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ENERGY ISLAND BORNHOLM – TRANSMISSION CABLE

Underwater Noise Modelling – Technical Report

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ENERGY ISLAND BORNHOLM – TRANSMISSION CABLE

Underwater Noise Modelling – Technical Report

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Description	**This study is an underwater noise propagation modelling for survey and construction activities of the proposed transmission cable**

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Contents

Terms and abbreviations

Units:
µm/s – micrometer per second
µPa – micropascal
dB – decibel
deg – degrees
Hz – hertz
kHz – kilohertz
km – kilometer
m – meter
ms – miliseconds
min – minute
mm – millimeter
MW – megawatt
Pa – pascal
s – second

Metrics:
TL – transmission loss
SPL_{pk} – zero-to-peak sound pressure level
SEL – sound exposure level
SEL_{cum} – cumulative sound exposure level
SPL – continuous sound pressure level
SPL_{rms} $(\mathrm{L}_{\mathrm{p,rms}})$ – Root mean squared sound pressure level
$\mathrm{L}_{\mathrm{eqT}}$ – Equivalent continous sound pressure level
T – averaging time
Z – acoustic characteristic impedance
c – sound velocity
f – frequency
n – count

Abbreviations:
DEA – Danish Energy Agency
EIA – Environmental impact assessment
GEBCO – The General Bathymetric Chart of the Oceans
HiPAP – High precision acoustic posistioning system
ICES – International Council for the Exploration of the Sea
PTS – permanent threshold shift
PCW – phocid carnivores in water, seals weighted sound level
RE. – Reference value
RMS – Root Mean Squared
SBP – Sub bottom profiler
SMM – Standard Mitigation Measures
SONAR – sound navigation ranging
TSHD – trailing suction hopper dredger
TTS – temporary threshold shift
USBL – ultra short baseline (acoustic positioning system)
VHF – very high frequency

1. Summary

This report describes the work carried out in relation to the modelling and assessment of the underwater noise as input to the Environmental impact assessment (EIA) for the offshore cable from Bornholm to Sjælland (Zealand) in Danish waters. This study is an underwater noise propagation modelling for the construction of the proposed offshore cable and addresses the project activities where acoustic equipment (hereafter referred to as surveys activities) is used and construction activities. Modelling scenarios were defined to reflect the actual project as well as possible, with the objective to determine expected noise levels, allowing for accurate impact assessment. The modelling included both cumulative and single strike sound exposure levels as well as zero-to-peak sound pressure levels. A comparison with various criteria from the literature leads to the following tables as a summary of worst-case impact ranges for harbor porpoises, seals and fish for survey and construction activities for the offshore cable route between Bornholm and Sjælland.

1.1 Summary Results

A summary of the results (maximum continuous and impact threshold distances) is provided here in Tables 1-1, 1-2 and 1-3 to give a general overview of the potential distances of continuous and impact underwater noise. Only worst-case results are shown in the tables, and it is stated in which cable corridor section the worst-case results were found (Bornholm or Øresund).

The model results show that permanent threshold shift (PTS) for harbor porpoises may occur within a maximum of 5 meters of the sound source when using USBL in the frequency range 20-34 kHz. PTS in harbor porpoises is not expected from the remaining project activities. Temporary threshold shift (TTS) in harbor porpoises is expected to occur within a maximum of 950 meters from the sound source when using the USBL in the frequency range 20-34 kHz, with smaller impact distances for the 5-10 kHz range, chirp, and construction activities, ranging from 300 to 0 meters.

Behavioral effects for harbor porpoises are expected to occur within a maximum of 6.4 km or 3.6 km from the sound source during dredging activities. Two calculations have been done for dredging, one for the worst-case, which is at 187 dB, and another that has been restricted to a 20% overlap with the nearby Natura 2000 area, such that the noise level was lowered to 178 dB.

Project activities are not expected to lead to PTS nor TTS for seals, while behavioral changes are only expected within 5 meters from the sound source when using USBL or chirp. Underwater noise from project activities are not expected to lead to injuries in fish. For detailed results see Section 9.

1.1.1 Harbor porpoise

Table 1-1. Summary of worst-case distances for different thresholds, PTS, TTS and behavior for survey activities among all seasons, for harbor porpoises. USBL subscript indicate the working frequency range in Hz.

Activity	Location	Working Frequency [kHz]	PTS	TTS	Behavior
Chirp	Øresund	5 – 15	0 m	90 m	3.7 km
$USBL_{5\text{-}10}$	Bornholm	5 – 10	0 m	300 m	4.7 km
$USBL_{20\text{-}34}$	Øresund	20 – 34	5 m	950 m	5.4 km

Table 1-2. Summary of worst-case distances for different thresholds, PTS, TTS and behavior for construction activities among all seasons, for harbor porpoises. Dredging subscript indicate the source level for the activity, in dB.

Activity	Location	PTS	TTS	Behavior
$Dredging_{178}$	Øresund	0 m	10 m	3.6 km
$Dredging_{187}$	Øresund	0 m	40 m	6.4 km
Rock cutting / drilling	Øresund	0 m	0 m	1.5 km
Survey Vessel	-	0 m	0 m	0 m

1.1.2 Seal

Table 1-3. Summary of worst-case distances for different thresholds, PTS, TTS and behavior for survey activities among all seasons, for seals. USBL subscript indicate the working frequency range in Hz.

Activity	Working Frequency [kHz]	PTS	TTS	Behavior
Chirp	5 – 15	0 m	0 m	5 m
$USBL_{5\text{-}10}$	5 – 10	0 m	0 m	5 m
$USBL_{20\text{-}34}$	20 – 34	0 m	0 m	5 m

Table 1-4. Summary of worst-case distances for different thresholds, PTS, TTS and behavior for construction activities among all seasons, for seals.

Activity	PTS	TTS	Behavior
Dredging	0 m	0 m	N/A
Rock cutting / drilling	0 m	0 m	N/A
Survey Vessel	0 m	0 m	N/A

1.1.3 Fish and Larvae

Table 1-5. Summary of worst-case distances for different thresholds, mortal injury, recoverable injury and TTS for survey activities among all seasons, for fish and larvae. USBL subscript indicate the working frequency range in Hz.

Activity	Working Frequency [kHz]	Mortal injury	Recoverable injury	TTS
Chirp	5 – 15	0 m	0 m	0 m
$USBL_{5\text{-}10}$	5 – 10	0 m	0 m	0 m
$USBL_{20\text{-}34}$	20 – 34	0 m	0 m	0 m

Table 1-6. Summary of worst-case distances for different thresholds, recoverable injury and TTS for construction activities among all seasons, for fish.

Activity	Recoverable injury	TTS
Dredging	0 m	0 m
Rock cutting / drilling	0 m	0 m
Survey Vessel	0 m	0 m

2. Introduction

Energinet is planning to construct an offshore transmission cable connection to connect Energy Island Bornholm with Zealand, see Figure 2-1. The transmission cable connection is a central part of the Danish Energy Island Bornholm project, that will significantly contribute to The Danish Government's ambitious commitment to a 70 % reduction in Greenhouse Gas Emissions (GHG) by 2030, and to EU's political commitment to be climate neutral by 2050 /3/.

This report serves as a technical background report for the environmental impact assessment (EIA) for Transmission Facilities Supporting Connection of Wind Energy to Bornholm Energy Island including the installation of the offshore transmission cable. This report presents an underwater noise modelling for the two sections of the cable corridor, which are placed within Danish waters. The two sections include the section from landfall on Bornholm to the Swedish EEZ (Bornholm section) and the section between the Swedish EEZ and landfalls on Sjælland (Zealand) in Køge Bugt (Øresund section). The cable located in Swedish international waters is not included as part of this assessment and is approved according to Swedish law.

The aim of the underwater noise modelling is, in relation to the Environmental Impact Assessment (EIA) application for the project, to provide as the background for the assessment of underwater noise impacts on marine mammals and fish in the EIA. This also includes an investigation of the expected noise propagation from survey and construction activities related to the offshore cables.

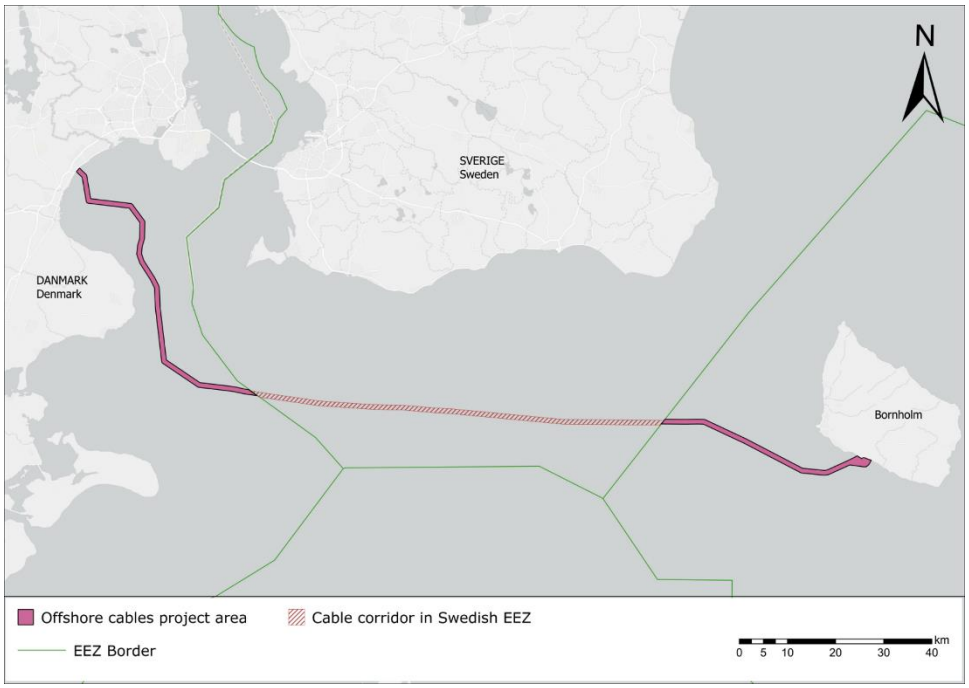


Figure 2-1. Overview of the offshore cable corridor in Danish and Swedish waters.

