NIRAS

OX2
Seismic Survey Triton

Underwater Noise Modelling

OX2

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Contents

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Summary

In connection with proposed seismic survey activities by OX2, in preparation for Triton Offshore Wind Farm in the Swedish part of the Baltic Sea 35 km south of Ystad, NIRAS has carried out underwater sound propagation modelling.

All proposed equipment was evaluated with regards to the potential for harmful noise impact on marine mammals, by assessing source level, frequency content, directivity and duty cycle. Detailed underwater noise modelling was carried out for the different types of equipment in dBSea, using detailed knowledge of site specific environmental conditions for the wind farm area and surroundings. These include parameters such as bathymetry, seabed sediment composition, temperature, salinity and sound speed in the water column for the worst case sound propagation scenario.

Calculations were carried out for three equipment scenarios. The full setup (scenario 1) uses an Innomar (Innomar SES-2000 Medium 100 parametric sub bottom profiler), a sparker (Geosource 200-400) and four mini airguns of the type MiniG (60 cu. Inch.). The second setup omits the sparker, and the third setup only includes the Innomar system. All source specific characteristics (e.g. source level, frequency content, duty cycle and directivity) were included in the underwater noise model in dBSea.

Sound propagation modelling was carried out for a representative 24-hour survey to determine distances to which avoidance behaviour, Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) would likely occur in harbour porpoises and seals.

The results showed variations between the different equipment setups and different source positions. Below are the resulting impact distances in accordance with the proposed threshold criteria for avoidance behaviour, Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS).

Area	Equipment scenario	Position	Threshold distance [m]				
			Harbour porpoise			Seal	
			Avoidance Behavior $SPL_{RMS-fast,VHF} = 100\ dB$	TTS $SEL_{C24h,VHF} = 140\ dB$	PTS $SEL_{C24h,VHF} = 155\ dB$	TTS $SEL_{C24h,PW} = 170\ dB$	PTS $SEL_{C24h,PW} = 185\ dB$
Triton OWF site	1: Sparker Airguns & Innomar	1	5050	1200-2700	375-950	100-350	< 25
		2	6550	1300-3000	425-1050	90-350	< 25
		3	4800	1175-2550	400-975	60-300	< 25
	2: Airguns & Innomar	1	3200	1200-2700	375-950	< 50	< 25
		2	3400	1300-3000	425-1050	< 50	< 25
		3	3250	1175-2550	400-975	< 50	< 25
	3: Innomar	1	3200	1200-2700	375-950	< 50	< 25
		2	3400	1300-3000	425-1050	< 50	< 25
		3	3250	1175-2550	400-975	< 50	< 25

Avoidance behavior distances are based on a single pulse and will therefore represent the avoidance behavior throughout the entire survey, relative to the vessel position.

For PTS and TTS the distances are given as a range from minimum impact distance to maximum impact distance, representing the dependency on marine mammal position relative to the survey vessel. Minimum distances represent marine mammals located “behind” or perpendicular to the vessel, while maximum distances

represent marine mammals located in front of the vessel. The results can be used to define the minimum distance, a marine mammal must be deterred to, relative to the survey vessel at the onset of full activities, in order to avoid the respective impact. Sufficient soft start/ramp up procedures should thus be carried out prior to the seismic survey.

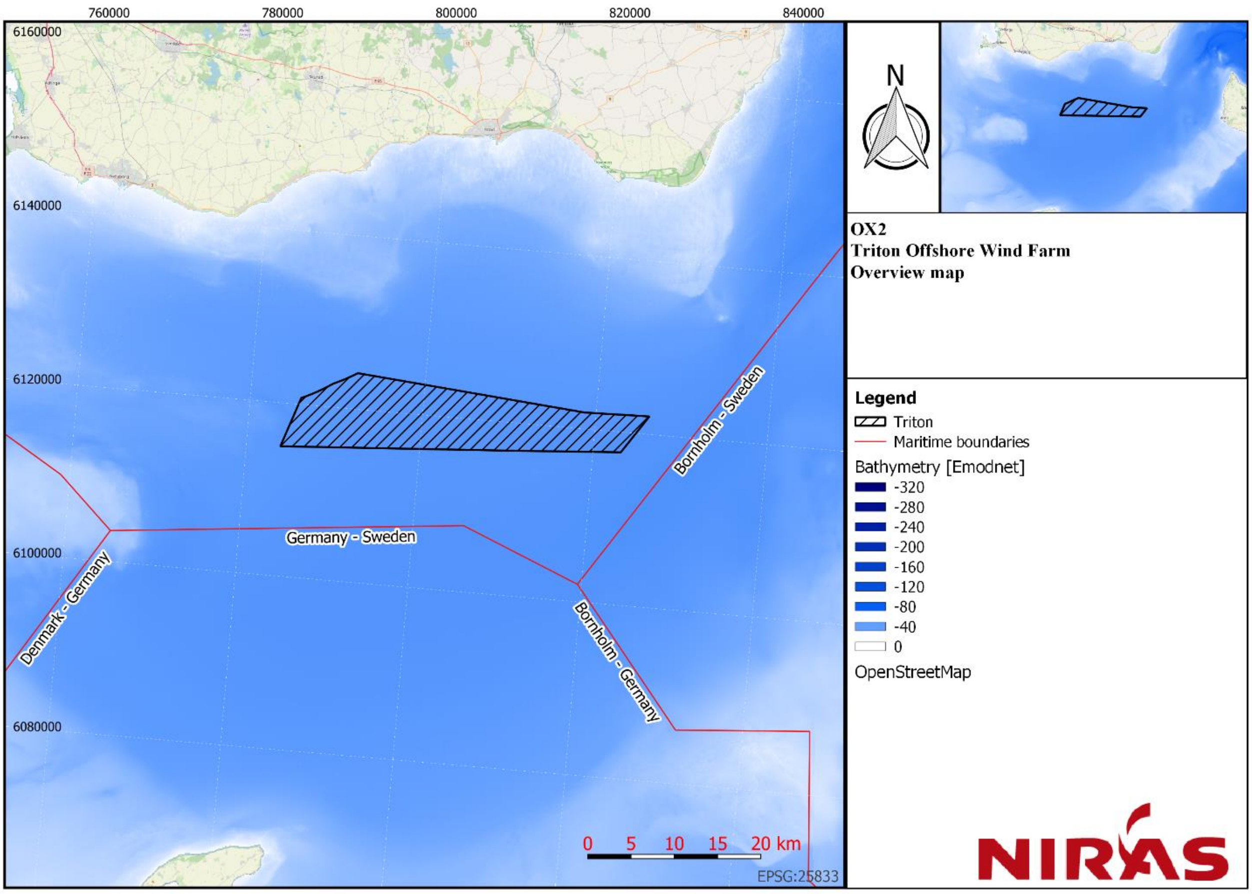
List of abbreviations

Full name	Abbreviation
Offshore Wind Farm	OWF
Sub-bottom profiler	SBP
Sound Exposure Level	SEL
Cumulative Sound Exposure Level	SEL_{C24h}
Sound Pressure Level	SPL
Permanent Threshold Shift	PTS
Temporary Threshold Shift	TTS
National Oceanographic and Atmospheric Administration	NOAA
Low-frequency	LF
High-frequency	HF
Very High-frequency	VHF
World Ocean Atlas 2018	WOA18
Normal modes	NM
Parabolic Equation	PE

1 Introduction

This report documents underwater sound propagation modelling performed in connection with proposed seismic survey activities by OX2 for the project Triton offshore wind farm (OWF). Triton OWF is located in the Swedish part of the Baltic sea, approximately 35 km south of Ystad, as shown in Figure 1.1. The wind farm site is located close to the German EEZ indicated by the red line called “Germany-Sweden” south of the wind farm site, see Figure 1.1. The OWF is also relative close to the Danish EEZ (Bornholm-Sweden) indicated by the red line to the east of the wind farm.

Figure 1.1: Overview map of Triton OWF (black).



OX2 has informed NIRAS, that a final decision about the supplier that will conduct the seismic surveys as well as equipment that will be used in the surveys, is not yet final. One of the potential suppliers has however proposed a list of equipment that could be used to obtain the necessary geophysical data.

This report evaluates the proposed survey equipment with regards to underwater noise emission. Detailed noise emission calculations are carried out for those sources, that can emit underwater noise levels capable of having a negative impact on marine mammals, either on a level of disturbance effects, or in the form of temporary or permanent hearing damage.

2 Purpose

The purpose of this report is to calculate and document the threshold distances for noise emission in relation to harbour porpoises and seals in the Triton OWF area. The analysis covers three types of potential impact (avoidance behaviour, Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS)) and is calculated for three different equipment setups.

3 Background

This chapter discusses general background knowledge for underwater noise, with definitions of used noise metrics, guideline requirements as well as threshold levels for quantifying the impact of noise.

3.1 Sound level metrics

In the following, the reader is introduced to the acoustic metrics used throughout the report for quantifying the sound levels.

3.1.1 Sound Pressure Level (SPL_{RMS})

In underwater noise modelling, the Sound Pressure Level (SPL) is commonly used to quantify the noise level at a specific position, and in impact assessments, is increasingly used for assessing the behavioural avoidance response of marine mammals as a result of noise emitting activities. The definition for SPL is shown in Equation *1* (Erbe, 2011):

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

Where p is the acoustic pressure of the noise signal during the time of interest, and T is the total time. SPL_{RMS} is the average unweighted SPL over a measured period of time. The time window must be specified. Often, a fixed time window of 125 ms, also called "fast", is used due to the integration time of the ear of mammals (Jakob Tougaard, 2018). The metric is then referred to as $SPL_{RMS-fast}$.

3.1.2 Sound Exposure Level (SEL)

Another important metric is the Sound Exposure Level (SEL), which describes the total energy of a noise event (Jacobsen & Juhl, 2013). A noise event can for instance be an airgun array or a sparker system firing, or it can be a single noise event like an explosion.

The SEL is normalized to 1 second, and is defined in Equation *2* (Martin, et al., 2019):

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

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 $1\ \mu Pa$.

When the SEL is used to describe the sum of noise from more than a single event, the term Cumulative SEL, or $SEL_{C,<duration>}$, is typically used. Another term of SEL which is used for reference to a single impulse, is SEL_{SS}.

