound speed profiles in the sea, particularly in areas with strong vertical stratification or gradients in temperature and salinity. These variations in sound speed can have important implications for underwater sound propagation.

As stated by Snell's law, Equation 8, sound waves bend toward regions of low sound speed (Jensen, Kuperman, Porter, & Schmidt, 2011). The implications for sound in sea water are, that sound, entering a low velocity layer in the water column, can get trapped there. This results in sound travelling far with very low propagation loss.

$$\frac{\cos(\theta)}{c} = \text{constant} \qquad \text{Equation 8}$$

Where θ is the ray angle [°] and *c* is the speed of sound $\left[\frac{m}{s}\right]$.

There are three main types of sound speed profiles for seawater:

1. **Uniform sound speed profile**: In a uniform sound speed profile, the speed of sound is the same at all depths. This can occur in regions of the sea where temperature and salinity are relatively constant with depth.
2. **Upward refracting sound speed profile**: When the sound speed increases with depth, it is called an upward refracting sound speed profile. Sound waves in this type of environment can be refracted upward and away from the seabed, potentially travelling over longer distances with lower absorption losses from seabed interaction.
3. **Downward refracting sound speed profile**: When the sound speed decreases with depth, it is called a downward refracting sound speed profile. Sound waves will, in this environment, be refracted downward to a higher degree and toward the seabed, potentially causing them to lose energy and travel shorter distances.

Special cases, where a low-speed region is present at a depth in between sea surface and seabed can create channels where specific ranges of frequencies can get trapped and propagate without ever reaching neither seabed nor sea surface. The potential transmission range in such a channel is significantly longer than in any of the typical three sound speed profile types listed above.

The sound speed profiles for a certain project area are calculated using Coppens equation (Coppens, 1981), based on available temperature and salinity data for the area. Data sources for the temperature and salinity profiles can be either based on empirical data, or predictive models. It is important to note, that while empirical data and predictive models can provide a historically likely scenario, they cannot accurately predict the weather conditions when the project activities will occur.

For the environmental model area, available sound speed profiles, as well as average temperature and salinity are extracted for the desired months. Temperature and salinity profiles for this project, were extracted from the data sources in Table 6.7, and through the NIRAS software tool "TRANSMIT", turned into sound speed profiles.

Table 6.7: Temperature, salinity, and sound speed data sources.

Data source	Reference
Temperature	2x2 km grid, monthly averages based on physical forecast (Copernicus, 2023)
Salinity	2x2 km grid, monthly averages based on physical forecast (Copernicus, 2023)
Sound speed profile	Coppens equation (Coppens, 1981) implemented in NIRAS "TRANSMIT"

The temperature and salinity change both temporally (over the year), as well as spatially. Both the period and position of the activities included in sound propagation modelling must therefore be considered, when evaluating which sound speed profiles should be used for any given model.

A realistic worst-case approach was agreed with European Energy, meaning the survey period of April – August was considered. The temperature, salinity and sound speed profiles for the area are therefore examined for this period, to determine which month has conditions most likely to result in the furthest sound propagation.

Temperature, salinity, and sound speed profiles were extracted for a radius of 10 km around the center of the investigation area, however due to the limited area size, only a single profile position was available in the database. Graphical representations of all monthly profiles are shown in Figure 6.9 (temperature), Figure 6.10 (salinity), and in Figure 6.11 (sound speed). From the monthly profiles, April has the potential for the strongest sound propagation, due to the low sound speed, near-iso sound speed profile and with the lowest sound speed occurring within the water column. In comparison, the rest of the monthly profiles exhibit strong downward refraction and would therefore be more likely to result in increased seabed sediment interaction, and thereby greater losses of sound level over distance.

To ensure a realistic worst-case approach for the prognosis, sound propagation modelling implements the profiles for April. The sound speed profile, average temperature and salinity were combined with the sediment profile through the NIRAS software tool "TRANSMIT", to produce the dBSea import file.

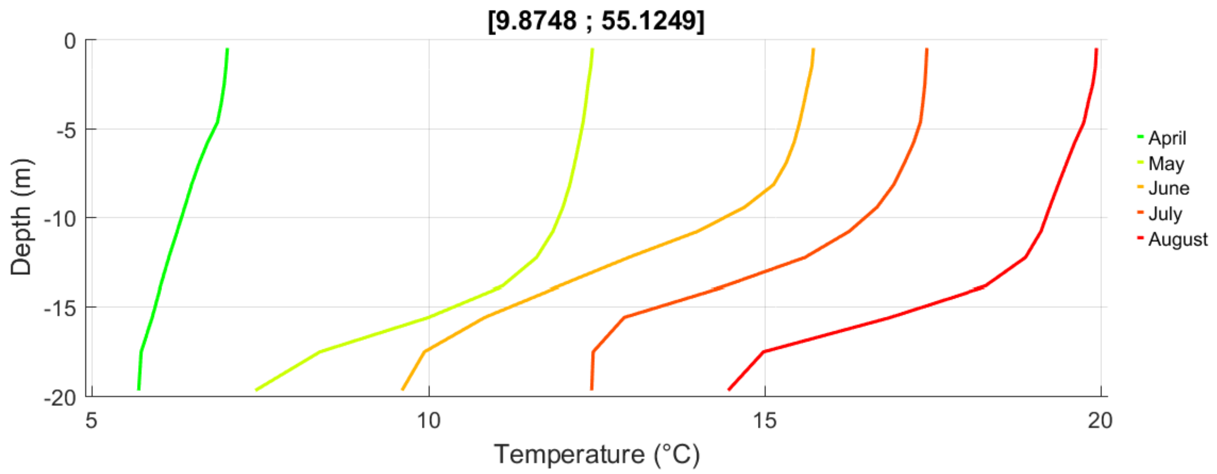

Figure 6.9: Temperature profiles for the area for April - August.