The offshore cable activities involve determining the seabed and cable conditions during various surveys with use of acoustic survey equipment, and cable installation activities that produce noise at levels that can potentially disturb or harm marine mammals and fish in the area.

The construction of an offshore cable involves activities that can produce underwater noise such as drilling and dredging and has the potential to disturb or harm marine mammals and fish in the area.

The purpose of this study is to provide the potential worst case underwater noise levels associated with survey activities and construction activities of the cable. The study of underwater noise propagation considers the following scenarios:

- Surveys and general use of acoustic equipment
- Construction

The sources identified in this study are based on the source level and the frequency composition, and from methods presented in the technical project description. Assumptions are required to be made, and other methods can be used as selected methods are the worst-case methods, giving freedom to use alternative methods, as these would have a lower noise impact.

The modelling will be performed in accordance with Environmental Impact Assessments (EIA) of similar Danish Energy Agency (DEA) guidelines on underwater noise assessment for continuous and impact noise: Guidelines for underwater noise, Prognosis for EIA and SEA assessments, Danish Energy Agency (DEA; Energistyrelsen) May 2022 /1/ and Guideline for underwater noise - Installation of impact or vibratory driven piles March 2023, DEA /2/. These guidelines form the basis for calculation and assessment of underwater noise.

For each phase of the project, "worst-case" noise sources will be identified, and based on this, representative modelling positions will be chosen. The modelling is based on the design for the actual project to the extent that concrete technical data is available, while a "worst-case" assumption will be applied for currently unspecified inputs. The modelling includes the determination of impact distances from the various activities where potential impact can occur.

3. Noise Modelling Positions

Multiple representative locations have been chosen for each model, which is split into the Bornholm section, and the Øresund section. Locations are selected based on the depth and proximity to land. The following positions have been chosen; close to the coast, in shallow waters and deep waters along the cable corridor, the depth is represented in blue, going from shallow (light blue) to deep (dark blue), see Figure 3-1 and Figure 3-2.

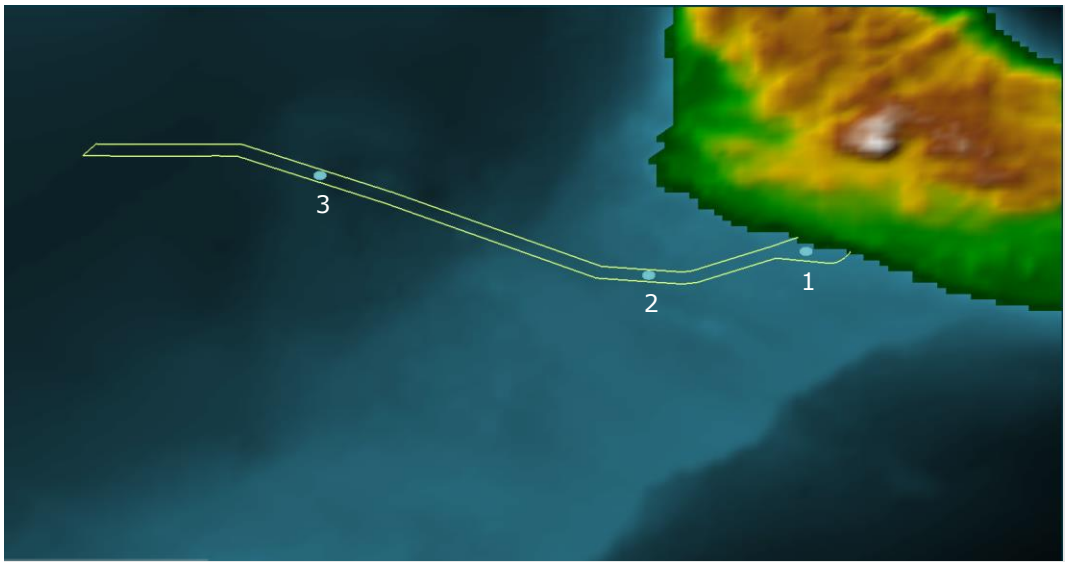


Figure 3-1. Selected source positions for Bornholm scenarios, both for construction and survey phases. Position 1 is near coast, position 2 is shallow waters and position 3 is in deeper waters than 1 and 2 (this can also be seen by the tones of blue going from a light blue (shallow) to a dark blue (deep).

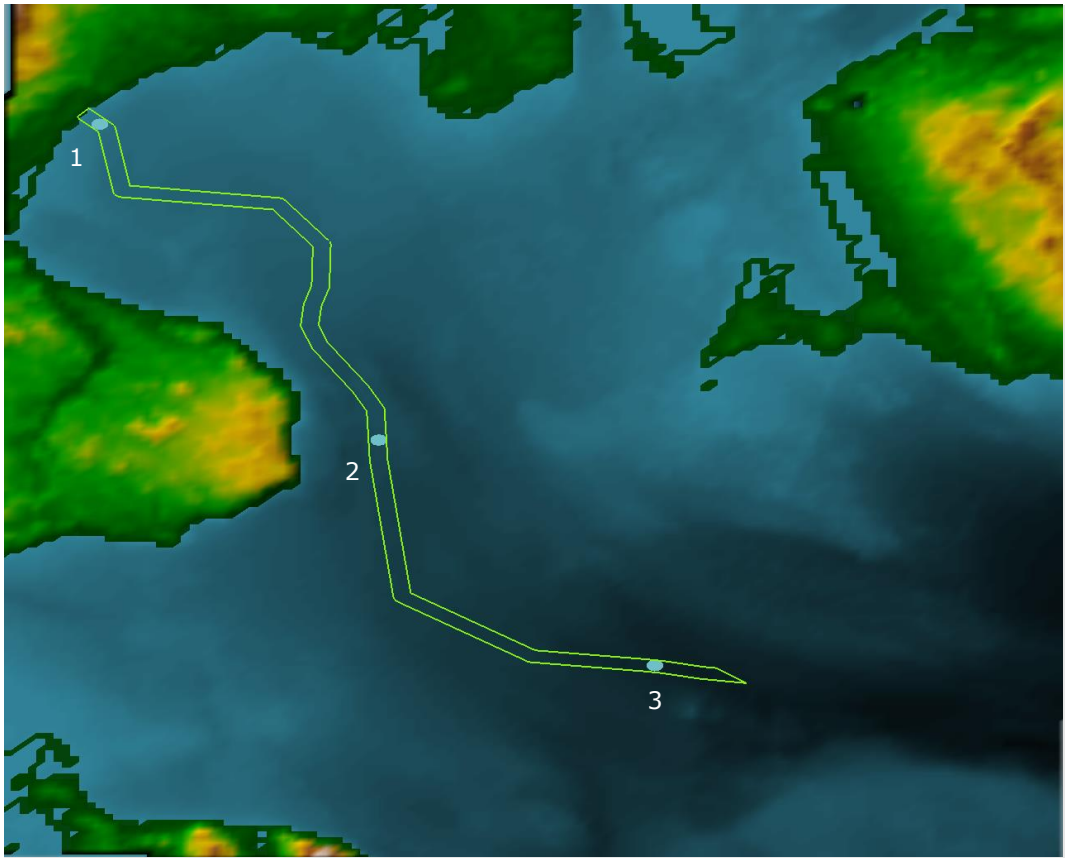


Figure 3-2. Selected source positions for Øresund scenarios, both for construction and survey phases. Position 1 is near coast, position 2 is shallow waters and position 3 is in deeper waters than 1 and 2 (this can also be seen by the tones of blue going from a light blue (shallow) to a dark blue (deep).

4. Underwater Sound

Underwater sound, like sound in the air, is disturbances from a source in a medium – here water – travelling in a three-dimensional manner as the disturbance propagates with the speed of sound.

Sound travels at different speeds in different media. The speed of sound is determined by the density and compressibility of the medium. Density is the amount of mass per volume, and compressibility is a measure of how much a substance could be compacted for a given pressure. The denser and the more compressible, the slower the sound waves would travel. Water is much denser than air, but since it is nearly incompressible the speed of sound is about four times faster in water than in air. The speed of sound can also be affected by temperature. Sound waves tend to travel faster at higher temperatures.

Underwater sound can be measured as a change in pressure and is described as sound pressure and can be measured with a pressure sensitive device (hydrophone).

Because of the large range of pressure amplitudes in sound, it is convenient to use decibel (dB), which is a logarithmic scale to quantify pressure levels. The underwater sound pressure level in decibels (dB) is defined in the following equation:

Sound Pressure Level (SPL) = $20\log_{10}(P/P_0)$

P is the pressure and P_0 is the reference pressure. The reference pressure is 1 micropascal (µPa) for underwater sound which is different from sound pressure levels in the air, which is 20 µPa. For this reason, sound pressure levels in the water and air cannot be directly compared.

Underwater sound levels vary in accordance with the sound source's time signature and acoustic environmental conditions and can be defined in terms of exposure, average and/or maximum levels. The following acoustic parameters are commonly used to assess the noise impact from underwater noise sources for the identified local marine life /17/.

Sound Pressure Level (SPL) – this quantifies the magnitude of a sound at a given point, i.e., how loud it is, and is measured in decibels (dB). As a relative unit, dB is quoted relative to 1 micropascal in underwater studies (units in dB re. 1 µPa).