For moving sources in combination with moving receivers, the cumulative SEL is proposed to be calculated using the approach presented in (Tougaard, 2016). Here the source vessel speed, and its direction relative to a moving receiver is used to calculate the cumulative SEL received by the receiver. In Equation 4, the distance between the source and receiver at the i'th pulse, r_i of a specific piece of survey equipment, given 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. Here, 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 3*

By summing the pulses from the entire survey given the transmission loss for the survey area,

Equation 4 gives the resulting SEL_{C24h}.

$$SEL_{C24h} = 10 * log_{10}\left(\sum_{i=1}^{N} 10^{\left(\frac{SEL_{Max} - X*\log_{10}(r_i) - A*(r_i)}{10}\right)}\right)$$ *Equation 4*

Where N is the total number of pulses for that piece of survey equipment, SEL_{Max} is the source level at 1 m distance, X and A describe the sound propagation losses for the specific project site. In the original equation by (Tougaard, 2016), it is assumed that the marine mammal moves in a straight line at constant speed directly perpendicular to the transect line (source vessel direction). In NIRAS' adaptation to the (Tougaard, 2016) model, it is however assumed that the marine mammal moves in a straight line directly away from the source. 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.

The parameters in Equation 3 and Equation 4 related to the source level, firing frequency, movement speed and source direction must be based on realistic assumptions and can be achieved through a site specific survey setup. The sound propagation parameters (X and A) must be determined through an advanced sound propagation model, in which all relevant site specific environmental parameters are taken into account.

Marine mammals can incur hearing loss, either temporarily or permanently as a result of exposure to high noise levels. The level of injury depends on both the intensity and duration of noise exposure, and the SEL is therefore a commonly used term to assess the risk of hearing impairment as a result of noise emitting activities. (Martin, et al., 2019).
The relationship between SPL_{RMS} in Equation 1 and SEL, in Equation 2, is given in Equation 5 (Erbe, 2011).

$$SEL = SPL_{RMS} + 10 * \log_{10}(T)$$ Equation 5

3.2 Underwater noise impact criteria for marine mammals

The noise related impact for both harbor porpoise and seal, is defined in relation to the PTS and TTS criteria, and is given in Table 3.1 along with avoidance behavior for harbor porpoise. PTS and TTS criteria are based on the use of species-dependent frequency weighted cumulative SEL ($SEL_{<Species>,24h}$). The harbour porpoise is classified as a Very High-Frequency (VHF) Cetacean in this regard (NOAA, April 2018), (Southall, et al., 2019). Avoidance behaviour is however evaluated based on the single pulse criteria $SPL_{RMS-fast,VHF}$ = 100 dB re. 1 µPa (Tougaard J, 2015), as the level 45 dB above the hearing threshold for porpoises. Seal (including harbour seals, grey seals and ringed seals, the three relevant seals species for the development area for Triton OWF) is classified as a Phocid Pinniped (PW) in this regard (NOAA, April 2018) and no avoidance behaviour criteria is specified for this classification.

Table 3.1: Species specific weighted threshold criteria for marine mammals. This is a revised version of Table AE-1 in (NOAA, April 2018) to highlight the important species in the project area (NOAA, April 2018).

Hearing group	Representa-tive species	Species specific weighted thresholds (Non-impulsive)		Species specific weighted thresholds (Impulsive)		
		$SEL_{C24h,<weighting>}$		$SEL_{C24h,<weighting>}$		$SPL_{RMS-fast}$
		TTS [dB]	PTS [dB]	TTS [dB]	PTS [dB]	Behaviour [dB]
Very High-Frequency Cetaceans	Harbour porpoise	153	173	140	155	100
Phocid Pinniped	Harbour seal	181	201	170	185	-
"-" Thresholds is not obtained for this hearing group.						

The thresholds in Table 3.1 are for impulsive noise such as airgun arrays, sparkers, boomers and other types of sub-bottom profilers (SBP). Different thresholds apply for continuous noise (e.g. ship noise) and whilst impulsive noise is expected to transition towards continuous noise over distance from the source, this transition is not expected to occur within the distances at which behavioural or temporary and permanent hearing impact can potentially occur as a result of these activities. In any case, threshold levels for continuous noise are more lenient, than those for impulsive noise, and use of the impulsive noise criteria, therefore provides conservative threshold distances. The non-impulsive thresholds will not be considered further in this report.

3.2.1 Threshold distance representation

The impact criteria as presented in section 3.2, rely on determining the distances at which the various thresholds are likely to occur.

As such, threshold distances for PTS and TTS describe the minimum distance from the source, a marine mammal must at least be deterred to, prior to onset of seismic survey, in order to avoid the respective impact. It does therefore not represent a specific measurable sound level, but rather a starting distance. It should furthermore be noted, that PTS and TTS distances are given as an interval, indicating the minimum – maximum distance for the harbour porpoise and seal. The minimum distance will relate to the marine mammals located behind the survey vessel, while the maximum will relate to the marine mammals located in front of the survey vessel. This difference is because of the movement of vessel and marine mammal causing the vessel to get closer and closer to a marine mammal located in front of the vessel in the beginning of the survey, while quickly creating distance to marine mammals located behind the vessel.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural avoidance responses are likely to occur.

3.2.2 Frequency weighting functions

As described in the previous section, the impact assessment for underwater noise includes frequency weighted threshold levels. In this section, a brief explanation of the frequency weighting method is given.

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 *6*.

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

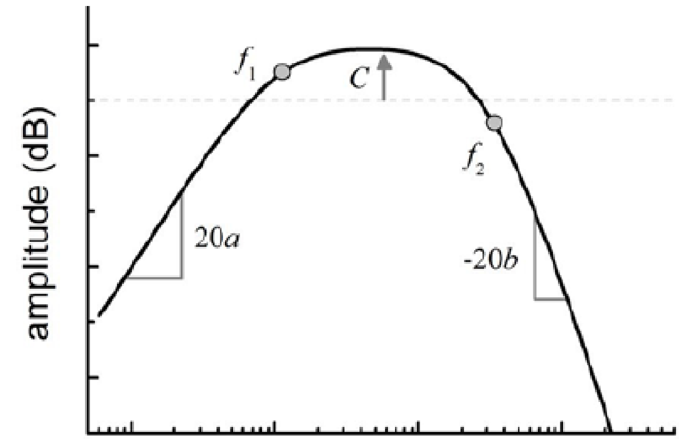
Equation 6

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.
- f_1 is the frequency at which the weighting function amplitude begins to decrease at the lower frequencies [Hz]
- f_2 is the frequency at which the weighting function amplitude begins to decrease at the higher frequencies [Hz]
- 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, April 2018).



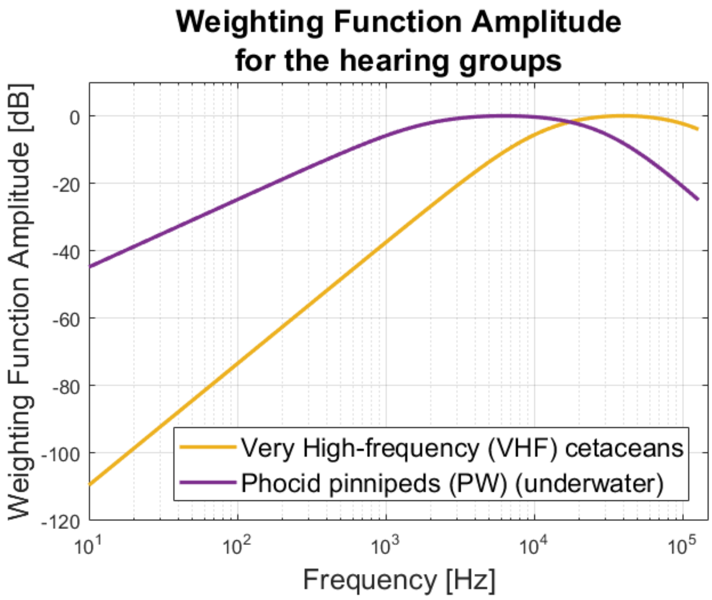
The parameters in Equation *6* are defined for the relevant hearing groups and the values are presented in Table 3.2.

Table 3.2: Parameters for the weighting function for the relevant hearing groups (NOAA, April 2018).

Hearing Group	a	b	f_2 (kHz)	f_2(kHz)	C (dB)
Very High-frequency (VHF) cetaceans	1.8	2	12	140	1.36
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75

By inserting the values in Table 3.2 into Equation *6*, the following spectra is obtained for the VHF cetacean (including harbour porpoises) and PW hearing groups (including harbour, grey and ringed seals).

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



4 Evaluation of proposed seismic survey equipment

The full setup, using all suggested types of equipment (Innomar, Sparker and Mini airguns) is referred to as Equipment scenario 1. It is assumed that this equipment setup will be used during the field survey throughout the OWF site. There might be parts of the survey within the site that will not require the use of the sparker, and calculations for this setup are referred to as Equipment scenario 2. It is also considered a possibility that certain parts of the survey within the site will require only the Innomar system. This setup is referred to as Equipment scenario 3. All three equipment scenarios are listed in Table 4.1.

Table 4.1: Overview of equipment scenarios.

Equipment Scenario	Equipment Types	Equipment models
1	Innomar	Innomar SES-2000 Medium 100
	Sparker	GeoSource 200-400
	Mini airguns	Sercel Mini G 60 Cu Inch
2	Innomar	Innomar SES-2000 Medium 100
	Mini airguns	Sercel Mini G 60 Cu Inch
3	Innomar	Innomar SES-2000 Medium 100

While Equipment scenario 1 is primarily used throughout the OWF site, Equipment scenario 2 and scenario 3 might also be used on site e.g. in areas where only the upper few meters of the seabed bottom needs to be examined.

It is assumed that the listed equipment models are representative for the equipment setup(s) that will be used for carrying out the field survey. If the final equipment setup(s) deviate from the proposed, it might be necessary to re-evaluate the noise emission and the impact before carrying out the seismic surveys.

Information, provided by GEO, on possible seismic survey equipment setup, are listed in Table 4.2 - Table 4.4, where additional calculated source level and directivity information has been added by NIRAS.

Table 4.2: Proposed seismic survey equipment source characteristics for Equipment scenario 1, using Innomar, Sparker and mini airguns.