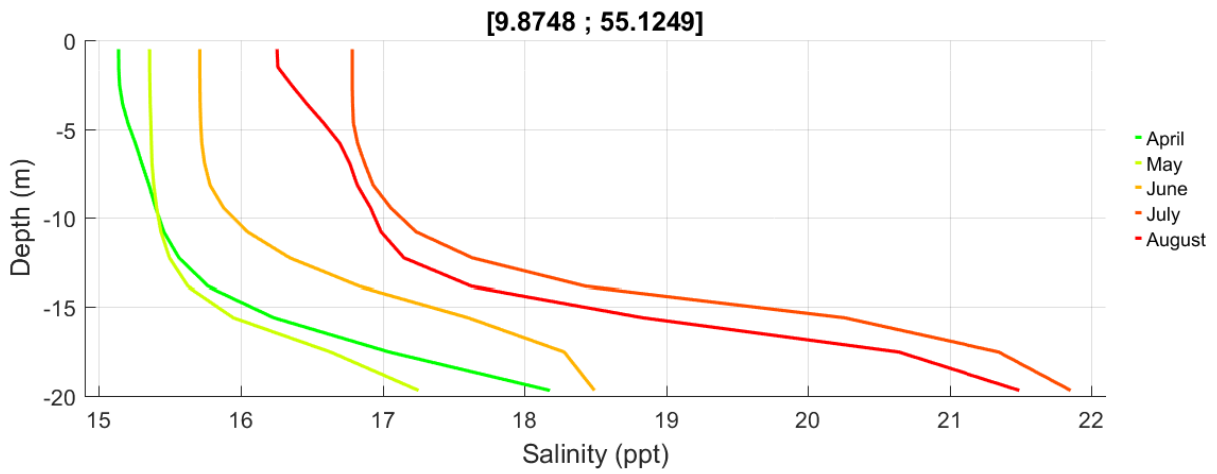

Figure 6.10: Salinity profiles for the area for April - August.

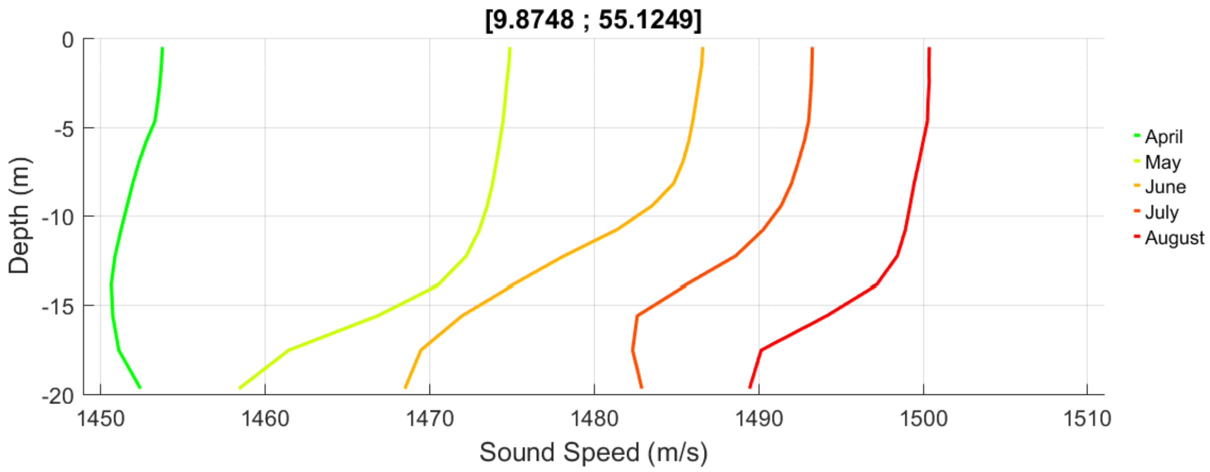

Figure 6.11: Sound speed profiles for the area for April - August.

6.3.4. Sea surface roughness

Sea surface roughness, either from waves or ice cover can cause sound waves to scatter in many different directions, making it more difficult to propagate through the water. This can result in increased attenuation, backscattering and reduced range of underwater sound propagation, particularly at high frequencies.

As a precautionary approach, sound propagation modelling typically regards the sea surface as a perfect mirror (calm water), as this is also the conditions under which pile installation would be preferred. The model is therefore likely to overestimate sound propagation for any conditions where calm water is not the case.

6.3.5. Volume attenuation

Another parameter that has influence on especially the high frequency propagation loss over distance is the volume attenuation, defined as an absorption coefficient dependent on chemical conditions of the water column. This parameter has been approximated using Equation 9, from which is inferred that increasing frequency leads to increased absorption (Jensen, Kuperman, Porter, & Schmidt, 2011).

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4} f^2 \quad \left[\frac{\text{dB}}{\text{km}}\right] \qquad \text{Equation 9}$$

Where f is the frequency of the wave in kHz.

Volume attenuation is taken into account within dBSea, which is used for sound propagation modelling.

6.4. Sound Propagation Software

Numerical models can be used to simulate and predict underwater sound propagation in sea water. These models involve a computer-based simulation that uses mathematical equations to describe the sound propagation as it travels through the sea. In this regard, environmental conditions such as temperature, salinity, sediment, and bathymetry must be taken into account. Different numerical models exist to treat different environmental and source specific conditions, and the choice of numerical model should always be based on the project specific environmental parameters.