Sound Exposure Level (SEL) – this is a decibel measure for describing how much sound energy a receptor (e.g., a marine mammal) has received from an event and is normalized to an interval of one second. It can be thought of as a logarithmic measure of sound exposure and hence a 3 dB increase in SEL equates to a doubling of sound energy (units in dB re. 1 μPa^2s).

Cumulative Sound Exposure (SEL_{cum}) – this is the time integral of the squared pressures over the duration of a sound or series of sounds. It enables sounds of differing duration and level to be characterized in terms of total sound energy normalized to an interval of one second (units in dB re. Pa^2s).

Peak pressure level (SPL_{pk}) – the zero-to-peak sound pressure at a given point in time.

Root mean square (RMS) – the sound pressure averaged over a given time; The SPL_{rms} is commonly used to evaluate the effects of continuous noise sources. The RMS sound pressure level or SPL_{rms} (symbol; $L_{p,\,rms}$) is the root mean squared sound pressure level. This is the Root Mean Square (RMS) of the sound pressure taken over a time interval $T=t_2-t_1$ [s]. The related level in dB is often referred to as "equivalent continuous sound pressure level", (symbol: L_{eqT}) over time interval T. The sound pressure level is abbreviated as SPL. The reference value for underwater sound pressure is p_0=1 µPa. For the purpose of evaluating behavioral reactions to the noise, the RMS-sound pressure level calculated over a time interval corresponding to the average integration time of the mammalian ear (125 ms) is used.

Pulsed/impulsive sound – a discontinuous sound source comprising one or more instantaneous sounds such as piledriving or munitions clearing (blasting).

Continuous sound – sound source, like a vessel engine, or humming as in drilling operation.

Sonar - (Sound navigation ranging) is a technique that uses underwater sound propagation for site surveys and navigation by emitting pulses of sounds (at specific frequencies) and listening for echoes. Specific geophysical survey equipment such as seismic pingers are considered to be Sonar.

5. Underwater Noise Propagation Model

For the underwater noise propagation model the program dBSea 2.3.4 is used. The underwater noise propagation model calculates estimates of the sound field generated from underwater noise sources. The modelling results are used to determine the potential impact distances (noise maps/contour plots) from the identified significant underwater noise sources for the various

identified marine life in the area. Based on source location and underwater source noise level, the acoustic field at any range from the source is estimated using dBSea's acoustic propagation model (Parabolic equation method (≤500 Hz), and ray tracing (> 500 Hz)) /4/. The noise propagation modelling uses acoustic parameters appropriate for the specific geographic region of interest, including the expected water column sound speed profile, the contours of the seabed floor called the bathymetry, and the bottom geo-acoustic properties, to produce site-specific estimates of the radiated noise field as a function of range and depth. The acoustic model is used to predict the directional transmission loss from source locations corresponding to receiver locations. The received level at any three-dimensional location away from the source is calculated by combining the source level and transmission loss, both of which are direction dependent. Underwater acoustic transmission loss and received underwater noise levels are a function of depth, range, bearing, and environmental properties. The output values can be used to compute or estimate specific noise metrics relevant to safety criteria filtering for frequency-dependent marine mammal hearing capabilities.

The model assumes that outgoing energy dominates over scattered energy and computes the solution for the outgoing wave equation. An approximation is used to provide two-dimensional transmission loss values in range and depth, i.e., computation of the transmission loss as a function of range and depth within a given radial plane is carried out independently of neighboring radials (reflecting the assumption that noise propagation is predominantly away from the source).

The received underwater noise levels at any location within the region of interest are computed from the 1/3-octave band source levels by subtracting the numerically modelled transmission loss at each 1/3-octave band center frequency and summing across all frequencies to obtain a broadband value. For this study, transmission loss and received levels were modelled for 1/3-octave frequency bands between 20 and 80,000 Hz. Because the source of underwater noise considered in this study are predominantly low-frequency sources, this frequency range is sufficient to capture essentially all of the energy output. The received levels will be converted to all the applicable underwater acoustic parameters.
Predictions have been performed for summer and winter. The underwater noise propagation is dependent on the water temperature, salinity, and depth, also known as the water column profile. The noise level is calculated based on these parameters and the maximum distance and/or noise level will be shown based on the entire water column profile.

The noise propagation model will run with the source levels, activity time and environmental parameterization and will be generated into noise maps. The levels depicted in the noise maps will be the maximum predicted level for that location at any depth down to the bottom of the sea floor and will include the following acoustic parameters for each of the identified sound sources:

- SEL, Sound Exposure Level (unweighted, VHF and PCW weighted), dB re. 1µPa^{2}s.
- SEL$_{cum}$, Cumulative Sound Exposure Level (VHF and PCW weighted), dB re. 1µPa^{2}s.
- SPL$_{rms,125ms}$ levels (unweighted, VHF weighted), dB re. 1µPa.
- SPL$_{Pk}$ (unweighted), from zero to peak dB re. 1µPa

The results of the acoustic modelling (noise maps and impact distances) will be reported in terms of the underwater noise levels of each specific acoustic metric for distances up to 50 km. A vertical noise propagation profile plot for the dominant noise source frequency band will be generated to show the variation in underwater noise propagation with regards to sea depth.
To provide adequate resolution of impact distances, the calculation grid set in dBSea can be seen in Table 5-1.

Table 5-1. The settings for dBSea calculation, the interpolation grid given in x,y and z, points. Where radial slices determine the number of slices the model is divided into, where range points define the amount of calculation points per radial slice.

Parameter	Value	Description
Points (x)	250	x-value for calculation grid
Points (y)	250	y-value for calculation grid
Points (z)	40	z-value for calculation grid
Radial slices	35	The amount of calculation slices around a source
Range points	300	The number of calculation points along each slice

6. Baseline for Underwater Noise Impact Assessment

The source sound pressure levels and associated impact zones can be viewed as indicative precautionary ranges. It is important to note that it is highly unlikely that any marine mammal would stay at a stationary location or within a fixed radius of any other noise source. The behavior of receptors (animals) is included in a model of exposure. A worst-case assumption of a stationary animal can be made, but this is likely to overestimate the extent of especially the impact threshold zones considerably and therefore included is a simple model for animal escape, including a threshold for reaction followed by movement away from the source, either in a straight line perpendicular to the track line or radially away from the sound source. Marine mammal movement is modelled as a movement with a speed of 1.5 m/s /2/.

Fish are assumed to flee differently from the noise source /5/. Fish fleeing will be modelled in calculating the sound exposure level. For Herring, 1.04 m/s and for Cod 0.38 m/s (juvenile) and 0.9 m/s (adult) have been use for this study.

The fleeing of the animal will be affected by the overall sound exposure for a 24-hour activity period and is included in the calculations as described in the Guidelines for underwater noise, Prognosis for EIA and SEA, Danish Energy Agency (DEA) May 2022 /1/.

6.1 Marine Mammals

Generally, the effect of noise on marine mammals can be divided into four broad categories that largely depend on the individual's proximity to the sound source:

- Detection
- Masking
- Behavioral changes
- Physical damages

The limits of each zone of impact are not sharp, and there can be an overlap between the zones. The four categories are described below /6/.

Detection ranges depend on background noise levels as well as hearing thresholds for the animals in question.

Masking occurs when noise interferes with an animal's ability to perceive (detect, interpret, and/or discriminate) a sound. There are still many uncertainties regarding how masking affects marine mammals.

The occurrence and significance of a **behavioral change** varies by individual, species, and circumstances. Some sounds may not cause any response, while others may result in minor to significant changes in a variety of behaviors, such as diving, surfacing, vocalizing, feeding, and/or mating.

Physical damage to marine mammals relates to damage to the hearing organ. Physical damages to the hearing organ may lead to permanent changes in the animals' detection threshold (permanent threshold shift, PTS). This can be caused by the destruction of sensory cells in the inner ear, or by metabolic exhaustion of sensory cells, support cells or even auditory nerve cells. Hearing loss is usually only temporary (temporary threshold shift, TTS) and the animal will regain its original detection abilities after a recovery period. For PTS and TTS, the sound intensity is an important factor for the degree of hearing loss, as is the frequency, the exposure duration, and the length of the recovery time.

The proposed criteria for PTS, TTS and behavioral response in this report are based on results presented in scientific literature and/or commonly and currently used in environmental impact assessments of underwater noise. The behavior of receivers (animals) is essential to include in a model of exposure.

6.1.1 Marine Mammal Auditory Weighting Function

The ability to hear sounds varies across a species' hearing range. Most mammal audiograms have a typical "U-shape," with frequencies at the bottom of the "U" being those to which the animal is more sensitive, in terms of hearing. Auditory weighting functions best reflect an animal's ability to hear a sound (and do not necessarily reflect how an animal will perceive and behaviorally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted. Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS/TTS acoustic thresholds expressed in the SELcum metric, which consider what is known about marine mammal hearing /7/. Very High Frequency (VHF) weighted impact threshold limits are applicable to harbor porpoises. Phocid Carnivores in Water (PCW) weighted threshold limits are applicable to seals.

6.1.2 Noise Source Characteristics

When analyzing the auditory effects of noise exposure, it is often helpful to broadly categorize noise as either impulse noise — noise with high peak sound pressure, short duration, fast rise-time, and broad frequency content — or non-impulsive (i.e., steady state) noise. When considering auditory effects, sonars, other coherent active sources, and vibratory pile driving are non-impulsive sources, while explosives, impact pile driving, and air guns are treated as impulsive sources. Note that the terms non-impulsive or steady-state do not necessarily imply long duration signals, only that the acoustic signal has sufficient duration to overcome starting transients and reach a steady-state condition. For harmonic signals, sounds with duration greater than approximately 5 to 10 cycles are generally considered to be steady state.