Type	Equipment model	Source Noise Level SPL_{rms} (dB re 1 μPa @ 1m)	Primary Frequency Range (Hz)	Pulse Length	Beam Width	Sound Exposure Level (dB re 1 $\mu Pa^2/s$ @ 1m	Duty cycle over a 24 hour period
Innomar	Innomar SES-2000 Medium 100	243 dB	1k - 150k	0,07 – 2 ms	2°	213 dB	4 Hz
Sparker	GeoSource 200-400	216 dB (@1000 J)	250 - 3.25k	2 ms	60° @ 1 kHz 30° @ 2 kHz 15° @ 4 kHz	189 dB	0.5 Hz
Mini airguns	Sercel Mini G 60 Cu Inch	140 dB (@4x2000 PSI)	20-2k	<100 ms	omni	197 dB	0.5 Hz

Table 4.3: Proposed seismic survey equipment source characteristics for Equipment scenario 2, using Innomar and mini airguns.

Type	Equipment model	Source Noise Level SPL_{rms} (dB re 1 μPa @ 1m)	Primary Frequency Range (Hz)	Pulse Length	Beam Width	Sound Exposure Level (dB re 1 $\mu Pa^2/s$ @ 1m	Duty cycle over a 24 hour period
Innomar	Innomar SES-2000 Medium 100	243 dB	1k - 150k	0,07 – 2 ms	2°	213 dB	4 Hz
Mini airguns	Sercel Mini G 60 Cu Inch	140 dB (@4x2000 PSI)	20-2k	<100 ms	omni	197 dB	0.5 Hz

Table 4.4: Proposed seismic survey equipment source characteristics for Equipment scenario 3, using Innomar.

Type	Equipment model	Source Noise Level SPL_{rms} (dB re 1 μPa @ 1m)	Primary Frequency Range (Hz)	Pulse Length	Beam Width	Sound Exposure Level (dB re 1 $\mu Pa^2/s$ @ 1m	Duty cycle over a 24 hour period
Innomar	Innomar SES-2000 Medium 100	243 dB	1k - 150k	0,07 – 2 ms	2°	213 dB	4 Hz

For the Innomar system, a technical note including a frequency spectra (Wunderlich, 2016) was supplied. For the Sercel Mini G airguns, a GUNDALF report was supplied by Sercel, however for a single airgun, see Appendix 1, and from that, a conservative source level for 4 airguns was calculated by NIRAS. For the GeoSource 200-400 sparker, a source directivity profile derived from sound source verification measurements was used.

Below, each of the listed equipment models is evaluated with regards to underwater noise emission.

4.1 Innomar SES-2000 Medium 100

The Innomar SES-2000 Medium 100 system, is a parametric echo sounder with that can give a detailed mapping of the upper seabed layers. It emits two closely spaced high primary frequencies of e.g. 90 kHz and 100 kHz, both with high sound pressure level. When the pulses interact in the water column, a secondary frequency, corresponding to the difference between the two primaries will occur. The primary frequencies will quickly dissipate in the water, while the secondary frequency and harmonics persist and can be used for analyzing the seabed. This is explained in greater detail in (Wunderlich, 2016). It is a system with very focused, and downward angled directivity, achieving significant sound level reduction at an angle up to approximately -40 dB in the horizontal direction at the primary frequency. With a per pulse SEL of up to 213 dB re. 1 μPa²s @ 1m in the downward direction it is the source with the highest acoustic energy output in the proposed equipment setup. The frequency content, however, is predominantly around the primary frequency of 100 kHz (Wunderlich, 2016), where especially harbour porpoise have a good hearing. The noise source is therefore included in the detailed underwater noise propagation modelling.

4.2 Sparker, GeoSource 200-400

The proposed sparker, "GeoSource 200-400" from Geo Marine Survey Systems, is a multi-tip electrode sparker, discharging energy through a number of electrodes. The electrodes are arranged in a uniformly spaced planar grid of 0.7 x 1.0 m, creating a downward focused beam, the directivity of which is mentioned in Table 4.2 at key frequencies where most of the source energy is located. The dominant frequency content for the emitted acoustic signals are between 250 Hz to 3.25 kHz, which is outside the frequency-range, where harbour porpoises have good hearing. Seals on the other hand have a relatively good hearing in this frequency range. Although being downward focused, the directivity is limited, and significant sound energy will be emitted at higher angles. Thus, the noise source has the potential to cause long impact ranges, and is therefore included in the detailed underwater noise propagation modelling.

4.3 Mini airguns, 4x MiniG 60 Cu Inch

Four mini airguns of the model, Sercel Mini G 60 Cu Inch mini airguns, are suggested to investigate the seabed composition down to approximately 70 m depth below seafloor level. Airguns work by rapidly releasing compressed air, causing a release of a focused pressure pulse towards the seabed.

Unlike the Innomar system, airgun arrays are very low frequent in nature, with the primary frequency content between 10 Hz – 1 kHz, and the highest energy level around 20 – 40 Hz. It is therefore partly below the hearing range of harbor porpoise and seal. The low frequency nature of the source however allows the sound to propagate with low energy loss over distance. The airgun array is proposed by the supplier to be operated in a "flip/flop" operation where airguns fire two at a time every 0.5 sec., meaning each airgun will fire once per second, however with a break of 1 sec between a full sequence, in effect resulting in all four airguns firing once every 2 seconds.

Sercel has supplied a GUNDALF report for their Mini GI airgun of 60 Cu inch, (for more details see Appendix 1), reporting a source level of, SEL = 197 dB re. 1 μPa²s @ 1m per pulse, in the proposed "flip/flop" operation where 2 airguns fire at a time. Due to the high source level and a omnidirectional beam pattern, this source type is included in the detailed underwater noise propagation modelling.

4.4 Detailed Source Level and Frequency Spectrum

As discussed in previous sections, the Innomar, sparker and mini airguns need to be considered with regards to noise emission and sound propagation distances in relation to the potential impact on marine mammals. The detailed sound source levels both species-specific frequency weighting for Very High Frequency (VHF) Cetaceans (NOAA, April 2018), (Southall, et al., 2019) and Phocid Pinniped (PW) are included in the dBSea sound propagation modelling, and are presented in Table 4.5.

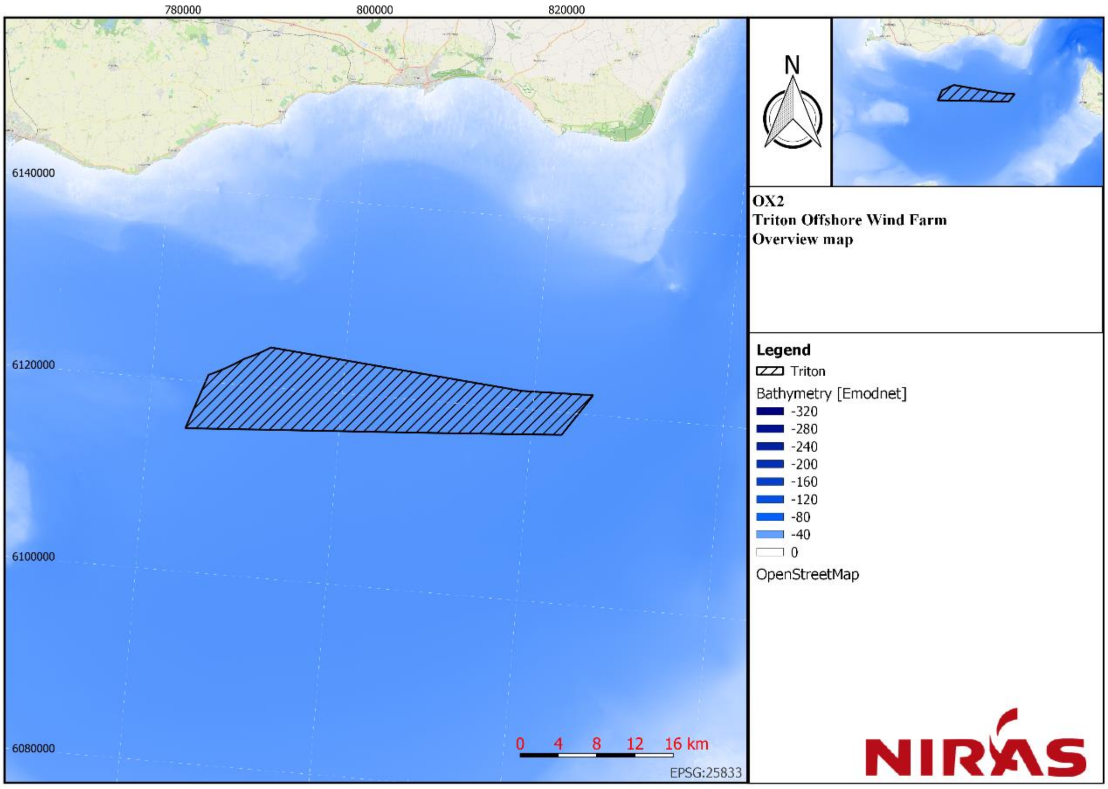
Table 4.5: Detailed source level information for the Innomar SES-2000 medium 100, Geosource 200-400 Sparker and 4x MiniG 60 Cu. Inch airguns.

Source	Fre-quency weighting	Source Level SEL @1m in 1/1 octave bands [dB re. 1 µPa2s]														
		Broad-band	16 Hz	31,5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz	32 kHz	64 kHz	128 kHz
Innomar SES-2000	VHF Cetaceans	209,6	15,6	26,4	37,2	48	84,3	111,2	135,2	142,8	149	169,5	160,6	172	201,9	208,8
	Phocid Pinniped	192,3	76,4	82,3	88,4	94,4	125,9	147,7	166,1	166,8	164,6	177	161,4	166,5	189,3	188,9
Geo Source 200 Sparker	VHF Cetaceans	158,8	1,3	31	59,4	85,9	110	135,5	149,9	155	154,5	147,6	138	125,1	109,6	91,4
	Phocid Pinniped	183,5	62,2	87	110,6	132,2	151,6	172	180,8	178,9	170,2	155,1	138,7	119,6	96,9	71,5
Sercel Mini G 60 Cu Inch	VHF Cetaceans	134,6	92,7	101,9	108,1	113,3	116,6	119,3	120,9	122,6	124,5	128,2	128,5	126,5	124,1	115,4
	Phocid Pinniped	165,9	153,5	157,9	159,3	159,6	158,2	155,7	151,8	146,5	140,2	135,7	129,3	121,1	111,4	95,5

5 Description of activities

The seismic survey site for the Triton OWF is located in the Baltic sea. More precisely it is located around 35 km south from Ystad. Triton covers a total area of 252 km^2. In Figure 5.1, the OWF site is shown with black outline

Figure 5.1: Survey site Triton boundaries in black frames.