NIRAS uses the software tool dBSea, which incorporates three numerical algorithms for predicting sound propagation in complex underwater environments: dBSeaRay, dBSeaPE, and dBSeaNM.

dBSeaRay is a ray-tracing algorithm that simulates the paths of individual sound rays as they travel through the sea, taking into account the effects of sea properties, such as temperature, salinity, and bathymetry, on sound propagation. This allows users to predict sound propagation in a wide range of ocean environments. Inherent limitations for this algorithm make its use in shallow waters for very low frequencies below a few hundred Hz, potentially problematic.

dBSeaPE is a parabolic equation algorithm that solves the parabolic wave equation to simulate sound propagation in the ocean. It is particularly useful for modelling sound propagation over long distances or in areas with complex bathymetry. It however lacks computational efficiency at higher frequencies and is primarily suited for low frequencies.

dBSeaNM uses the normal modes method to predict sound propagation in the ocean. This algorithm takes into account the effects of vertical variations in ocean properties, such as sound speed and density, on sound propagation. It is particularly useful for predicting sound propagation in regions with significant vertical mixing or internal waves, and is most suitable for low frequencies, up to several hundred Hz.

Depending on the local environment and source characteristics, a mix of two numerical models may provide the best result, whereby one algorithm handles the low frequencies, and another handles the high frequencies.

Typically, dBSeaNM or dBSeaPE is used for low frequencies and dBSeaPE or dBSeaRay for high frequencies with a split frequency between the two algorithms, based on $f = \frac{8 \cdot c}{d}$ [Hz], where c is the speed of sound in water [m/s] and d is the average bathymetry depth [m]. For very high frequencies, dBSeaRay is typically preferred.

Output from dBSea is primarily numerical, where each modelled sound propagation radial (direction from source) is represented by the maximum-over-depth (MOD) sound level at each modelled range step. MOD, in this regard, is found by taking the maximum sound level for each range step over all modelled depths. It therefore does not represent the sound level at a specific depth but is a more conservative measure for the highest possible exposure at every range. An example of this concept is shown in Figure 6.12, showing the sound level (x-axis) in dB over depth (y-axis), for a specific distance and direction. On the left side, the MOD is located at 1 m depth below sea-surface and is 114.2 dB, while on the right side, in another direction from the source, MOD is located at 28 m depth and is 114.6 dB. The sound levels at all other depths are ignored in the result output.

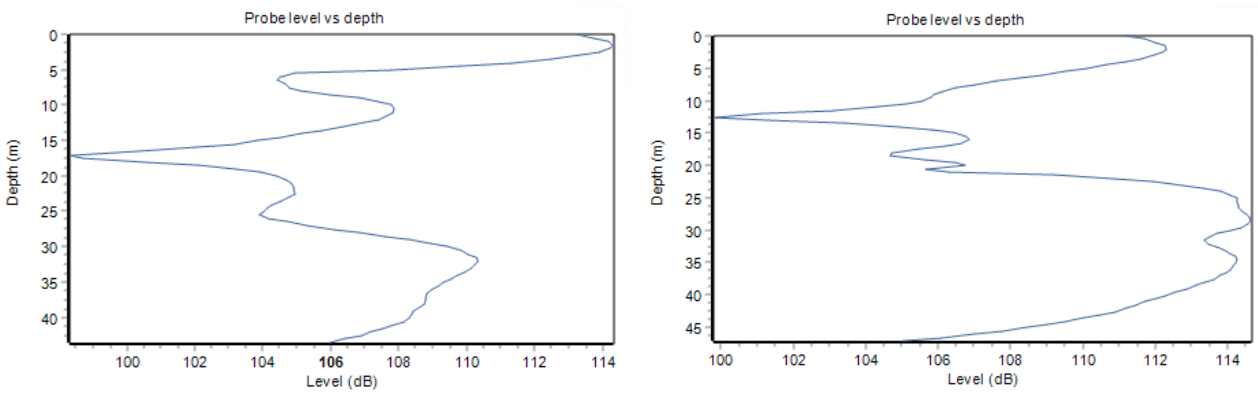

Figure 6.12: Concept of MOD, where the maximum sound level at any depth is extracted for each distance and radial interval. Example shows an MOD value of 114.2 dB (left side) at 1 m depth, and MOD value of 114.6 dB (right side) at 28 m depth.

Prognosis specific parameters for the dBSea setup is specific to the source types included and is therefore described separately for the different source types in the prognosis.

6.4.1. Settings

The software tool dBSea was used for sound propagation modelling, with the configuration listed in Table 6.8.

Table 6.8: Sound propagation modelling tool settings for dBSea.

Parameter	Value
Software version	2.4.12
Grid (range x depth) resolution	25 m x 0.5 m
Number of radials/transects	180 (2°)
Solver	dBSeaPE (Airgun) dBSeaRay (Sparker, Innomar, USBL)
Solver frequency range	12.5 Hz – 5 kHz (Airgun) 12.5 Hz – 160 kHz (Sparker, Innomar, USBL)

Post-processing of the raw sound propagation results into impact ranges was done in NIRAS software tool "SI-LENCE", which implements Equation 7, page 15 for batch processing of different installation scenarios and threshold criteria.

6.5. Results

Sound propagation modelling was conducted in dBSea and post-processing of raw sound levels into impact ranges in NIRAS SILENCE, using the threshold criteria in chapter 4. The results are presented in the following formats:

- **Numerical result tables**: showing the maximum range in any direction from the source to respective threshold criteria.
- **Noise contour maps**: showing the direction specific impact range for certain threshold criteria, along with the total area affected, and overlap with Natura 2000 areas.