6.2 Harbor porpoise Criteria

Table 6-1 summarizes criteria for assessing impacts for marine mammals (harbor porpoise). The criteria are associated with different impacts and limits. These threshold values for impact have been determined by an assessment of available values from the most recent scientific literature and accepted limits /2//7/.

Table 6-1. Harbor porpoise noise threshold criteria for hearing loss and behavior.

Species	Functional hearing group	Noise effect	Threshold (Impulsive noise)	Threshold (Non-impulsive noise)	Reference
Harbor porpoise	Very High frequency cetaceans	PTS	155 dB SELcum (weighted)	173 dB SELcum (weighted)	*DEA 2023*
		TTS	140 dB SELcum (weighted)	153 dB SELcum (weighted)	*DEA 2023*
		Behavior	103 dB SPLrms,125 ms (weighted)	103 dB SPLrms,125 ms (weighted)	*DEA 2023*
Weighted thresholds are VHF (Very High Frequency) weighted. *PTS- and TTS-threshold include fleeing speed of 1.5 m/s (DEA 2023)*					

6.3 Seals Criteria

Table 6-2 summarizes criteria for assessing impacts for marine mammals (seals). The criteria are associated with different impacts and limits. These threshold values for impact have been determined by an assessment of available values from the most recent scientific literature and accepted limits /2//7//8/.

Table 6-2. Seal noise threshold criteria for hearing loss and behavior.

Species	Functional hearing group	Noise effect	Threshold (Impulsive noise)	Threshold (Non-impulsive noise)	Reference
Seals	Phocid carnivores in water (Grey and harbor seals)	PTS	185 dB SELcum (weighted)	201 dB SELcum (weighted)	*DEA 2023*
		TTS	170 dB SELcum (weighted)	181 dB SELcum (weighted)	*DEA 2023*
		Behavior	151 dB SELss (unweighted)	-	*Russel et al. 2016*
Weighted thresholds are PCW (Phocid carnivores in water) weighted. *PTS- and TTS-threshold include fleeing speed of 1.5 m/s (DEA 2023)*					

6.4 Fish Criteria

Sound, at higher intensities, may have a diverse range of effects on fish. These may include death, hearing impairment, damage to anatomical structures, and changes in physiology, neural function, behavior, and development.

Table 6-3 summarizes criteria for assessing impacts for fish. The criteria are associated with different impacts and limits. These threshold values for impact have been determined by an assessment of available values from the most recent scientific literature and accepted limits /5//9/.

Definition of effects:

- *Mortality and mortal injury:* immediate or delayed death.
- *Recoverable injury*: injuries, including hair cell damage, minor internal or external hematoma, etc. None of these injuries are likely to result in mortality.
- *TTS:* short- or long-term changes in hearing sensitivity that may or may not reduce fitness.

Exposure distances for herring and cod including escape rates. For herring this study will use 0.9 m/s and for cod this study has used 0.38 m/s (juvenile) and 1.04 m/s (adult).

Table 6-3. Fish and larvae threshold criteria for hearing loss and injury. Juv=juvenile.

Species	Flee speed [m/s]	Noise effect	Threshold (Impulsive noise)	Threshold (Impulsive noise)	Threshold (Continuous noise)
Fish	Cod (juv) – 0.38 Herring – 0.9 Cod (adult) – 1.04	Mortal injury	207 dB SPLpk	207 dB SELcum	-
	Cod (juv) – 0.38 Herring – 0.9 Cod (adult) – 1.04	Recoverable injury	207 dB SPLpk	203 dB SELcum	222 SELcum,48h
	Cod (juv) – 0.38 Herring – 0.9 Cod (adult) – 1.04	TTS	-	186 dB SELcum	204 SELcum,48h
Larvae	0	Mortal injury	207 dB SPLpk	210 dB SELcum	-
All levels are broadband unweighted. *Reference to guidelines by Popper 2014*					

7. Underwater Noise Source Model Inputs

The following sections presents the significant underwater noise sources for each phase of the project and give their respective sound source levels, characteristics, and frequency spectrum. These parameters were determined based on available measurement data and adjusted to meet the offshore cable proposed design concepts and were used as input to the underwater noise propagation model.

Based on existing underwater noise measurements, the noise source levels and frequency spectrum for the identified significant noise sources for potential underwater noise impacts have been estimated.

Where applicable, in order to obtain an equivalent source level at 1 meter from the source, for the purpose of acoustic propagation modelling, the pressure field was backpropagated according to cylindrical spreading loss, or 15·log(r). The purpose of the back-propagation step is to determine the effective source level at 1 meter that is used in the acoustic propagation model.

7.1 Site Investigation Noise Sources

The following site investigation noise source levels and characteristics are based on supplier data sheets and available published measurement data. Some of the sources have a directivity, focusing towards the seafloor, which have been included in the modelling. The USBL has been modelled with two different frequency ranges in mind, the default frequency range is from 20 kHz to 34 kHz, which is standard for most USBL equipment. The second range is the project frequency range limit from 5 kHz to 10 kHz. The project frequency limit is set due to the standard working frequency range of a USBL being within the hearing range of harbor porpoises. Thus, if this constraint can be implemented, it could reduce the impact distances. All survey sources are presented in Table 7-1.

Table 7-1. Source information and source levels used in the sound propagation model for survey equipment. The "-" marks information that has not been acquired or is irrelevant, for that particular activity.

Source	Duration (hours/day)	Speed (knots/h)	Model type (Reference)	Sound type	Source depth (meter)	Frequency (kHz)	$SPL_{rms, 125\ ms}$ (dB)	SEL (dB)	SPL_{pk} (dB)	"Pulse" length (ms)	Shot rate (Hz)	Directionality (degrees)
SBP - Chirp	24	4	iXblue - Echoes 10000	Impulsive	2	5 to 15	202 / 162*	193 / 153*	-	-	1	30
USBL - positions system	24	4	Kongsberg HiPAP	Impulsive	2	5 to 10 and 20 to 34	166 (Low mode)**	157	-	-	1	360

* These sources are directional; thus, the source level is reduced in directions greater than the stated degrees in the directionality column, meaning the low value is outside and the high value is inside the directionality.

** It is possible to activate a "low mode" setting on certain supplier equipment, this reduces the SPL output comparatively to other equipment modes, meaning less noise to the surroundings.

7.2 Construction Activity Source Levels

The noise source levels identified for the construction activities are based on project specific empirical modelling of unmitigated noise levels /10//11//12//13//14/. The sources identified for construction that can have a potential impact on marine mammals and fish are dredging, rock cutting/drilling and the tug vessel, see Table 7-2.

The noise level from the tug vessel is based on empirical measurement data. The noise level from the vessel is difficult to determine as the noise level and spectrum can vary quite a bit from vessel to vessel.

The TSHD has been set in order to accommodate the maximum allowed overlap between behavioral impact distances and Natura 2000 areas.

Table 7-2. Source information and source levels used in the sound propagation model for construction activities. Subscript for dredging is the source level. The "-" marks information that has not been acquired or is irrelevant, for that particular activity.

Source	Duration (hours/ day)	Speed (knots/h)	Model type (Reference)	Sound type	Source depth (m)	Frequency (kHz)	$SPL_{rms, 125ms}$ (dB)	SEL (dB)	SPL_{pk} (dB)	"Pulse" length (ms)	Shot rate (Hz)	Directionality (degrees)
$Dredging_{178}$ – TSHD*	24	1.2	8000 m³ capacity (Wyatt 2008)	Non-impulsive	Sea floor	0.01 to 10	178	169	-	-	-	360
$Dredging_{187}$ – TSHD*	24	1.2	8000 m³ capacity (Wyatt 2008)	Non-impulsive	Sea floor	0.01 to 10	187	178	-	-	-	360
Rock cutting / drilling	24	-	(Barham 2017)	Non-impulsive	2 m above sea floor	0.03 to 2	185.3	176.3	-	-	-	360
Tug Vessel	24	8.7	(Wyatt 2008)	Non-impulsive	1	0.02 to 10	175	166	-	-	-	360

* TSHD (Trailing suction hopper dredging), which is a method of dredging involving a ship with a pump and a hopper, the pump is connected to a pipe which sucks up sand and gravel from the seafloor as the ship moves.

8. Geoacoustic Modelling Inputs

8.1 Bathymetry

The structure of the sea floor is an important parameter affecting the propagation of underwater noise, and detailed bathymetric data are therefore essential to accurate modelling.
A base-level-resolution bathymetric dataset for the entire study area was obtained from a public source, GEBCO (General Bathymetric Chart of the Oceans).

8.2 Geoacoustic Properties

Seabed layer information is the same as layers used for the Baltic pipe project /15/. This is based on what is known about the seabed layers in the area and areas close by.
Table 8-1 and Table 8-2 shows the seabed layers used near Bornholm and Øresund respectively.

Table 8-1. Sediment layers used in the sound propagation model for Bornholm.

Seabed layer	Material	Geoacoustic properties
0 – 5 meters	Sand	C_p = 1,650 m/s and α = 0.8 dB/λ
5 – 10 meters	Mud	C_p = 1,700 m/s and α = 1 dB/λ
10 meters and under	Basalt	C_p = 5,250 m/s and α = 0.1 dB/λ

Table 8-2. Sediment layers used in the sound propagation model for Øresund.