6 Sound propagation modelling methodology

The impact of underwater noise on marine mammals is determined using sound propagation modelling software and the best available source and environmental data. This chapter provides a brief overview of underwater sound propagation theory and the software program used in the modelling, followed by a description of the inputs used for the propagation model. This includes environmental site specific and source input parameters.

6.1 Underwater sound propagation theory

This section is based on Jensen et al. (Jensen, et al., 2011) chapter 1 and chapter 3 as well as (Porter, 2011), and provide a brief introduction to sound propagation in saltwater. For a more detailed and thorough explanation of underwater sound propagation theory, see (Jensen, et al., 2011) chapter 1.

Sound pressure level generally decreases with increasing distance from the source. However, many parameters have an impact on the propagation and makes it a complex process.

The speed of sound in the sea, and thus the sound propagation, is a function of both pressure, salinity and temperature, depending on depth and the climate above the sea surface.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile importance, as stated by Snell's law, Equation 7.

$$\frac{\cos(\theta)}{c} = constant \qquad \text{Equation 7}$$

Where:

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

This relationship implies that sound waves bend toward regions of low sound speed (Jensen, et al., 2011). The implications for sound in water are, that sound that enters a low velocity layer in the water column can get trapped there. This results in the sound being able to travel far with very low sound transmission loss.

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to, as an upward refraction. This causes the sound waves to be reflected by the sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes reduced transmission loss, and thus a minimal loss of sound energy. This scenario will always be the worst case situation in terms of sound transmission loss. For some sound propagation models, this can introduce an overestimation of the sound propagation, if the surface roughness is not included.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled steeper towards the seabed rather than the sea surface, and it will thus be the nature of the seabed that determines the transmission loss. Depending on the composition of the seabed part of the sound energy will be absorbed by the seabed and while another part will be reflected. A seabed composed of a relatively thick layer of soft mud will absorb more of the sound energy compared to a seabed composed of hard rock, that will cause a relatively high reflection of the sound energy.

In any general scenario, the upward refraction scenario will cause the lowest sound transmission loss and thereby the largest sound emission.

In waters with strong currents, the relationship between temperature and salinity is relatively constant as the water is well-mixed throughout the year.

As an example, in the Swedish waters, as Kattegat, Skagerrak and the Baltic Sea, an estuary-like region with melted freshwater on top, and high saline sea water at the bottom, the waters are generally not well-mixed and great differences in the relation between temperature and salinity over depth can be observed. Furthermore, this relationship depends heavily on the time of year, where the winter months are usually characterized by upward refracting or iso-velocity sound speed profiles. In the opposite end of the scale, the summer months usually have downward refracting sound speed profiles. In between the two seasons, the sound speed profile gradually changes between upward and downward refracting.

The physical properties of the sea surface and the seabed further affect the sound propagation by reflecting, absorbing and scattering the sound waves. Roughness, density and media sound speed are among the surface/seabed properties that define how the sound propagation is affected by the boundaries.

The sea surface state is affected mainly by the climate above the sea surface. The bigger the waves, the more rough the sea surface, and in turn, the bigger the transmission loss from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective medium with very low sound absorption, causing the sound to travel relatively far. In rough seas, the sound energy will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss. As previously mentioned, this is not always possible to include in sound propagation models, and the transmission loss can therefore be underestimated, leading to higher noise forecasts than what would actually occur.

Another parameter that has influence on especially the high frequency transmission loss over distance is the volume attenuation, defined as an absorption coefficient reliant on chemical conditions of the water column. This parameter has been approximated by Equation 8 (Jensen, et al., 2011):

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11 f^2}{1 + f^2} + \frac{44 f^2}{4100 + f^2} + 3.0 \times 10^{-4} f^2 \quad \left(\frac{dB}{km}\right) \qquad \text{Equation 8}$$

Where f is the frequency of the wave in kHz. This infers that increasing frequency also leads to increased absorption.

6.2 Sound propagation models

There are different algorithms for modelling the sound propagation in the sea, all building on different concepts of seabed interaction and sound propagation, however only one that allows for the use of directional sources. This algorithm is called dBSeaRay, and is built on Ray tracing theory.

Ray tracing has a good accuracy when working with frequencies above 200 Hz, however in very shallow waters, the minimum frequency would be higher, as the rays need space to properly propagate. Different techniques can be applied for ray tracing to improve and counteract certain of its inherent shortcomings (Jensen, et al., 2011). Ray tracing furthermore, is the only algorithm that inherently supports directional sources, that is, sources that do not radiate sound equally in all directions.

6.3 Underwater sound modelling software

NIRAS uses the commercial underwater noise modelling tool: dBSea version 2.3.2, developed by Marshall Day Acoustics.

The software uses 3D bathymetry, sediment and sound speed models as input data to build a 3D acoustic model of the environment and allows for the use of either individual sound propagation algorithms or combinations of multiple algorithms, based on the scenario and need. For shallow water scenarios, a combination approach is usually preferred due to the individual algorithm limitations presented. The software furthermore supports the use of moving source modelling, where the motion is defined for each vessel in terms of speed, turning points and firing rate.

6.4 Environmental model

In this section, the environmental conditions are examined to determine the appropriate input parameters for the underwater noise model. The sound propagation depends primarily on the site bathymetry, sediment and sound speed conditions. In the following, the input parameters are described in general.

6.4.1 Bathymetry

dBSea incorporates range-dependent bathymetry modelling and supports raster and vector bathymetry import.

Figure 6.1 shows the bathymetry map for Europa, where darker colours indicate deeper areas, and lighter colours indicate more shallow water. The map is obtained from EMODnet and this version was released in December 2020. The resolution of the map is 115 x 115 metres. EMODnet has created the map using Satellite Derived Bathymetry (SDB) data products, bathymetric survey data sets, and composite digital terrain models from a number of sources. Where no data is available EMODnet has interpolated the bathymetry by integrating the GEBCO Digital Bathymetry (EMODnet, 2021).

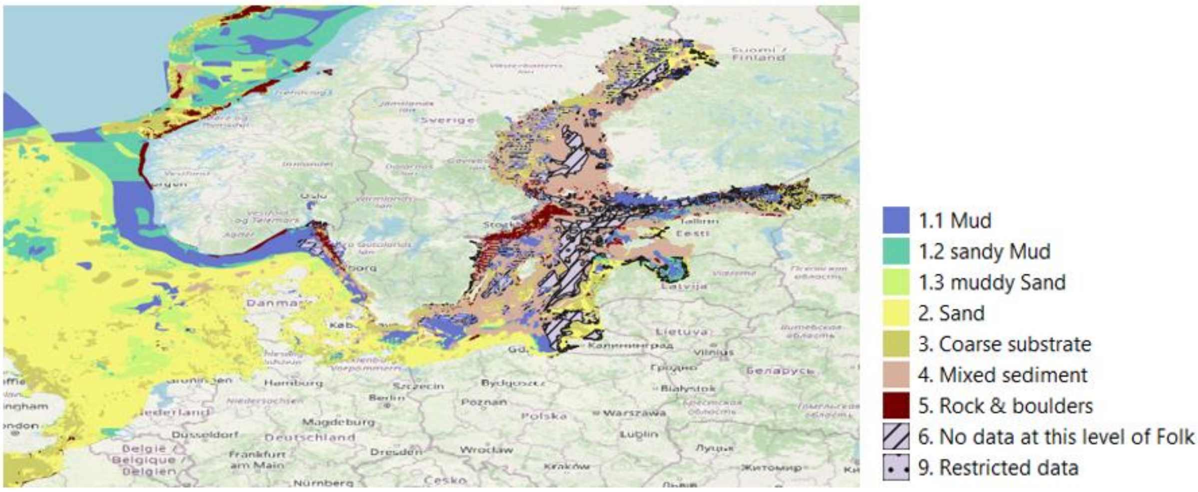
Figure 6.1: Bathymetry map over European waters from Emodnet [EMODnet, 2021].

6.4.2 Seabed sediment composition

In dBSea, the sound interaction with the seabed is handled through specifying the thickness and acoustic properties of the seabed layers all the way to bedrock. It can often be difficult to build a sufficiently accurate seabed model as the seabed composition throughout a project area is rarely uniform. The thickness and acoustic properties of the layers, from seabed all the way to bedrock, is generally obtained thought literature research in combination with available site specific seismic survey findings.

For determining the top layer type, the seabed substrate map (Folk 7) from https://www.emodnet-geology.eu/ is generally used. This map is shown in Figure 6.2.

Figure 6.2: A section of the seabed substrate map, (Folk 7) [EMODnet, 2021].



6.4.3 Sound Speed Profile

The sound propagation depends not only on bathymetry and sediment but also on the season dependent sound speed profile. To create an accurate sound speed profile, the temperature and salinity must be known throughout the water column for the time of year where the activities take place.

NIRAS examined NOAAs WOA18, freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, (NOAA, 2019) which contains temperature and salinity information at multiple depths throughout the water column.

For each of the sediment model positions, the nearest available sound speed profile, as well as average temperature and salinity was extracted for the different months.

6.5 dBSea settings and site specific environmental parameters

In the following, the project specific input parameters are summarized.

6.5.1 dBSea settings

For this project, the dBSea settings listed in Table 6.1 were used.