Distance to PTS, TTS and injury threshold criteria describe the minimum distance from the source, a marine mammal must at least be deterred to, prior to onset of survey activities, to avoid the respective impact.

Distance to behavioural threshold criteria describe the range at which behavioural reactions are likely to occur when the survey operates at full intensity. During soft start, the impact ranges will be shorter.

6.5.1. Impact ranges for marine mammal threshold criteria

For marine mammals, PTS and TTS threshold criteria are based on the frequency weighted $L_{E,cum,24h,vf,w}$ [dB re. 1 µPa^{2}s], where "w" refers to the species-specific weighting function. Species specific fleeing behaviour as outlined in section 4.1 is assumed. Threshold criteria for behaviour reaction is based on the frequency weighted $L_{p,125ms,w}$ [dB re. 1 µPa]. Resulting impact ranges are provided in Table 1.2 for harbour porpoise, and in Table 6.10 for seals.

Table 6.9: Impact ranges for very high-frequency cetaceans (harbour porpoise).

Activity and activity ID	Position	Impact range for harbour porpoise threshold criteria				
		Impulsive* criteria			Non-impulsive* criteria	
		$L_{E,cum,24h,1.5ms^{-1},VHF}$ $[dB\ re\ 1\mu Pa^2 s]$		$L_{p,rms,125ms,VHF}$ $[dB\ re\ 1\mu Pa]$	$L_{E,cum,24h,1.5ms^{-1},VHF}$ $[dB\ re\ 1\mu Pa^2 s]$	
		PTS 155 dB	TTS 140 dB	Behaviour# 103 dB	PTS 173 dB	TTS 153 dB
Sparker (2A) Model: Duraspark 400 Method: Numerical model Month: April Distances relative to towed equipment	1	60 - 200 m	300 - 950 m	0.95 - 1.3 km	-	-
	2	50 - 180 m	350 - 950 m	1.1 - 1.4 km	-	-
SBP (1A,1B,1C) Model: Innomar Medium 100 Method: Numerical model Month: April Distances relative to vessel	1	-	-	0.7 - 1.1 km	< 25 m	180 - 650 m
	2	-	-	0.9 - 1.1 km	< 25 m	180 - 550 m
	3	-	-	0.8 - 1.1 km	< 25 m	170 - 550 m
	4	-	-	450 - 800 m	25 - 50 m	120 - 450 m
USBL transceiver 1 (offshore) (1A,3A) Model: Kongsberg HiPaP 352P Method: Numerical model Month: April Distances relative to vessel and tow	1	-	-	1.7 - 2.5 km	25 - 70 m	300 - 850 m
	2	-	-	1.8 - 2.3 km	25 - 70 m	350 - 850 m
USBL transceiver 2 (nearshore) (1B,1C,3B,3C) Model: Easytrak Nexus 2 Method: Numerical model Month: April Distances relative to vessel and tow	3	-	-	1.6 - 2.2 km	25 - 110 m	350 - 900 m
	4	-	-	0.45 - 4.4 km	50 - 110 m	0.25 - 1.2 km
Seismic Refraction – mini airgun (4B,4C) Model: Mini G SODERA 20 cu. In. Method: Numerical model Month: April Distances relative to towed equipment	3	< 25 m	< 25 m	130 - 160 m	-	-
	4	< 25 m	< 25 m	90 - 180 m	-	-

*: Based on the equipment sound source characteristics, either impulsive or non-impulsive impact ranges are calculated.
#: Behaviour criterion is calculated for both impulsive and non-impulsive source types, however the threshold criterion is only supported in literature for impulsive source types and should therefore be considered with caution for non-impulsive sources.

The maximum Impact ranges for harbour porpoise behaviour threshold criterion is up to 4.4 km, however in a limited number of directions, when using the USBL system "Easytrak Nexus 2" at maximum source level. This equipment type is active in activities 1B, 1C, 3B and 3C (see section 2.1 for further explanation of activity ID). For activities 1A and 3A, a maximum impact range for the behavioural threshold is 2.5 km, also resulting from the use of USBL. For activity 2A, the sparker is the only active source, and results in a maximum impact range of 1.4 km. For activity 4B and 4C, the impact range is limited to 180 m, primarily due to the very low-frequent nature of the mini airgun used in this activity. It should be noted that the behaviour criterion is only considered valid for impulsive noise sources (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021), however, as no threshold criteria have been established by science for non-impulsive sources, the impulsive criterion is used as a conservative proxy.

Impact ranges for harbour porpoise PTS are limited to 200 m for the 3D UHRS survey (2A) and is below 200 m for all other survey activities, while TTS impact ranges extend to 1.2 km in the worst case, resulting from use of USBL in activities 1B, 1C, 3B and 3C. For activity 1A and 3A this is reduced to 850 m, also from using USBL. For the 3D UHRS survey (2A) a TTS impact range of up to 950 m is observed.

Table 6.10: Impact ranges for phocid carnivores (seals).

Activity	**Position**	**Impact range for seal threshold criteria**			
		Impulsive* criteria $L_{E,cum,24h,1.5ms^{-1},PCW}$ $[dB\ re\ 1\mu Pa^2 s]$		Non-impulsive* criteria $L_{E,cum,24h,1.5ms^{-1},PCW}$ $[dB\ re\ 1\mu Pa^2 s]$	
		PTS 185 dB	TTS 170 dB	PTS 201 dB	TTS 181 dB
Sparker (2A) Model: Duraspark 400 Method: Numerical model Month: April Distances relative to towed equipment	1	< 25 m	50 - 150 m	-	-
SBP (1A,1B,1C) Model: Innomar Medium 100 Method: Numerical model Month: April Distances relative to vessel	1	-	-	< 25 m	< 25 m
USBL transceiver 2 (nearshore) (1B,1C,3B,3C) Model: Easytrak Nexus 2 Method: Numerical model Month: April Distances relative to vessel and tow	4	-	-	< 25 m	< 25 m
Seismic Refraction – mini airgun (4B,4C) Model: Mini G SODERA 20 cu. In. Method: Numerical model Month: April Distances relative to towed equipment	4	< 25 m	< 25 m	-	-

*: Based on the equipment sound source characteristics, either impulsive or non-impulsive impact ranges are calculated. For "All sources active", both impulsive and non-impulsive impact ranges are evaluated from the respective types of equipment.