Seabed layer	Material	Geoacoustic properties
0 – 25 meters	Sand	C_p = 1,650 m/s and α = 0.8 dB/λ
25 meters and under	Basalt	C_p = 5,250 m/s and α = 0.1 dB/λ

8.3 Sound Speed Profiles and Water Properties

Water column profiles (salinity, temperature, and depth) for summer and winter are based on publicly available data from ICES (International Council for the Exploration of the Sea). Data measurements are from stations positioned near the study area for this project. The data is used to calculate the sound speed profile for the modelling positions and used as input in the underwater noise propagation model /5/.

Predictions were performed for winter and summer. Water column profiles are different based on the seasonal conditions, and thus have different sound propagation characteristics. Table 8-3 shows the water conditions and Table 8-4 shows the sound speed profiles depending on season.

The sound speed profile between summer and winter is different and can vary due to the expected higher surface temperature of water during summer compared to winter. This temperature gradient changes the way the sound behaves in water.

Table 8-3. Water conditions for each season of the two locations, Bornholm and Øresund.

	Bornholm		Øresund	
Season	Summer	Winter	Summer	Winter
Avg. Temperature [°C]	14.1	4.3	19.2	3.4
Avg. Salinity [ppt]	8	9	11	12

Table 8-4. Water column profiles, showing the speed of sound at each depth. Shown are for summer and winter season for Bornholm and Øresund.

	Bornholm		Øresund	
Depth [m]	**Summer speed of sound [m/s]**	**Winter speed of sound [m/s]**	**Summer speed of sound [m/s]**	**Winter speed of sound [m/s]**
0	1473.6	1429.7	1491.3	1431.5
5	1477.8	1431.5	1491.5	1431.5
10	1479.5	1432.3	1492.1	1435.2
15	1479.3	1432.3	1498.3	1447.9
20	1477.5	1432	1515.1	1475.1
30	1470.4	1431.8	1601.1	1593.8
40	1461.3	1434.6		
50	1453.3	1443.6		
60	1449.2	1461.7		
70	1452.1	1491.9		
80	1465.2	1600.5		
100	1533	1585		

Note: Øresund is significantly shallower waters, hence greyed cells.

9. Underwater Noise Modelling Results

The sound propagation model was run with the source levels, source spectrum and environmental parameterization described in previous sections. The distances predicted to the various threshold limits are the maximum at any depth down to the bottom. The following tables summarize the results of the acoustic modelling in terms of the maximum radial distances from the investigation activities to the applicable assessment underwater noise threshold levels specified for winter and summer.

Due to the relatively even sea floor bathymetry in some positions, the underwater noise does propagate relatively equally in all directions. For the purposes of worst-case assumptions, the maximum distances are given to the impact threshold limits. The following figures are examples showing the propagation in the horizontal and vertical plane, to show 3-dimensional sound propagation of underwater noise.

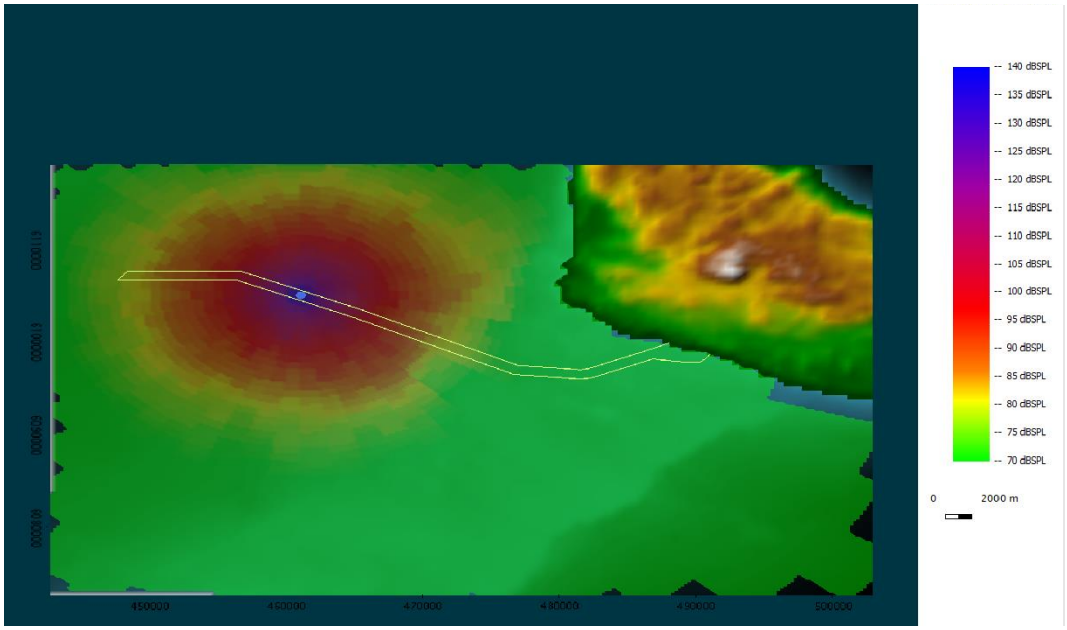


Figure 9-1. Horizontal cross-section noise propagation example from dredging activity near Bornholm.

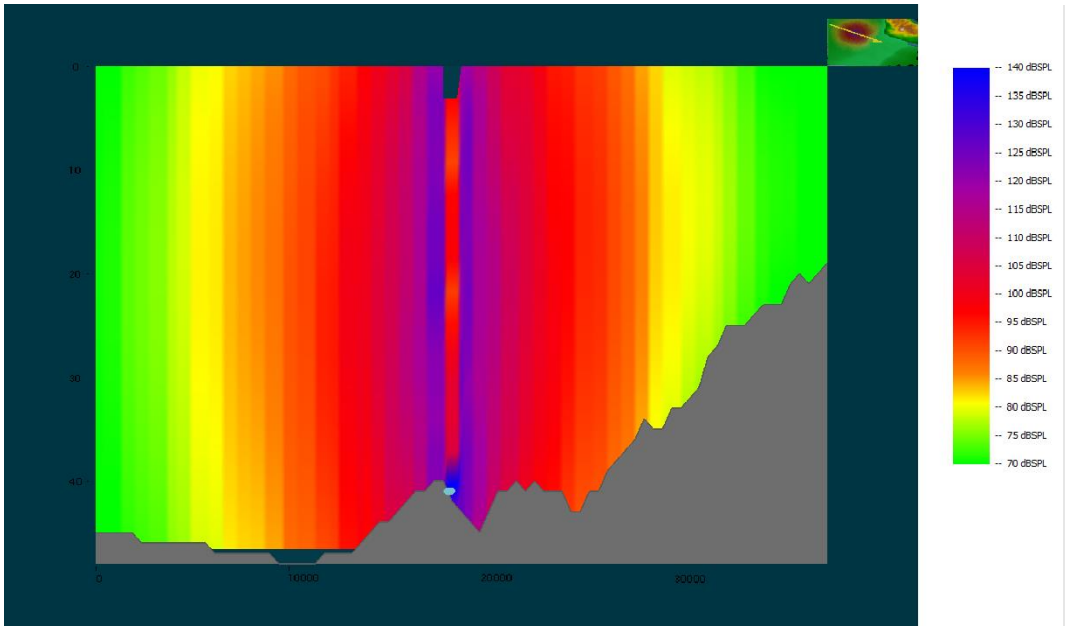


Figure 9-2. Vertical cross-section noise propagation example (same as above) from dredging activity near Bornholm.

The following sections summarize the results of the acoustic modelling in terms of the maximum radial distances from the activities to the applicable assessment underwater noise threshold levels specified in Section 6.

9.1 Harbor porpoises – Distances to Applicable Assessment Thresholds

Table 9-1. Distances to the different threshold limits for harbor porpoises in the survey phase. USBL subscript indicate the working frequency range in Hz.

Corridor	Equipment	Working Frequency [kHz]	Impulsive PTS (VHF weighted)	Impulsive TTS (VHF weighted)	Behavior (VHF weighted)
Harbor Porpoise (Winter)			**155 SELcum**	**140 SELcum**	**103 SPLrms,125ms**
Bornholm	Chirp, iXblue, Echoes 10000	5 – 10	0 m	30 m	2.2 km
Bornholm	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	250 m	4.3 km
Bornholm	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	5 m	700 m	4.4 km
Øresund	Chirp, iXblue, Echoes 10000	5 – 10	0 m	70 m	3.4 km
Øresund	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	200 m	4.4 km
Øresund	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	5 m	600 m	3.9 km
Harbor Porpoise (Summer)			**155 SELcum**	**140 SELcum**	**103 SPLrms,125ms**
Bornholm	Chirp, iXblue, Echoes 10000	5 – 10	0 m	30 m	2.2 km
Bornholm	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	300 m	4.7 km
Bornholm	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	5 m	850 m	5 km
Øresund	Chirp, iXblue, Echoes 10000	5 – 10	0 m	90 m	3.7 km
Øresund	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	300 m	4.6 km
Øresund	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	5 m	950 m	5.4 km

Table 9-2. Distances to the different threshold limits for harbor porpoises in the construction phase. Dredging subscript indicate the source level in dB.