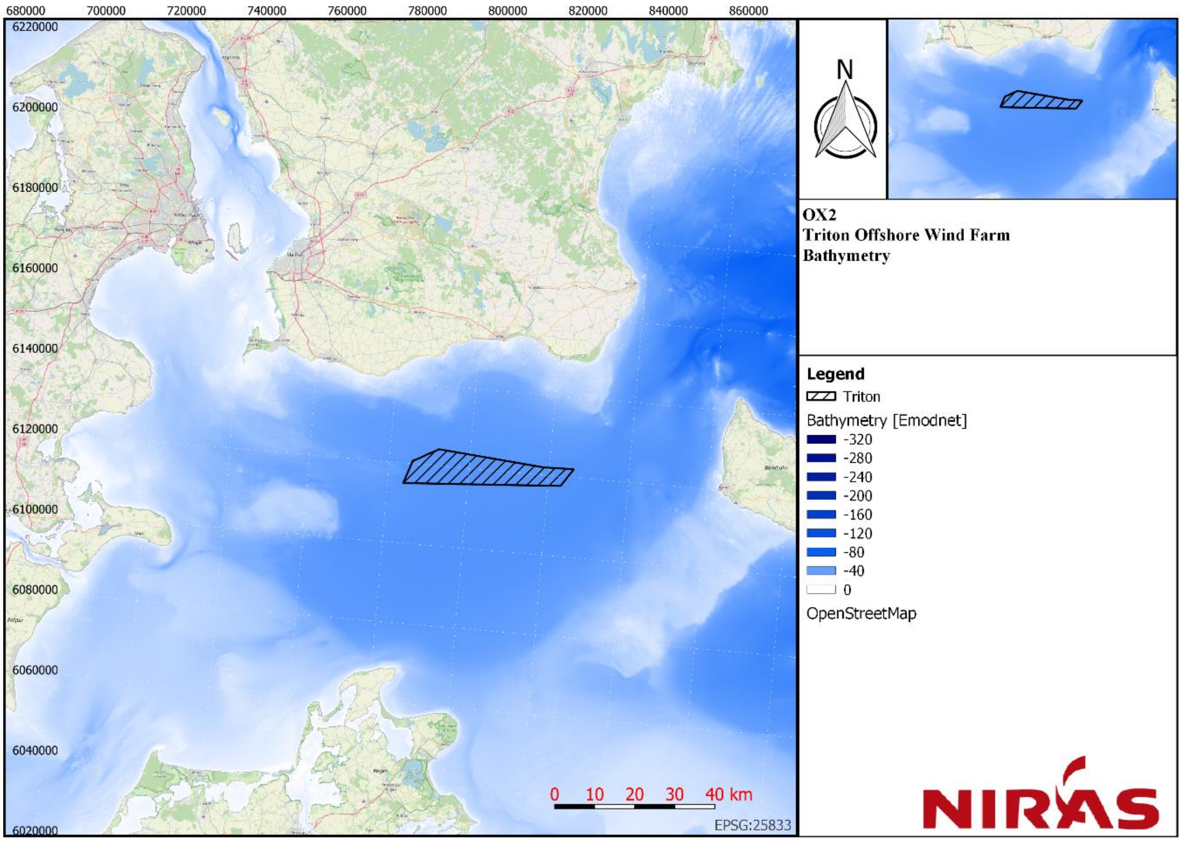
Table 6.1: dBSea Settings

Technical Specification		
Octave bands		1/1-octave
Grid resolution (range, depth)		50 m x 1 m
Number of transects		180 (2° resolution)
Sound Propagation Model Settings		
Model	Start frequency band	End frequency band
dBSeaRay (Ray tracing)	16 Hz	128 kHz

6.5.2 Bathymetry

The bathymetry implemented for this project, is shown in Figure 6.3, and includes the wind farm site and around 125 km to each side (extracted from the bathymetry map in Figure 6.1). In the area of relevance, the bathymetry ranges from a depth of 100 m, indicated by the darker colours, to a depth of 0 m (land), indicated by the lighter colours.

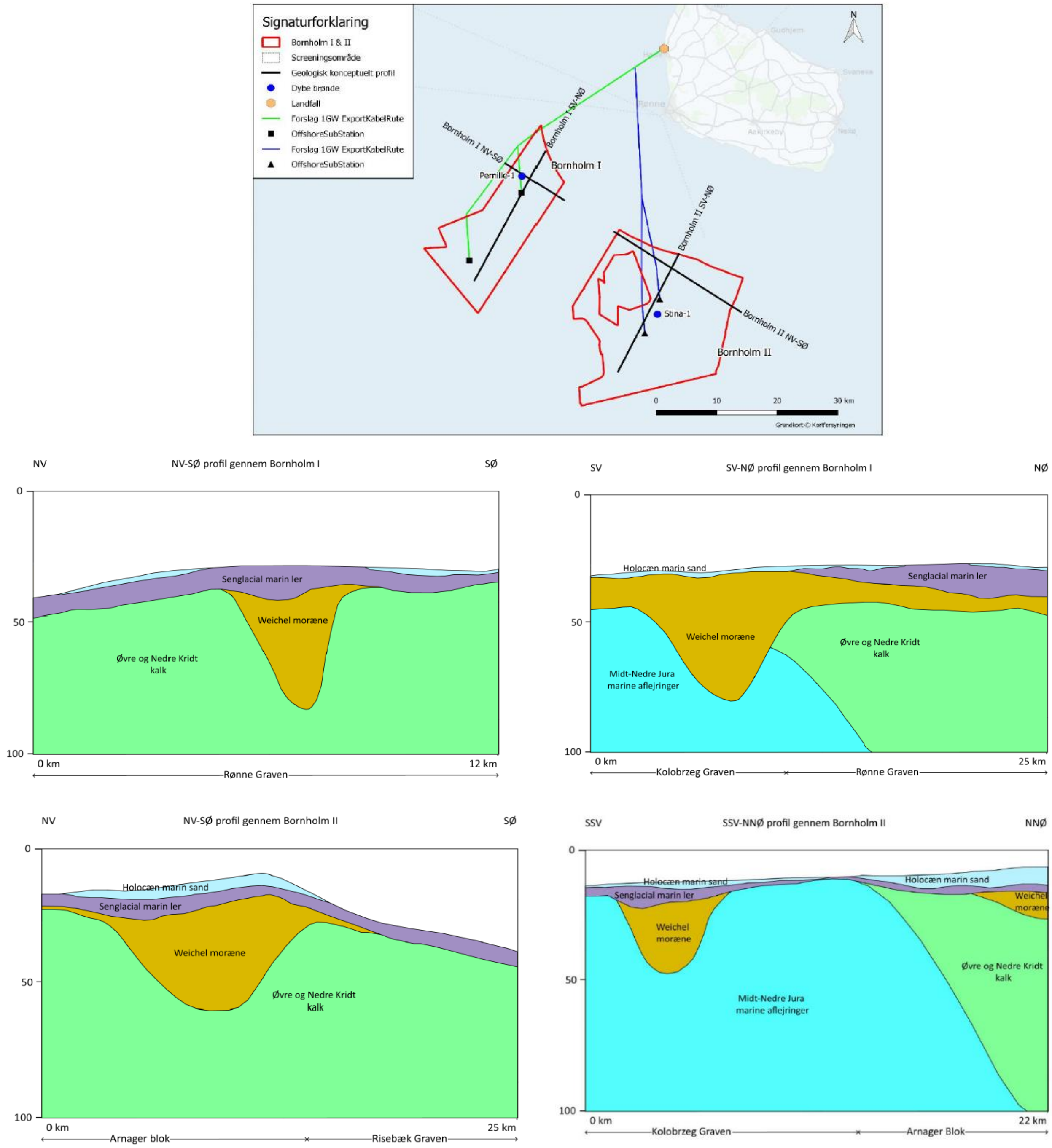
Figure 6.3: Bathymetry map for the Triton site and surroundings.



6.5.3 Sediment

It can often be difficult to build a sufficiently accurate seabed model as the seabed composition throughout a project area is rarely uniform and the information available is often scarce. The thickness of the layers, from seabed all the way to bedrock, is obtained through literature research, where the following source, (COWI, 2020), was found. Therefore, Figure 6.4 from (COWI, 2020) provided information on local layer depths through sediment profiles. The profiles are from seismic survey transects obtained near the project area, and are therefore included in the sediment model layer composition.

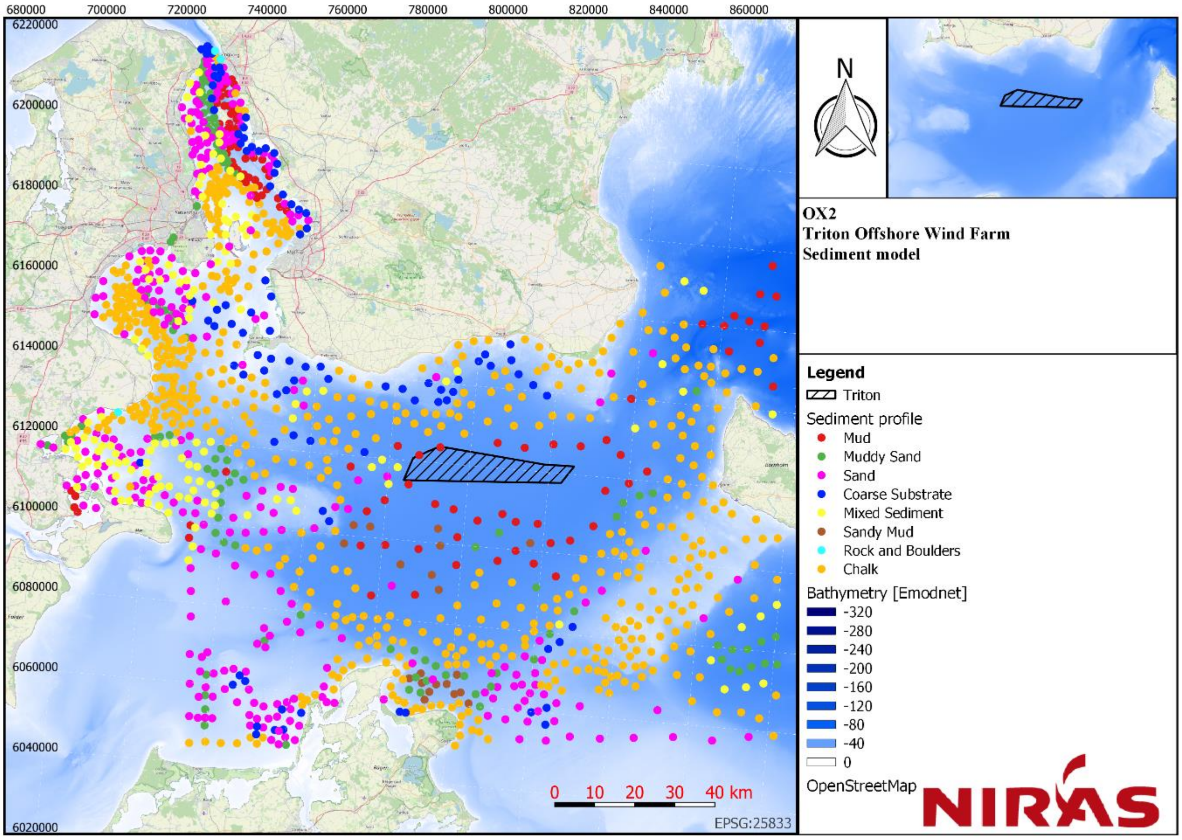
Figure 6.4: Interpreted geological profile from (COWI, 2020).