The impact ranges for seal, are less than 25 m for all thresholds, except for TTS during the 3D UHRS survey, with a maximum impact range of 150 m. This is due to the sparker system which emits sound in the frequency range where seals are sensitive to sound.

The overlap of the noise contours in exceedance of the TTS and behaviour threshold criteria for harbour porpoise, with the Natura 2000 area "Bredgrund" are provided in Table 6.11. No other Natura 2000 area is affected over the investigated threshold criteria.

Table 6.11: Area of Natura 2000 site "Bredgrund" where sound levels exceed harbour porpoise TTS and behaviour criteria.

Equipment	Position	Affected Natura 2000 area [km^2 / % of Natura 2000 area]	
		TTS	Behaviour
Sparker (2A) Model: Duraspark 400 Method: Numerical model Month: April Distances relative to towed equipment	1	0.4 km^2 [0.1 %]	1.7 km^2 [0.3 %]
	2	0 km^2 [0 %]	0 km^2 [0 %]
SBP (1A,1B,1C) Model: Innomar Medium 100 Method: Numerical model Month: April Distances relative to vessel	1	0.2 km^2 [0 %]	1.1 km^2 [0.2 %]
	2	0 km^2 [0 %]	0 km^2 [0 %]
	3	0 km^2 [0 %]	0.2 km^2 [0 %]
	4	< 0.1 km^2 [0 %]	0.1 km^2 [0 %]
USBL transceiver 1 (offshore) (1A,3A) Model: Kongsberg HiPaP 352P Method: Numerical model Month: April Distances relative to vessel and tow	1	0.4 km^2 [0.1 %]	5.8 km^2 [0.9 %]
	2	0 km^2 [0 %]	0 km^2 [0 %]
USBL transceiver 2 (nearshore) (1B,1C,3B,3C) Model: Easytrak Nexus 2 Method: Numerical model Month: April Distances relative to vessel and tow	3	0 km^2 [0 %]	3.1 km^2 [0.5 %]
	4	0.3 km^2 [0 %]	4.6 km^2 [0.7 %]

Noise contour maps for harbour porpoise behavioural impact and for TTS criteria are shown in Figure 6.13 - Figure 6.16. Noise contours are not shown for harbour porpoise PTS and for seal PTS and TTS due to the short impact ranges.