Corridor	Activity	Non-impulsive PTS (VHF weighted)	Non- impulsive TTS (VHF weighted)	Behavior (VHF weighted)
Harbor Porpoise (Winter)		**173 SELcum**	**153 SELcum**	**103 SPLrms,125ms**
Bornholm	TSHD Dredging$_{178}$	0 m	10 m	3.3 km
Bornholm	TSHD Dredging$_{187}$	0 m	25 m	5.2 km
Bornholm	Rock cutting / drilling	0 m	15 m	1.2 km
Bornholm	Vessel	0 m	0 m	0 km
Øresund	TSHD Dredging$_{178}$	0 m	10 m	3.4 km
Øresund	TSHD Dredging$_{187}$	0 m	40 m	6.2 km
Øresund	Rock cutting / drilling	0 m	15 m	1.5 km
Øresund	Vessel	0 m	0 m	0 km
Harbor Porpoise (Summer)		**173 SELcum**	**153 SELcum**	**103 SPLrms,125ms**
Bornholm	TSHD Dredging$_{178}$	0 m	10 m	2.8 km
Bornholm	TSHD Dredging$_{187}$	0 m	25 m	5.8 km
Bornholm	Rock cutting / drilling	0 m	15 m	1.2 km
Bornholm	Vessel	0 m	0 m	0 km
Øresund	TSHD Dredging$_{178}$	0 m	10 m	3.6 km
Øresund	TSHD Dredging$_{187}$	0 m	30 m	6.4 km
Øresund	Rock cutting / drilling	0 m	15 m	1.2 km
Øresund	Vessel	0 m	0 m	0 km

9.2 Seals – Distances to Applicable Assessment Thresholds

Table 9-3. Distances to the different threshold limits for seals in the survey phase. USBL subscript indicate the working frequency range in Hz.

Corridor	Equipment	Working Frequency [kHz]	Impulsive PTS (PCW weighted)	Impulsive TTS (PCW weighted)	Behavior (unweighted)
Seal (Winter)			**185 SELcum**	**170 SELcum**	**151 SELss**
Bornholm	Chirp, iXblue, Echoes 10000	5 – 10	0 m	0 m	5 m
Bornholm	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	0 m	5 m
Bornholm	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	0 m	0 m	5 m
Øresund	Chirp, iXblue, Echoes 10000	5 – 10	0 m	0 m	5 m
Øresund	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	0 m	5 m
Øresund	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	0 m	0 m	5 m
Seal (Summer)			**185 SELcum**	**170 SELcum**	**151 SELss**
Bornholm	Chirp, iXblue, Echoes 10000	5 – 10	0 m	0 m	5 m
Bornholm	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	0 m	5 m
Bornholm	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	0 m	0 m	5 m
Øresund	Chirp, iXblue, Echoes 10000	5 – 10	0 m	0 m	5 m
Øresund	$USBL_{5-10}$, Kongsberg, HiPAP	5 – 10	0 m	0 m	5 m
Øresund	$USBL_{20-34}$, Kongsberg, HiPAP	20 – 34	0 m	0 m	5 m

Table 9-4. Distances to the different threshold limits for seals in the construction phase. Dredging subscript indicate the source level in dB.

Corridor	Activity	Non-impulsive PTS (PCW weighted)	Non- impulsive TTS (PCW weighted)
Seal (Winter)		**201 SELcum**	**181 SELcum**
Bornholm	TSHD Dredging$_{178}$	0 m	0 m
Bornholm	TSHD Dredging$_{187}$	0 m	0 m
Bornholm	Rock cutting / drilling	0 m	0 m
Bornholm	Vessel	0 m	0 m
Øresund	TSHD Dredging$_{178}$	0 m	0 m
Øresund	TSHD Dredging$_{187}$	0 m	0 m
Øresund	Rock cutting / drilling	0 m	0 m
Øresund	Vessel	0 m	0 m
Seal (Summer)		**201 SELcum**	**181 SELcum**
Bornholm	TSHD Dredging$_{178}$	0 m	0 m
Bornholm	TSHD Dredging$_{187}$	0 m	0 m
Bornholm	Rock cutting / drilling	0 m	0 m
Bornholm	Vessel	0 m	0 m
Øresund	TSHD Dredging$_{178}$	0 m	0 m
Øresund	TSHD Dredging$_{187}$	0 m	0 m
Øresund	Rock cutting / drilling	0 m	0 m
Øresund	Vessel	0 m	0 m

9.3 Fish – Distances to Applicable Assessment Threshold

Table 9-5. Distances to the different threshold limits for fish and larvae in the survey phase. Results for winter are the same as summer. J= juvenile, a=adult.

Corridor	Activity	Species, Flee Speed [m/s]	TTS SELcum	Recov. Injury SPLpk	Recov. Injury SELcum	Mortal Injury SPLpk	Mortal Injury SELcum
Fish and Larvae (Summer), Impulsive noise			**186 dB**	**207 dB**	**203 dB**	**207 dB**	**207/210 dB**
Bornholm	Chirp, iXblue, Echoes 10000	Larvae, 0	N/A	N/A	N/A	0 m	0 m
		Cod (j), 0.38	0 m	0 m	0 m	0 m	0 m
		Herring, 0.9	0 m	0 m	0 m	0 m	0 m
		Cod (a), 1.04	0 m	0 m	0 m	0 m	0 m
Bornholm	USBL, Kongsberg, HiPAP (5 – 10 kHz)	Larvae, 0	N/A	N/A	N/A	0 m	0 m
		Cod (j), 0.38	0 m	0 m	0 m	0 m	0 m
		Herring, 0.9	0 m	0 m	0 m	0 m	0 m
		Cod (a), 1.04	0 m	0 m	0 m	0 m	0 m
Bornholm	USBL, Kongsberg, HiPAP (20 – 34 kHz)	Larvae, 0	N/A	N/A	N/A	0 m	0 m
		Cod (j), 0.38	0 m	0 m	0 m	0 m	0 m
		Herring, 0.9	0 m	0 m	0 m	0 m	0 m
		Cod (a), 1.04	0 m	0 m	0 m	0 m	0 m
Øresund	Chirp, iXblue, Echoes 10000	Larvae, 0	N/A	N/A	N/A	0 m	0 m
		Cod (j), 0.38	0 m	0 m	0 m	0 m	0 m
		Herring, 0.9	0 m	0 m	0 m	0 m	0 m
		Cod (a), 1.04	0 m	0 m	0 m	0 m	0 m
Øresund	USBL, Kongsberg, HiPAP (5 – 10 kHz)	Larvae, 0	N/A	N/A	N/A	0 m	0 m
		Cod (j), 0.38	0 m	0 m	0 m	0 m	0 m
		Herring, 0.9	0 m	0 m	0 m	0 m	0 m
		Cod (a), 1.04	0 m	0 m	0 m	0 m	0 m
Øresund	USBL, Kongsberg, HiPAP (20 – 34 kHz)	Larvae, 0	N/A	N/A	N/A	0 m	0 m
		Cod (j), 0.38	0 m	0 m	0 m	0 m	0 m
		Herring, 0.9	0 m	0 m	0 m	0 m	0 m
		Cod (a), 1.04	0 m	0 m	0 m	0 m	0 m

Table 9-6. Distances to the threshold limits for fish and larvae in the construction phase. Flee speed is not included in these calculations for continuous noise (summer). Dredging subscript indicate the source level in dB.

Corridor	Activity	Species, Flee Speed [m/s]	TTS SELcum,12h	Recov. Injury SELcum,48h
Fish and Larvae (Summer), Non-impulsive noise			**204 dB**	**222 dB**
Bornholm	TSHD Dredging$_{187}$ TSHD Dredging$_{178}$	Larvae, 0 Cod (j), 0.38 Herring, 0.9 Cod (a), 1.04	N/A 0 m 0 m 0 m	N/A 0 m 0 m 0 m
Bornholm	Rock cutting / drilling	Larvae, 0 Cod (j), 0.38 Herring, 0.9 Cod (a), 1.04	N/A 0 m 0 m 0 m	N/A 0 m 0 m 0 m
Bornholm	Vessel	Larvae, 0 Cod (j), 0.38 Herring, 0.9 Cod (a), 1.04	N/A 0 m 0 m 0 m	N/A 0 m 0 m 0 m
Øresund	TSHD Dredging$_{187}$ TSHD Dredging$_{178}$	Larvae, 0 Cod (j), 0.38 Herring, 0.9 Cod (a), 1.04	N/A 0 m 0 m 0 m	N/A 0 m 0 m 0 m
Øresund	Rock cutting / drilling	Larvae, 0 Cod (j), 0.38 Herring, 0.9 Cod (a), 1.04	N/A 0 m 0 m 0 m	N/A 0 m 0 m 0 m
Øresund	Vessel	Larvae, 0 Cod (j), 0.38 Herring, 0.9	N/A 0 m 0 m	N/A 0 m 0 m

		Cod (a), 1.04	0 m	0 m

Table 9-7. Distances to the threshold limits for fish and larvae in the construction phase. Flee speed is not included in these calculations for continuous noise (winter). Dredging subscript indicate the source level in dB.

Corridor	Activity	Species, Flee Speed [m/s]	TTS SELcum.12h	Recov. Injury SELcum,48h
Fish and Larvae (Winter), Non-impulsive noise			**204 dB**	**222 dB**
Bornholm	TSHD Dredging$_{187}$ TSHD Dredging$_{178}$	Larvae, 0	N/A	N/A
		Cod (j), 0.38	0 m	0 m
		Herring, 0.9	0 m	0 m
		Cod (a), 1.04	0 m	0 m
Bornholm	Rock cutting / drilling	Larvae, 0	N/A	N/A
		Cod (j), 0.38	0 m	0 m
		Herring, 0.9	0 m	0 m
		Cod (a), 1.04	0 m	0 m
Bornholm	Vessel	Larvae, 0	N/A	N/A
		Cod (j), 0.38	0 m	0 m
		Herring, 0.9	0 m	0 m
		Cod (a), 1.04	0 m	0 m
Øresund	TSHD Dredging$_{187}$ TSHD Dredging$_{178}$	Larvae, 0	N/A	N/A
		Cod (j), 0.38	0 m	0 m
		Herring, 0.9	0 m	0 m
		Cod (a), 1.04	0 m	0 m
Øresund	Rock cutting / drilling	Larvae, 0	N/A	N/A
		Cod (j), 0.38	0 m	0 m
		Herring, 0.9	0 m	0 m
		Cod (a), 1.04	0 m	0 m
Øresund	Vessel	Larvae, 0	N/A	N/A
		Cod (j), 0.38	0 m	0 m

		Herring, 0.9 Cod (a), 1.04	0 m 0 m	0 m 0 m

10. Implementation of Danish Energy Agency underwater noise standard mitigation measures for marine surveys

The Danish Energy Agency sets a series of standard mitigation measures (SMM) to be implemented when conducting marine surveys /16/. These measures aim to minimize the impact on marine mammals from underwater noise and are expected to be implemented and used during operations where there is potential impact on marine mammals when doing surveys or using acoustic equipment. For the current project, the SMM are expected to be implemented for surveys during, but not limited to, the preparational and construction phases, where survey equipment requiring the use of USBL or chirp is in effect. If surveys are conducted at any point during the project's other phases, the SMM will also have to be implemented.