To be able to make a detailed model that takes the seabed substrate into account as well as the varying bathymetry, a 1348 point sediment model was built. Figure 6.5 shows the distribution of the sediments points with the corresponding seabed sediment from Folk 7 (EMODnet, 2021).

The sediment model uses the information from the seabed substrate map to determine the top layer type, while the literature was used to determine average thickness at the different positions. The top sediment layer thickness varies throughout the area and literature indicates that below the top sediment Chalk is reached. By looking at Figure 6.4 it can be noted that there are very local valleys of moraine, these are not consider in the sediment profile since they are very local and obtained from over 20 km from the wind farm site.

Figure 6.5: Sediment model for Triton project area and surroundings.



6.5.4 Sound speed profile

Figure 6.6 shows the extracted sound speed profiles at the available positions. Note that the gridded layout of the sound speed profiles indicate their respective position geographically.

Examining Figure 6.6, this would indicate March as the worst case month and June-July as the best case. As no specific installation time is yet known, it was decided, in cooperation with OX2, to work with the worst case approach. In Figure 6.7 the sound speed profiles for the worst case month of march is shown.

Figure 6.6: Historic averages for Sound speed profiles for Triton project area for all months of the year.

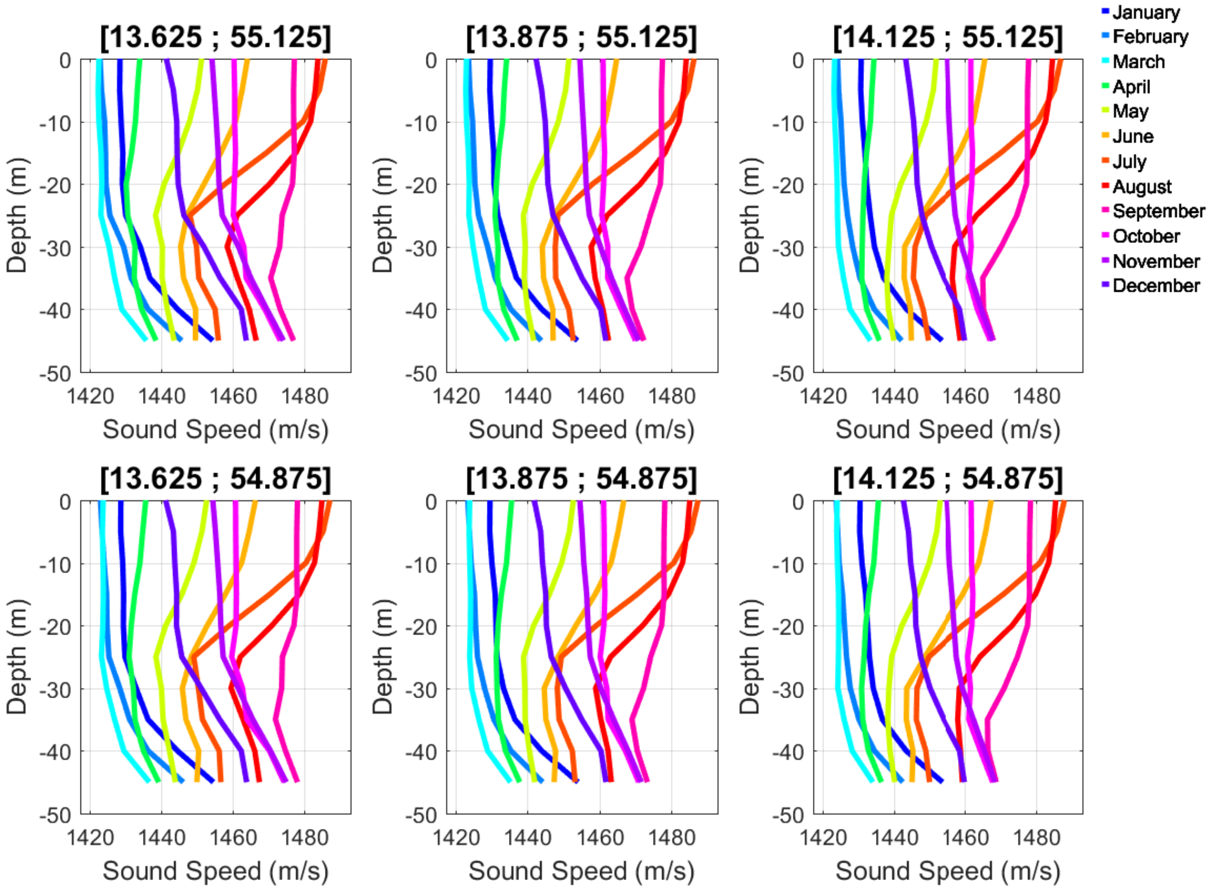
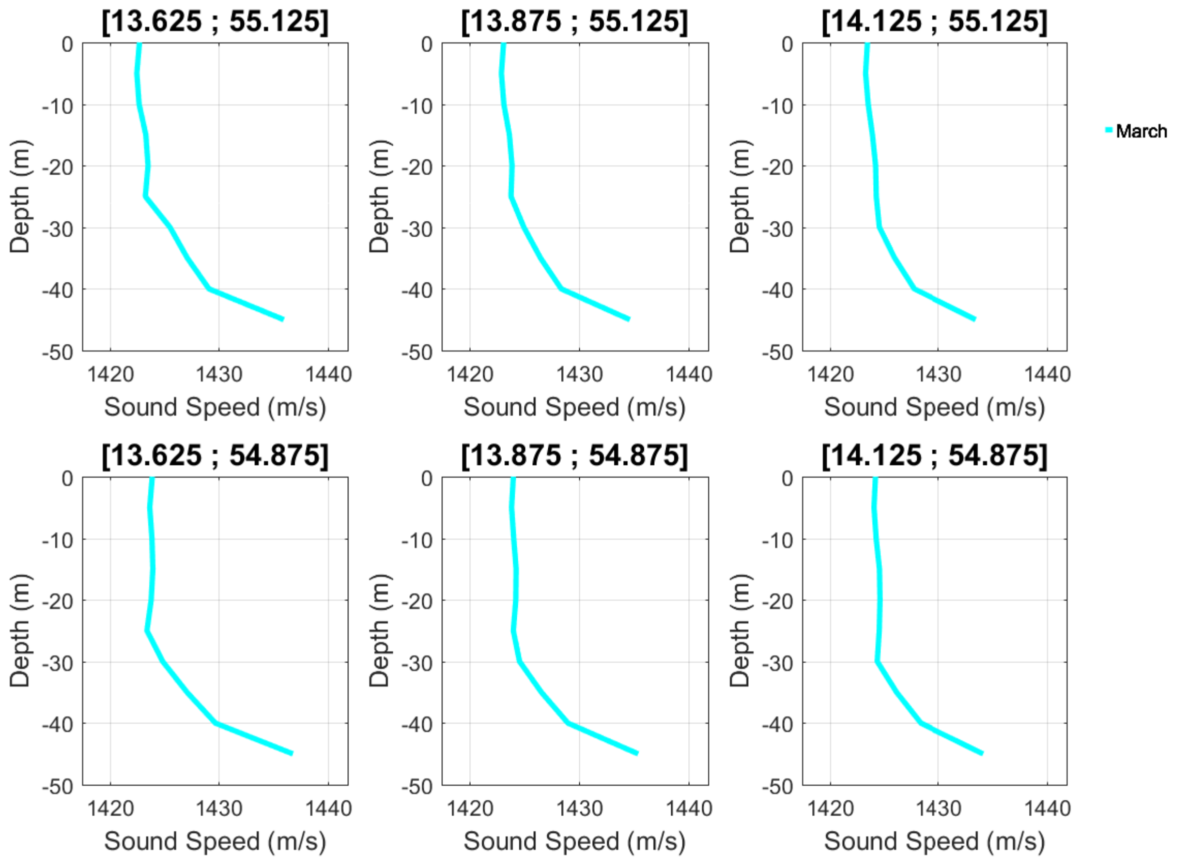


Figure 6.7: Historic averages for Sound speed profile for the worst case month in the project area of Triton.



6.6 Source modelling

In order to determine impact distances to each of the threshold levels listed in section 3.2, underwater sound propagation modelling is performed for each equipment setup scenario, as identified in section 4. For Equipment scenario 1 this comprise the Innomar system as well as the sparker and mini airguns. For Equipment scenario 2, the Innomar system and the mini airguns are included in the underwater noise propagation model. Whereas for Equipment scenario 3, only the Innomar system is included in the underwater noise propagation model.

The surveys are carried out by a single source vessel sailing at 4 knots in a straight line (source vessel transect) until it reaches the boundary of the survey site, where it performs a turn and continues on the next transect. The source vessel will be equipped with the equipment listed in section 4, some of it mounted on the vessel itself, some of it towed behind the vessel.

To model cumulative sound levels, the following approach to source modelling has been agreed with OX2.

Table 6.2: Technical specification for source modelling.

Technical specification for source modelling		Note
Vessel speed	4 knots	
Time duration of the survey	24 h	
Fleeing behaviour	Included with 1.5 m/s fleeing speed	Fleeing behaviour considered is "negative phonotaxy" (Tougaard, 2016)
Number of transects	180 (2° resolution)	
Survey vessel route	Final routes not decided. Different likely worst-case options chosen for different areas of site.	