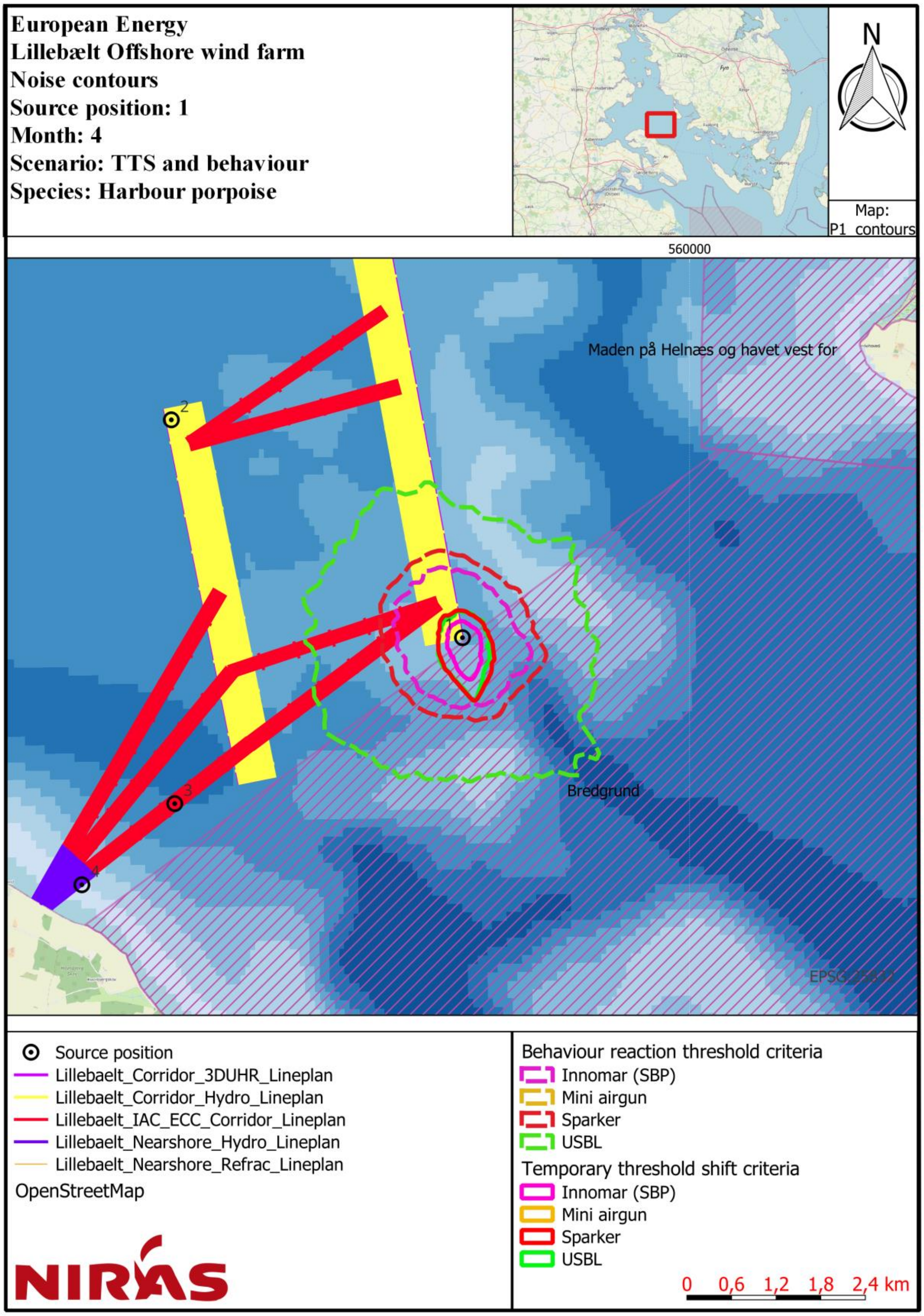

Figure 6.13: Noise contour map for Harbour porpoise, position 1.

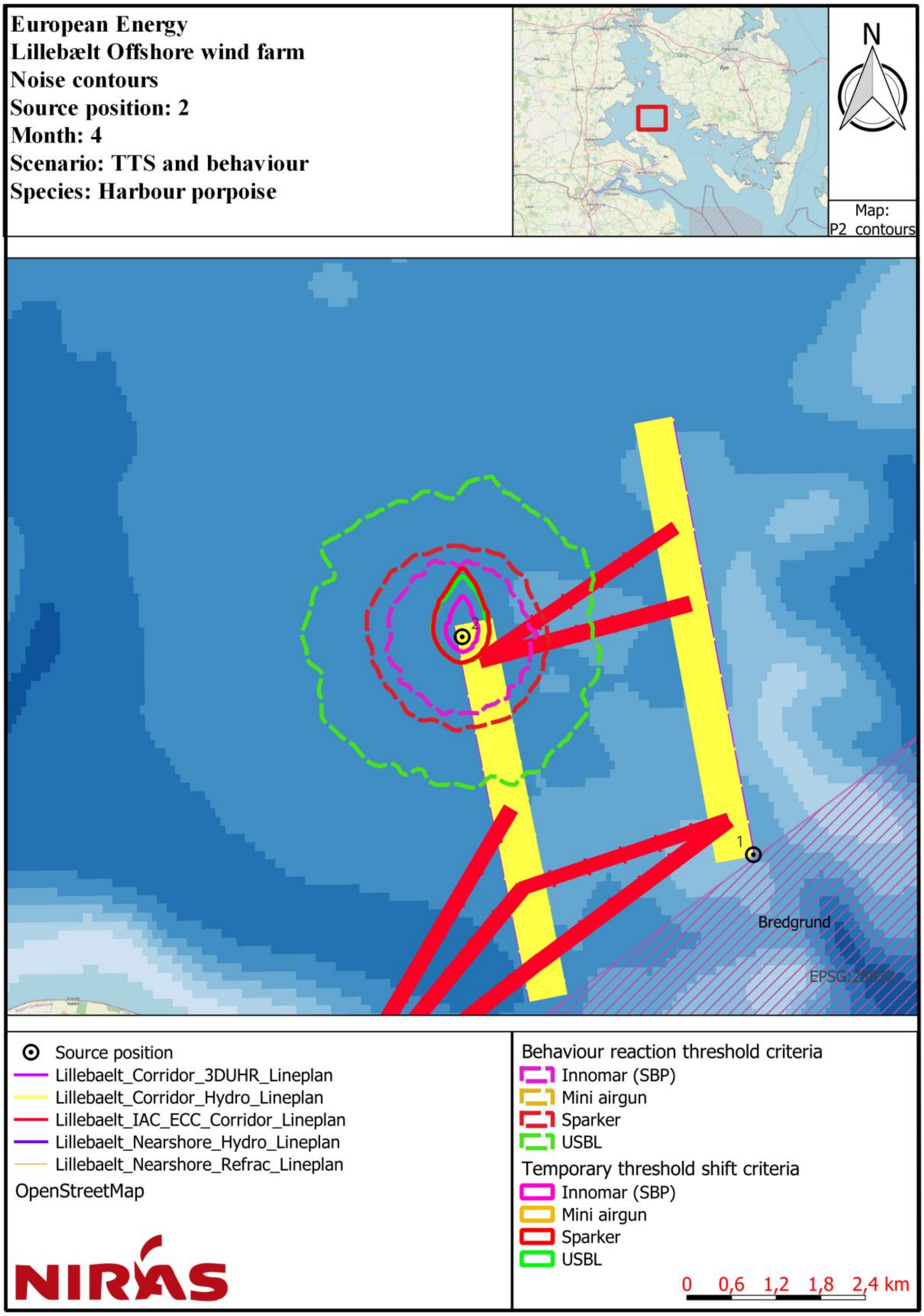

Figure 6.14: Noise contour map for Harbour porpoise, position 2.