The SMM describes a list of requirements relevant to the project. The requirements are listed and described in detail below:

1) Necessary precautions must be taken to minimize impacts on marine mammals from survey activities.
2) All survey activities must be performed in such a manner to minimize the emissions of underwater noise. This includes, but is not limited to, that source levels are not higher than what is required to successfully complete the survey. For example, an air gun array must not be bigger than what is necessary for a given survey.
3) In order to minimize the impact on marine mammals from underwater noise, a soft start procedure must be followed. The soft start procedure follows a decision tree, which is outlined in Figure 10-1.

Successful implementation of the SMM will lead to a reduction of the area in which marine mammals are potentially affected by underwater noise from survey activities. The combined steps in the SMM, being surveillance and soft start, will lead to an exclusion of marine mammals within the inner 500 meter, either because no marine mammals are present in the first place or because the soft start procedure or use of mitigation gun will lead to marine mammals moving out of the inner 500 meter of the vessel. Three marine mammal species are expected to be present in the project area: harbor porpoise, harbor seal and grey seal.

Results from the underwater noise modelling outlined in chapter 9 indicate that harbor porpoises may, at a maximum, experience TTS and exhibit behavioral changes within 950 meters and 5.4 km, respectively, from the emission source, when using USBL during surveys. The successful implementation of SMM will mitigate these impacts in the inner 500 meters of these impact areas, thus reducing the area of potential TTS to the outer 450 meters and the area of potential behavioral change to the outer 4.9 km.

Results from the underwater noise modelling indicate that there is no risk of PTS or TTS for seals, and that behavioral change is limited to 5 meters from the source when using USBL or chirp. Successful implementation of SMM will thus mean that the area within which seals are affected by underwater noise is reduced to zero.

It is worth noting that the energy level decreases as the underwater noise propagates farther away from the source due to attenuation. This means that the energy levels are lower the further away from the source and thus, the successful implementation of SMM will eliminate the risk of impact in the inner most energetic and harmful area nearest to the source.

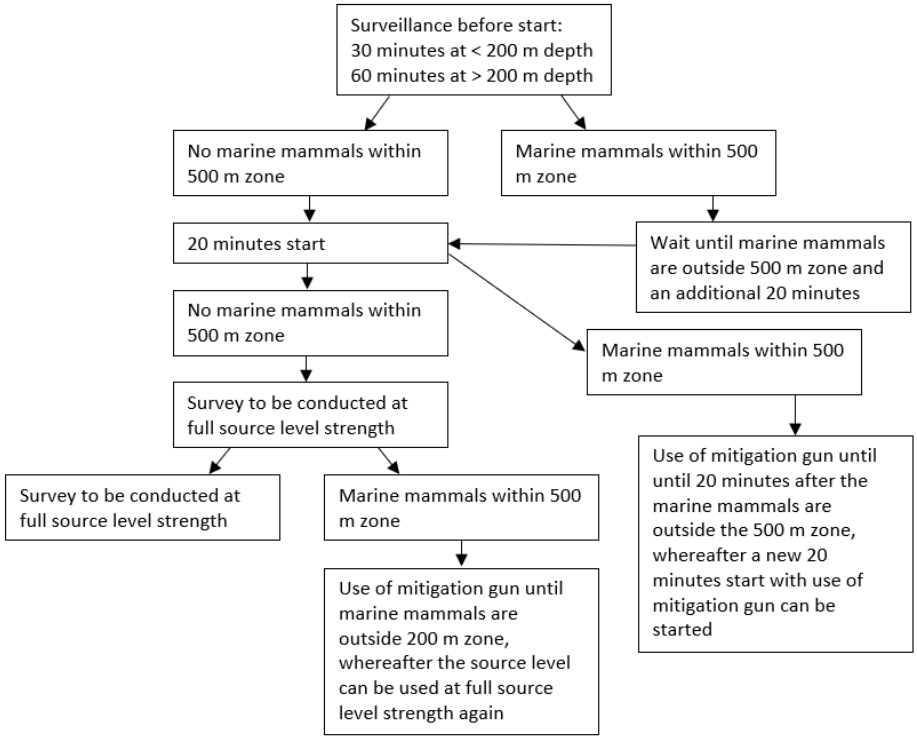


Figure 10-1 Decision tree for soft start procedure when conducting marine surveys (translated from /16/)

11. Conclusion

This study is an underwater noise propagation modelling for the life cycle phases of the proposed offshore cable. The purpose of this study is to provide the expected potential underwater noise levels and exposure levels needed for assessments of potential impact on the harbor porpoise population, seals and fish and provide relevant documentation as part of the environmental permitting process.

The modelled potential underwater noise levels and exposure levels were compared to relevant threshold limits for harbor porpoise, seals and fish. The following overall conclusion can be drawn from the results.

11.1 Harbor porpoise

11.1.1 Surveys and use of acoustic equipment

1) The modelling results show that there is a very small distance for the risk of permanent damage (PTS) with the USBL at 20 to 34 kHz. The temporary hearing loss between the different working frequency ranges of USBL, show that the TTS distance is significantly longer for 20 – 34 kHz, because harbor porpoises hearing range is within these frequencies. TTS distances are up to 950 meters, but use of required soft start procedures of 20 minutes (see chapter 10) will eliminate the risk of TTS in the inner 500 meters of the source.
2) The behavioral impact distances between the two working frequencies of the USBL, show that for the USBL with working frequency range in 5 – 10 kHz, behavioral impact distances are longer. While in a select few cases, behavioral impact distances in 20 – 34 kHz range, the distances are longer. Some cases also show that the behavioral impact distances are nearly the same. The USBL will have about a twofold longer behavioral impact distance than the chirp, with distances up to 5.4 km.

11.1.2 Construction Activities

3) The modelling results show no behavioral impact distances from vessels. However, vessel noise levels and spectrum vary with size and thrust type. Thus, it should be assumed that there may be smaller distances of disturbance in behavior, but most of the energy is at the low frequencies, and thus it is very typical that there are no TTS or PTS distances at all.
4) From the construction noise the dredging is the worst case as it is assumed to be trailing suction hopper dredging. This is by far the noisiest form of dredging according to current literature. No PTS occurs, but TTS can occur up to around 40 meters from the dredging activity.
5) The behavioral impact from dredging reaches distances up to 6.4 km.
6) Rock cutting / drilling shows no distances where the harbor porpoises are exposed to noise resulting in PTS. The activity can result in TTS in distances of about 15 meters. The behavior of harbor porpoises can be affected up to 1.5 km away from the rock cutting / drilling activity.

11.2 Seals

11.2.1 Surveys and use of acoustic equipment

1) The modelling results for surveys and use of acoustic equipment show that the only expected impacts on seals are from behavioral changes occurring up to 5 meters from the source.

11.2.2 Construction activities

2) The modelling results for construction activities show that the distances for PTS, TTS and behavioral changes are zero for seals.

11.3 Fish and Larvae

11.3.1 Surveys and use of acoustic equipment

1) There are no significant distances for site investigation when it comes to fish or larvae.

11.3.2 Construction activities

2) There are no significant distances for construction activities when it comes to fish or larvae.

12. References

/1/ Danish Energy Agency, 2022, "Guidelines for underwater noise, Prognosis for EIA and SEA assessments".

/2/ Danish Energy Agency, 2023, "Guidelines for underwater noise – Installation of impact or vibratory driven piles".

/3/ Energinet, "Project description", Document ID no. BEI-C-L0-2.0-12-AP01, November 21, 2023

/4/ Jensen, F.B., Kuperman, W.A., Porter, M., B., Schmidt, H., 2011, "Computational Ocean Acoustics", Second Edition Springer, New York, Dordrecht, Heidelberg, London.

/5/ Anderson et al., 2017, "A framework for regulating underwater noise during pile driving", Swedish Defence research Agency (FOI), Swedish Environmental Protection Agency 2017.

/6/ Southall, B.L., Bowles, A.E., Ellison, W.T., Fiineran, J.J., Gentry, R.L., Greence, C.R.J., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P., 2007, "Marine mammal noise exposure criteria: initial scientific recommendations, Aquatic Mammals 33, 411-512.

/7/ Southall, "Marine mammal noise exposure criteria: updated scientific recommendations for residual hearing, 2019, Aquatic Mammals, 45(2), 125-232.

/8/ Russell et al., 2016, "Avoidance of wind farms by harbor seals is limited to pile driving activities, Journal of Applied Ecology.

/9/ Popper, 2014, "Sound exposure guidelines for fishes and sea turtles: A technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI".

/10/ Wyatt et al., 2008, "Joint industry programme on sound and marine life review of existing data on underwater sounds produced by the oil and gas industry – Issue 1".

/11/ Barham, 2017, "App D13.09 – Underwater noise baseline and modelling", Subacoustech Environmental.

/12/ Robinson, S.P., et al., 2011, "Measurement of underwater noise arising from marine aggregate dredging operations", MALSF Reports.