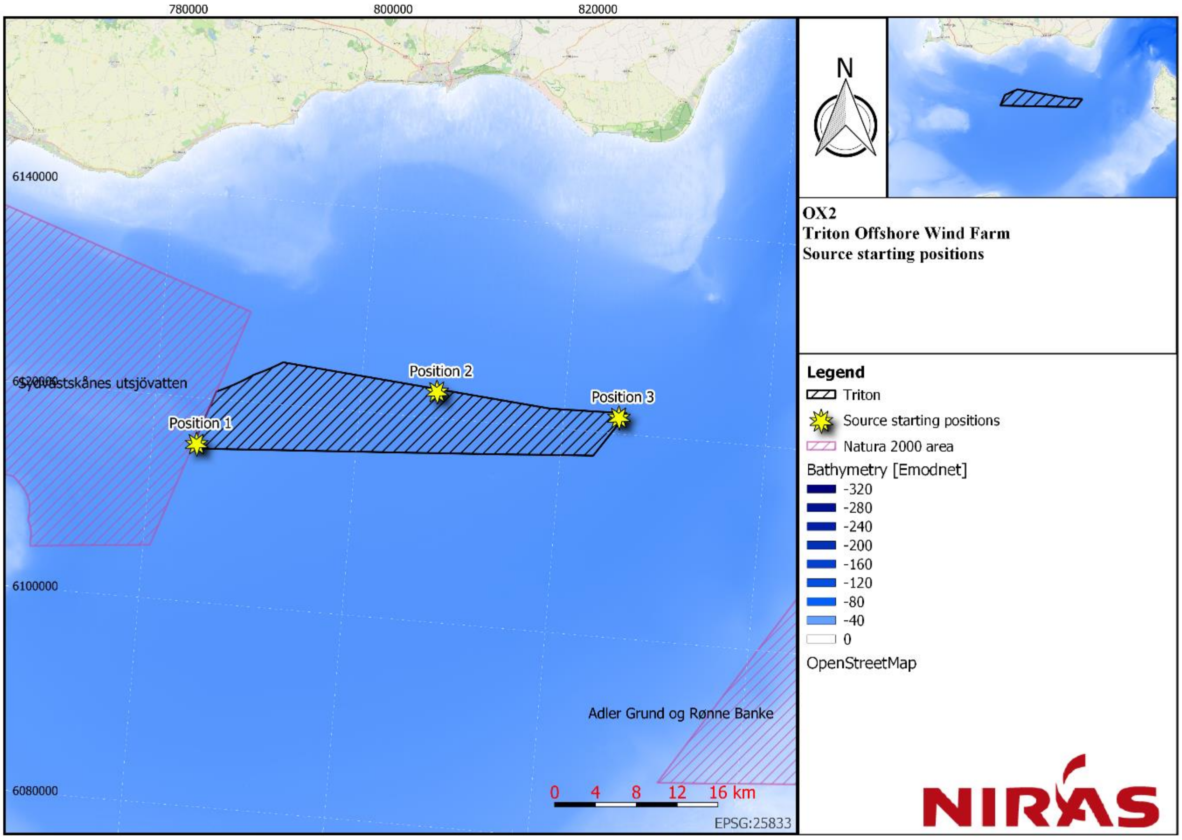
For calculating the threshold distances for PTS and TTS, all equipment within each of the equipment setup scenarios are considered operational in accordance with the operational parameters outlined in Table 4.2 - Table 4.4.

6.6.1 Source positions

Figure 6.8 shows the Triton OWF area and the surrounding Natura 2000 areas with a dimmed pink. In order to represent seismic survey activities within the site, four worst-case source positions were selected for underwater sound propagation modelling.

Positions 1 - 3 are located within the OWF site, and given the relatively flat bathymetry and similar sediment composition, within the entire OWF site, the chosen positions are expected to provide a good representation of the area. All positions are shown in Figure 6.8 as yellow stars. With the selected source positions, it is expected that the results will be representative for any position within the site.

Figure 6.8: Overview over the selected source starting positions indicated by the yellow stars.



6.7 Background noise

There will be several sources of noise, which are not included in the underwater sound propagation modelling. These include:

- Any biological sources, such as shrimps, whales and other marine mammals.
- Anthropogenic noise source e.g. from ships, both those towing the equipment, follower ships etc.
- Environmental noise, such as waves, currents, natural seismic activities.

It is not expected that any of these noise sources will be significant in terms of impact distances compared to the seismic sources used in the survey.

7 Results

Sound propagation modelling was carried out for three positions within the site for each of the three Equipment setup scenarios.

7.1 Impact distances

Worst case position sound propagation modelling was undertaken for likely avoidance behaviour, as represented by the threshold $SPL_{RMS-fast,VHF} = 100\ dB\ re\ 1\ \mu Pa$, while cumulative 24 hour modelling was undertaken for TTS and PTS. For harbour porpoise this is represented by the thresholds $SEL_{C24h,VHF} = 140\ dB\ re\ 1\ \mu Pa^2 s$ for TTS and $SEL_{C24h,VHF} = 155\ dB\ re\ 1\ \mu Pa^2 s$ for PTS. In regard to harbour seal it is represented by the thresholds $SEL_{C24h,PW} = 170\ dB\ re\ 1\ \mu Pa^2 s$ for TTS and $SEL_{C24h,PW} = 185\ dB\ re\ 1\ \mu Pa^2 s$ for PTS. Both TTS and PTS threshold calculations are based on marine mammals fleeing (negative phonotaxy) behaviour as described in section 3.1.2.

The resulting impact distances for the different thresholds are listed in Table 7.1.

Table 7.1: Threshold impact distances for the seismic survey activities divided by equipment setup scenarios. The distances for PTS and TTS indicate, at which range of distances, in meters, from the survey vessel, a marine mammal must at least be at the onset of full survey activities in order to avoid each of the given impacts. Results represent worst case survey month of march.

Area	Equipment scenario	Position	Threshold distance [m]				
			Harbour porpoise			Seal	
			Avoidance Behavior $SPL_{RMS-fast,VHF} = 100\ dB$	TTS $SEL_{C24h,VHF} = 140\ dB$	PTS $SEL_{C24h,VHF} = 155\ dB$	TTS $SEL_{C24h,PW} = 170\ dB$	PTS $SEL_{C24h,PW} = 185\ dB$
Triton OWF site	1: Sparker Airguns & Innomar	1	5050	1200-2700	375-950	100-350	< 25
		2	6550	1300-3000	425-1050	90-350	< 25
		3	4800	1175-2550	400-975	60-300	< 25
	2: Airguns & Innomar	1	3200	1200-2700	375-950	< 50	< 25
		2	3400	1300-3000	425-1050	< 50	< 25
		3	3250	1175-2550	400-975	< 50	< 25
	3: Innomar	1	3200	1200-2700	375-950	< 50	< 25
		2	3400	1300-3000	425-1050	< 50	< 25
		3	3250	1175-2550	400-975	< 50	< 25

For PTS and TTS, distances range from minimum impact distance to maximum impact distance, representing the dependency on marine mammal position relative to the survey vessel. Minimum distances represent marine mammals located "behind" or perpendicular to the vessel, while maximum distances represent marine mammals located in front of the vessel. The results can be used to define the minimum distance, a marine mammal must be deterred to, relative to the survey vessel at the onset of full activities, in order to avoid the respective impact. Sufficient soft start/ramp up procedures should thus be carried out prior to the seismic survey.

It should be noted, that impact distances for Equipment scenario 2 and scenario 3 are identical. This is due to the airguns having an insignificant effect on the overall noise levels with the frequency weightings applied, compared to the effect of the Innomar system.

It is also worth noting, that PTS and TTS distances for Equipment setup 1, 2 and 3, in position 1, 2 and 3, are very similar. This is due to the Innomar system being by far the dominant noise source with the VHF weighting, at distances up to 3-4 km from source, after which the sparker begins to contribute significantly to the overall noise level.

8 Recommended mitigation

The isolated ship noise from the seismic survey vessel (engine and propeller etc.) is expected to have a deterring effect on harbour porpoises (without any seismic survey equipment running). During visual boat surveys harbour porpoises have been shown to swim away when the boat is less than 50 m away (Sveegaard, et al., 2017).

As impact ranges are expected to exceed 50 m, the vessel noise alone will not ensure that marine mammals are deterred to a sufficient distance. It is therefore recommended that any seismic survey includes a soft start with ramp up to full power over a sufficiently long duration. As an example, a 30 minute soft start would allow a marine mammal swimming at 1.5 m/s to reach a distance of 2.7 km. Add to that the vessel speed of 4 knots (2.0 m/s), and the resulting distance between fleeing marine mammals and survey vessel will be over 5 km. This would be sufficient to avoid PTS and TTS effects for all equipment setups, with the 30 minute soft start procedure. This will allow marine mammals in the potentially hazardous zone near the seismic survey vessel to swim away, before the seismic survey is running at full power.

9 Conclusion

For harbour porpoise, it is concluded that all Equipment scenarios cause around the same impact distances with regards to Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS). This is due to the Innomar system being the dominant noise source at distances out to 3-4 km from the survey vessel, when VHF weighting is applied. PTS is therefore likely to occur in harbour porpoise present at distances out to 1050 m from the survey vessel at the onset of seismic survey activities, while for TTS, the distance is 3 km.

For seals, where PW weighting is applied, the sparker is the most significant noise source, and the threshold distances therefore differ between the Equipment scenarios. While PTS in seal is unlikely to occur beyond 25 m from source vessel in all Equipment scenarios, TTS is likely to occur for seals located at distances up to 350 m from the vessel for Equipment scenario 1, but only up to 50 m for Equipment scenario 2 and 3.

It should be noted, that the maximum impact distances represent marine mammals located directly in the path of the survey vessel, whereas those marine mammals located perpendicular to, or behind the survey vessel path, have significant lower impact distances.

It is assessed, that a 30 minute soft start procedure where non harmful sound is emitted from the survey vessel, or separate equipment deployed at the starting position for the survey, will be sufficient to deter harbour porpoise and seal from distances at which PTS and TTS can potentially be incurred.

For harbour porpoise avoidance behaviour, the impact distance was found to be up to ~ 6.55 km from the survey vessel with Equipment scenario 1 active, and up to ~3.4 km with equipment scenario 2 or 3 active. Contrary to the PTS and TTS, the behaviour distance disregards the duty cycle of the equipment types, and only considers a single pulse from each. This makes the sparker the dominant noise contributor for VHF behaviour distances, as it has a very low duty cycle (0.5 Hz) compared to the Innomar system (4 Hz).