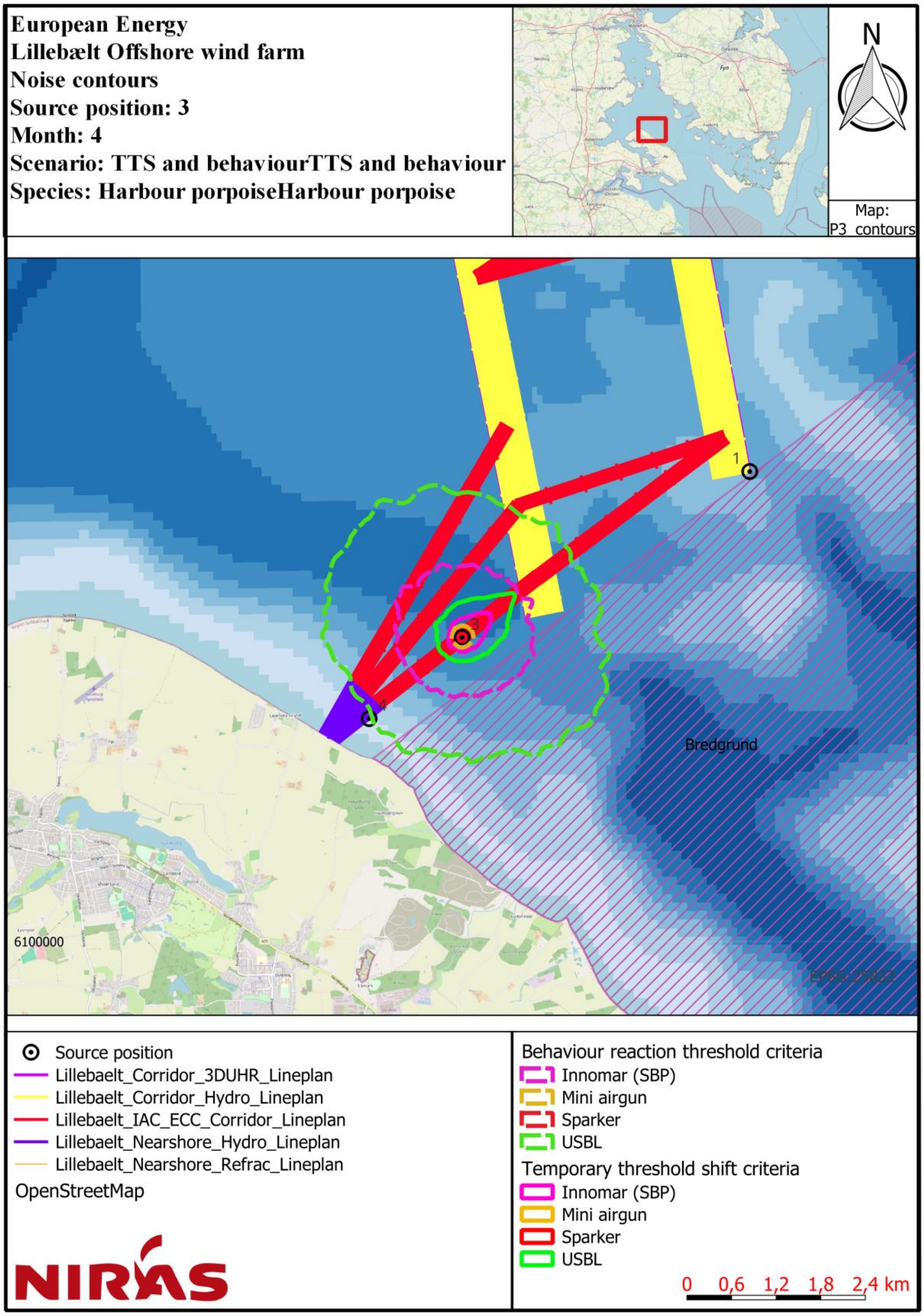

Figure 6.15: Noise contour map for Harbour porpoise, position 3.