/13/ de Jong et al., 2010, "Underwater noise of trailing suction hopper dredgers at Maasvlakte 2: Analysis of source levels and background noise", TNO Defence, Security and Safety.

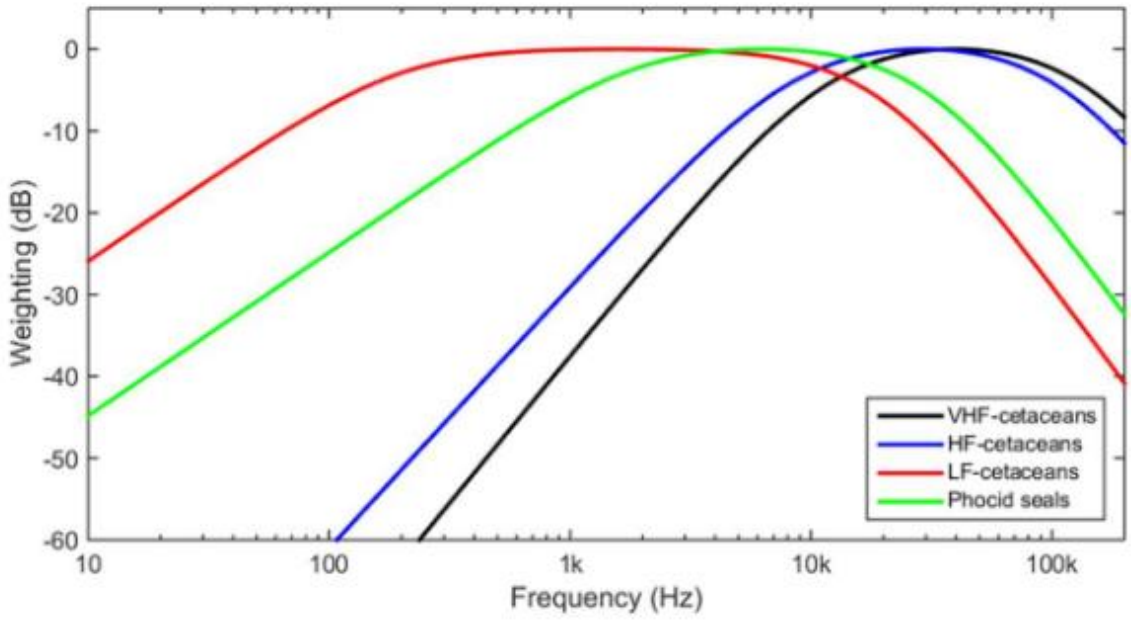
/14/ Suedel et al., 2019, "Evaluating effect of dredging-induced underwater sound on aquatic special: A literature review", ERDC.

/15/ Rambøll, 2018, Baltic pipe offshore pipeline – Permitting and design – Environmental impact assessment – Baltic sea – Denmark", Baltic pipe project.

/16/ Danish Energy Agency, 2018, "Standardvilkår for forundersøgelser til havs".

/17/ Danish Standards Association, 2017, "Underwater acoustics – Measurement of radiated underwater sound from percussive pile driving", DS/ISO 18406.

Appendix 1 - Weighting functions for mammals



Figur 0-1. Weighting functions for VHF (black line), HF (blue line), LF (red line) and phocid seals (green line) /2/.

Appendix 2 - HiPaP – USBL positioning system data sheet

HiPAP models overview

System	HiPAP 502	HiPAP 452	HiPAP 352	HiPAP 352P	HiPAP 102
Number of active elements	241	46	46	46	31
Max/recommended acoustic operating area below vessel	200º / 200º	160º / 120º	160º / 120º	160º / 120º	120º / 120º
Minimum gate valve size required	20 in / 500 mm	20 in / 500 mm	14 in / 350 mm	-	20 in / 500 mm
Transducer diameter	400 mm	400 mm	320 mm	345mm	460 mm
Angular accuracy* of X/Y directions (1 sigma figure)	20dB S/N:0,06º 10dB S/N:0,10º 0dB S/N:0,30º	20dB S/N:0,10º 10dB S/N:0,15º 0dB S/N:0,40º	20dB S/N:0,10º 10dB S/N:0,15º 0dB S/N:0,40º	20dB S/N:0,18º 10dB S/N:0,23º 0dB S/N:0,40º	20dB S/N:0,14º - -
Accuracy dual mode operation, two-TD system*	20db S/N:0.042º	-	-	-	-
Narrow pointing receiver beam	10º	15º	15º	15º	15º
Operating range*	1 - 5000 m	1 - 5000 m	1 - 5000 m	1 - 4000 m	1 - 10000 m
Number of transponder channels, CW / Cymbal	56 / 500+	56 / 500+	56 / 500+	56 / 500+	30 / 50
Frequency band	21 - 31 kHz	21 - 31 kHz	21 - 31 kHz	21 - 31 kHz	10 - 15 kHz
Range detection accuracy*	0.02 m	0.02 m	0.02 m	0.02 m	0.02 m
Hull unit for automatic transducer deployment through hull	Available	Available	Available	-	Available

Figur 0-1. Data sheet of the different HiPaP models from Kongsberg.

Appendix 3 - iXblue – Datasheet for Echoes 10000 model

Echoes 10 000

High-resolution sub-bottom profiler for shallow water

Echoes 10 000 is a high-performance sub-bottom profiler offering high-resolution of seismic reflexion profiles. Operating from 1m to 150m water depth, this portable system enables river, lake and ocean surveys regardless of the seabed topography.

FEATURES

- Widest spectrum coverage (5 – 15 kHz)
- Portable Chirp system
- Vertical resolution < 8cm
- Penetration up to 40 m in clays
- Pole-mounted system

DELPH SEISMIC SOFTWARE

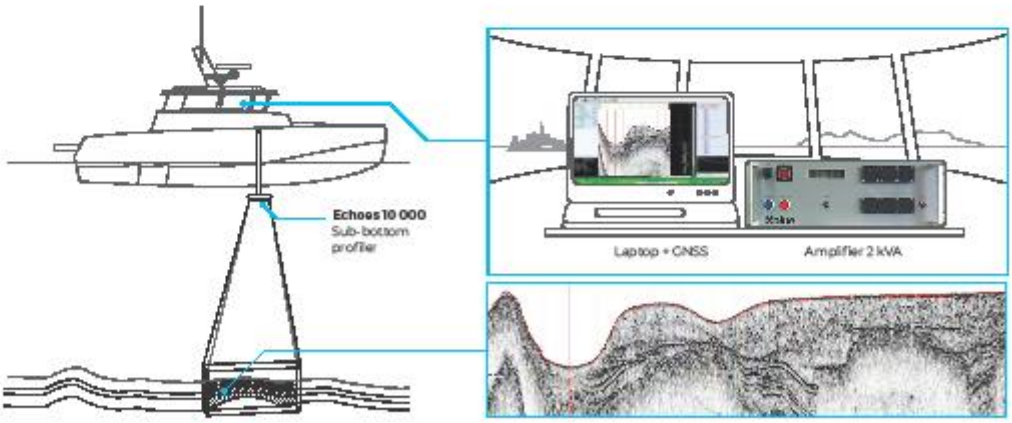
- All-in-one optimized geophysical processing and interpretation
- Easy access to all data collected for geologists and geophysicists
- Compatible with leading industry sensors and formats
- Best possible 2D/3D QC
- Visualization and reporting capabilities

BENEFITS

- True flat bandwidth ultimate resolution capacity and power efficiency
- One-man portable system
- Perfect positioning and heave compensation
- Compatible with any bathymetric echosounder

APPLICATIONS

- Pre and post dredging
- Sedimentology / Paleoseismology
- Archeology and Geo-archeology
- Buried objects detection (boulders, pipelines)
- De-risking survey



2020-07-03 - Echoes10000

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iXblue

Technical specifications

Array configuration	7 tonpilz transducers mounted on a plate
Operational frequency range	5000 Hz - 15000 Hz
Mean acoustic level	202 dB (ref 1µPa@1m) @ 2kVA
RVS (Receiving Voltage Sensitivity) (ref. 1µPa)	-172 dB
Beam aperture @ 10 kHz	30°
Vertical resolution (c=1500m/s)	8 cm

Mechanical specifications

Echoes 10 000 Array

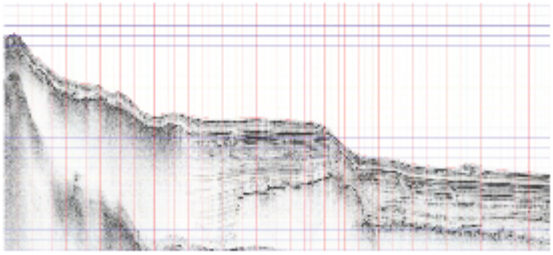
Recommendation for water depth below transducers	1 to 150 m
Height	191 mm
Diameter	380 mm
Weight in air / water	26 kg / 12 kg

Echoes 10 000 Topside unit

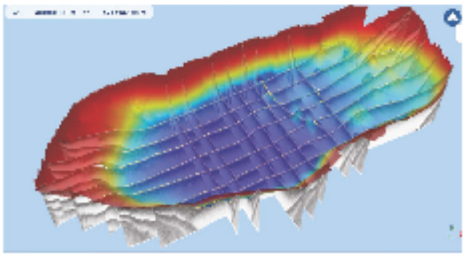
Signal emission power / Echoes mean power	2 kVA / 350 W
Length / width / height	486 mm / 483 (19") mm / 177 (4U) mm
Weight	15 kg
Mounting	Rack-mounted
Deck cable length	20 m

Results

High-resolution sub-bottom profiling data



Bathymetry & layers modeling using Delph



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