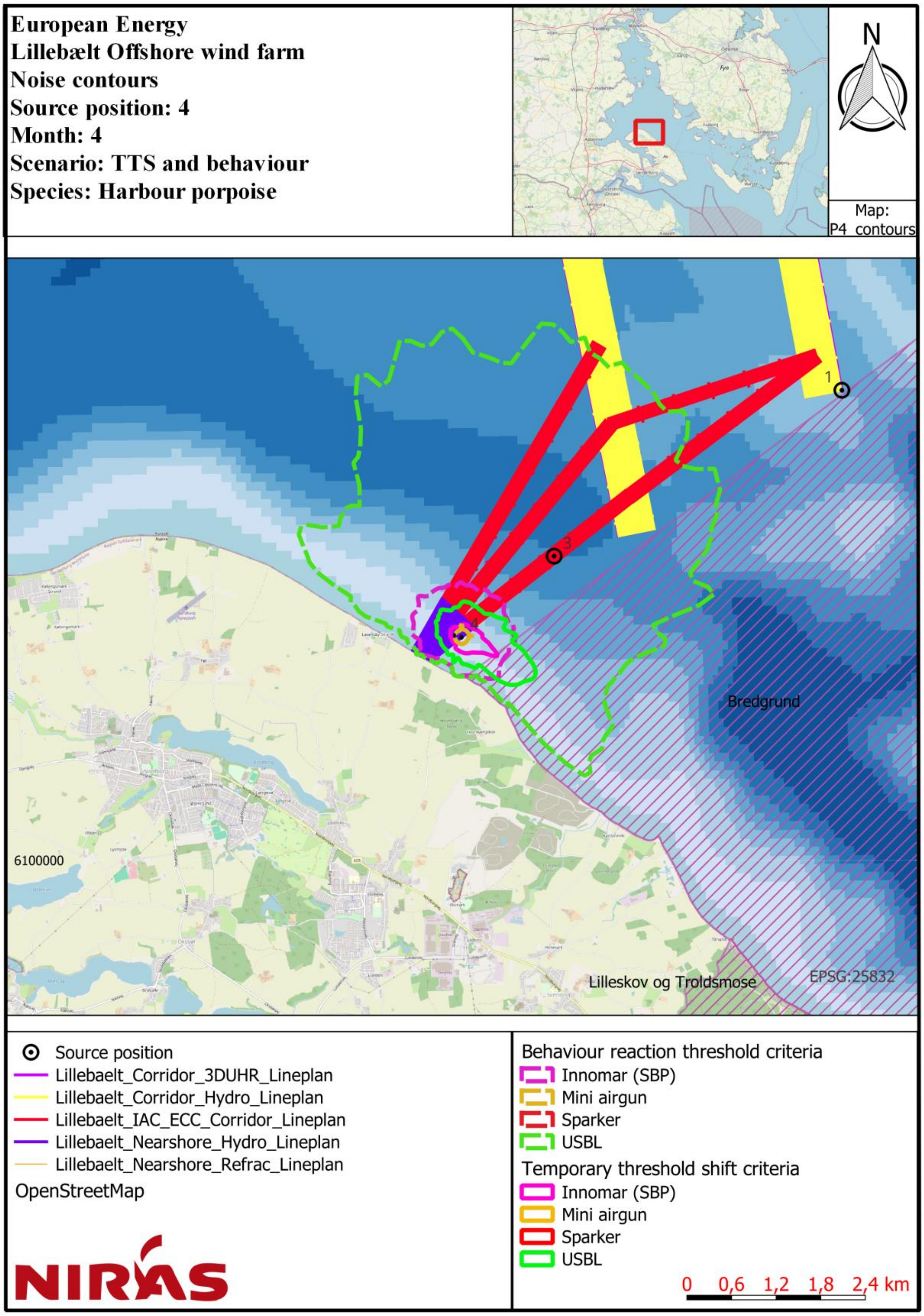

Figure 6.16: Noise contour map for Harbour porpoise, position 4.

7. Bibliography

Copernicus, M. S. (2023). Baltic Sea Physics Analysis and Forecast model, https://doi.org/10.48670/moi-00010.

Coppens, A. (1981). Simple equations for the speed of sound in Neptunian waters. *J. Acoust. Soc. Am. 69(3)*, 862-863.

Danmarks Geologiske Undersøgelse (DGU). (1994). *Pre-Quarternary surface topography of Denmark.* Copenhagen: DGU.

DS/ISO 18405. (2017). DS/ISO 18405 - Underwater acoustics - Terminology.

EC Decision 2017/848. (2017). laying down criteria and methodological standards on good environmental status of marine waters.

EMODnet. (2021). *EMODnet-Geology portal, Seabed Substrate layer*. Retrieved 2021, from https://www.emodnet-bathymetry.eu/data-products

EMODnet. (2022). *EMODnet bathymetry portal*. Retrieved December 2020, from https://portal.emodnet-bathymetry.eu/

EMODnet, CLS. (2022). *EMODnet web portal (Human Activities, vessel density), Collecte Localisation Satellites (CLS)*. Retrieved 06 14, 2023, from https://emodnet.ec.europa.eu/en/human-activities

Energistyrelsen. (2023). *Guideline for underwater noise - Installation of impact or vibratory driven piles.* March.

Erbe, C. (2011). Underwater Acoustics: Noise and the Effects on Marine Mammals. jasco.

Hamilton, E. (1980, November). Geoacoustic modeling of the sea floor. *J. Acoust. Soc. Am., Vol. 68, No. 5*, pp. 1313 - 1340, doi: 10.1121/1.385100.

ICES. (2014). ICES Continuous Underwater Noise dataset. Copenhagen.

ICES. (2018). ICES Continuous Underwater Noise dataset. Copenhagen.

Jacobsen, F., & Juhl, P. M. (2013). FUGA. In *Fundamentals of General Linear Acoustics* (p. 285). Wiley.

Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H. (2011). Computational Ocean Acoustics, 2nd edition. Springer.

Madsen, P., Wahlberg, M., Tougaard, J., Lucke, K., & Tyack, P. (2006). Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. *Marine Ecology Progress Series 309: 279-295.*

Martin, B., Morris, C., & O'Neill, C. (2019). Sound exposure level as a metric for analyzing and managing underwater.

NOAA. (2018). *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0), NOAA Technical Memorandum NMFS-OPR-59.* Silver Spring, MD 20910, USA: April, National Marine Fisheries Service.

OSPAR. (2022). *OSPAR*. Retrieved May 4th, 2022, from https://www.ospar.org/work-areas/eiha/noise

Pace, F., Robinson, C., Lumsden, C., & Martin, S. (2021). *Underwater Sound Sources Characterisation Study: Energy Island, Denmark, Document 02539, Version 2.1.* Technical report by JASCO Applied Sciences for Fugro Netherlands Marine B.V.

Southall, B., Finneran, J., Reichmuth, C., Nachtigall, P., Ketten, D., Bowles, A., . . . Tyack, P. (2019). Marine mammal noise exposure criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals, 45(2), 125-323.

Tougaard, J. (2016). *Input to revision of guidelines regarding underwater noise from oil and gas activities - effects on marine mammals and mitigation measures.* Aarhus University, DCE – Danish Centre for Environment and Energy, 52 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 202.

Tougaard, J. (2021). *Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy.* Aarhus: Aarhus University DCE – Danish Centre for Environment and Energy, 32 pp. Technical Report No. 225 http://dce2.au.dk/pub/TR225.pdf.

Tougaard, J., & Beedholm, K. (2018). Practical implementation of auditory time and frequency weighting in marine bioacoustics. Department of Bioscience, Aarhus University, Denmark.