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Appendix 1: Mini GI 60 Cu. Inch. Airgun, Gundalf Report

GUNDALF array modelling suite - Marine mammal noise impact report

Gundalf revision AIR8.1n, Date 2018-03-30, Epoch 2018-03-30

Mon Mar 23 09:14:02 Paris, Madrid 2020 (Sercel)

Report pre-amble

Author: JLA

Author Organisation: SERCEL

Customer Organisation: NIRAS

Survey Details: Mini GI SOURCE 60 cuin

Contents

Signature filtering policy

For marine environmental noise reports, Gundalf performs no signature filtering other than that inherent in modelling at a sample interval small enough to simulate an airgun array signature at frequencies up to 50kHz, and any requested marine animal weighting functions.

For all other kinds of reports, Gundalf performs filtering in this order:-

- If a pre-conditioning filter is chosen, for example, an instrument response, it is applied at the modelling sample interval.
- If the output sample interval is larger than the modelling sample interval, Gundalf applies appropriate anti-alias filtering. (This can be turned off in the event that anti-alias filtering is included in the pre-conditioning filter, in which case Gundalf will issue a warning.)
- Finally, Gundalf applies the chosen set of post-filters, Q, Wiener and band-pass filtering as specified, at the output sample interval. If none are specified, (often known as unfiltered), only the above anti-alias and/or pre-conditioning are applied.

In reports, when filters are applied, they are applied to the notional sources first so that signatures, directivity plots and spectra are all filtered consistently. The abbreviation muPa is used for microPascal throughout.

Finally note that modelled signatures always begin at time zero for reasons of causality.

In this report, no filtering other than the appropriate anti-alias filtering has been performed.

Environmental background

This report models the acoustic radiation field of an array of airguns and displays its information in a form suitable for estimating the environmental noise impact on marine mammals.

It particularly uses reference material described in

- "Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals" National Oceanic and Atmospheric Administration (NOAA), (2013) Original draft December 23, p. 1-67 updated to March 2016 proposed changes.
- "Marine mammals and noise" by Richardson, Greene, Malme and Thomson, (1995), Academic Press ISBN 0-12-588441-9.
- "Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations" by Southall et. al. (2007), Aquatic Mammals (33) 4, p. 411-509 ISSN 0167-5427.

Note that calibration information for frequencies above 2kHz is sparse. In normal seismic surveying with airguns down to perhaps 20m, the bandwidth up to 1kHz is very well served by existing calibration data as can be seen by consulting Gundalf's Help -> Calibration section. However for frequencies above this, data is a little more sparse. The first available dataset was acquired by IFRC in 2003 in the Gulf of Mexico. This dataset has deep-deployed hydrophone information at discrete points in the acoustic radiation field recording out to 25kHz or so. Gundalf has been calibrated out to 25kHz using these high-quality data and is within +/- 10db at 20kHz against this data as can be seen at:-

http://www.leshatton.org/UN2008_Southampton_Hatton.html

It is very unlikely that modelling will get much better than this at these high frequencies as the oscillating bubble itself is highly turbulent and very anisotropic as can be seen by studying:-

http://www.leshatton.org/two_airgun_videos.html

A more detailed data set appeared through the Svein Vaage experiment in 2009-2013. This was acquired in a Norwegian fjord based measurement facility but is for a limited range of depths. It produces data consistent with that of the 2003 experiment.

Measuring acoustic impact

The output radiated energy in an airgun array signature is normally measured in bar-m. peak to peak. This is only partially suitable for measuring the potential impact on marine mammal hearing as mammals tend to integrate over the amplitude spectrum in a complex non-linear frequency dependent way. In the above mentioned references, a standardised method of measuring impact is now beginning to emerge. This involves two measurements:-

- SPL (Sound Pressure Level). This measures the rapidity of the onset and is the peak to peak measure in dB. relative to 1 muPa at 1m. Some references use zero to peak but Gundalf is conservative here and uses peak to peak. Gundalf predicts the necessary reflection coefficient using a sophisticated model based on detailed measurements taken in a calibration facility.
- SEL (Sound Exposure Level). This measure allows an estimate of continued exposure and its effects on TTS (Temporary Threshold Shift) and PTS (Permanent Threshold Shift) to be assessed. It is commonly measured as 90% of the sum of squared pressures over a signal duration measured from the time when the signal reaches 5% of its total, to the time when it reaches 95% of its total. This is then normalised to 1s. Its units are dB. relative to 1 muPa^2-s.

Both these measures depend on the bandwidth at which a signal is measured. However they are particularly useful to marine biologists and provided the sample interval is sufficiently small, this is not an issue as the airgun is not a high frequency source with very little residual energy above 10kHz and are typically at least 20dB down on a ship's depth transponder at 18kHz according to recent experiments carried out by the IFRC and published by Hatton (2004).

Since version 8.1d, Gundalf only uses SPL and SEL so as not to cause confusion in this complex area.

Finally with regard to spectral weighting to adapt to the audiogram response of an animal, Gundalf now uses the increasingly widely adopted M-Weighting described in Southall et. al. (2007), enhanced to include the Cetacean Auditory Weighting Functions described in the NOAA report (March 2016 updates).

db. or not dB.

Unfortunately, 'dB' is often used inconsistently in environmental impact reporting. dB are dimensionless and are defined as 20 log10(A2/A1) where A2 and A1 are amplitude values in some units. To tie them to some absolute unit, dB should always be stated relative to something as follows:

- *dB relative to 1 nm/s (nanometre/s)*. This is the standard ANSI unit for the measurement of acoustic particle velocity.
- *dB relative to 1 muPa per Hz. at 1m*. This is the standard unit for pressure in the amplitude spectral domain used in exploration seismology following the work of Fricke, Davis and Reed (1985) 'A standard quantitative calibration

procedure for marine seismic sources', Geophysics, 50(10), p. 1528-1532. It is independent of signal duration, sample interval and measurement position.

- *dB relative to 1 muPa at 1m*. This is exactly the same as the previous unit but it has been integrated over some part of the amplitude spectrum, for example, 1/3 octave or 1 octave around some central frequency as reported in Richardson et. al. (1995). The fact that the spectrum is integrated removes the 'per Hz.' present in the previous unit but for precision, the central frequency, shape and width of the band should be given as for example '160 dB rel. 1 muPa at 1m integrated uniformly over 1/3 octave around 1000 Hz.'

  This unit is also used for the SPL, with or without M-weighting or CAWF described in Southall et. al. (2007) and NOAA (March 2016 updates) respectively.

- *dB relative to 1 muPa^2-s*. This unit is used for the SEL.

Frequency response of common marine mammals

There are basically five categories of marine mammal functional hearing groups highlighted in the Southall et. al. report and updated in the later NOAA report:-

- **Low-frequency (LF) cetaceans**, (baleen whales): Functional Hearing Range 7Hz - 30 kHz.
- **Mid-frequency (MF) cetaceans**, (dolphins, toothed whales, beaked whales, bottlenose whales): Functional Hearing Range 150Hz - 160 kHz.
- **High-frequency (HF) cetaceans**, (true porpoises, Kogia, river dolphins, cephalorhynchid, Lagenorhynchus cruciger and L. australis): Functional Hearing Range 200 - 180 kHz.
- **Phocid pinnipeds**, (true seals): Functional Hearing Range 75Hz - 100 kHz.
- **Otariid pinnipeds**, (sea lions and fur seals): Functional Hearing Range 100 - 40 kHz.

Some example environmental criteria

NOAA draft criteria(2013,2015,2016)

A very detailed set of criteria for Impulsive / Non-impulsive PTS and TTS onset levels for all five defined categories of marine mammals. Building on the influential Southall criteria described below, these were initially proposed in December 2013. These were subject to a second comment period in July 2015 following various proposed changes and again in a third comment period to March 2016 which consolidated various independent work. These represent probably the most comprehensive guidelines currently available although may still be subject to further changes as more research becomes available.

Southall et. al. criteria (2007)

This report is currently the authoritative source on Marine Mammal Noise Exposure and is likely to become the most influential work in regulatory processes.

Note that each of the regulatory regimes which follows may define its own criteria but in our opinion, it will always be helpful to the regulator to include the performance of the current array relative to the relevant guidelines in the Southall criteria given their authoritative status and ubiquity.

So far, the most commonly used guidelines are the injury criteria on p. 443 of the report and repeated in the table below with corresponding worst case values for the current array (vertically down). The table is relevant to multiple pulse sources and the SEL Mxx refers to the relevant M-weighting, (essentially 3-octave band-pass filters with slopes of 12dB per octave, centred between around 500Hz for low-frequency cetaceans to around 10kHz for high-frequency cetaceans). SPL/SEL values for this array are conservative based on the vertically down pulse, so the corresponding section later in the report should be consulted for more detail.

Category	SPL (Sound Pressure Level) dB re 1muPa (peak) 10Hz - 25 kHz	SEL (Sound Exposure Level) dB re 1muPa^2-s (Mxx) 10Hz - 25 kHz
Low-frequency Cetaceans (max)	230	198
Mid-frequency Cetaceans (max)	230	198
High-frequency Cetaceans (max)	230	198
Pinnipeds (in water) (max)	218	186
Current array at 500m.	184.1	138.0
Current array at 1000m.	178.4	132.0
Current array at 2000m.	172.7	126.0
Current array at 3000m.	169.4	122.5

Current array at 5000m.	165.1	118.0
Current array at 10000m.	159.4	112.0

Bureau of Ocean Energy Management (BOEM-0327) (USA) (www.boem.gov)

The relevant part of these guidelines can be found in section D. In particular, D.3 solicits tabular information indicating *the manufacturer of the source, model, total energy output per impulse in dB (RMS), peak to peak in db, frequency in Hz (if applicable) etc*. In particular, column 5 asks for *Total Energy Output Peak to Peak in db, Amp, etc.*. Unfortunately, this does not state what the dB value is relative to. The closest relevant measure in the Southall criteria above is probably the SPL, (Sound Pressure Level) which is the zero to peak value measured in dB. re 1 muPa at some reference distance. This is most usefully given at the edge of the mitigation zone so that it represents the maximum an animal would experience anywhere outside that zone. The table above shows this at various typical values for the radius of this zone.

Column 6 asks for *Total Energy Output rms in db*. Arguably the most relevant of the Southall criteria for this is the SEL (Sound Exposure Level). This rms value is given in dB re 1muPa^2-s relative to some reference distance. Again, this is most usefully given at the edge of the mitigation zone and is shown in the table above.

Column 7 is optional and requests the frequency range in Hz - kHz. Since there is no reference to slopes or cut-offs, it is difficult to interpret. An airgun array has most of its energy below 1kHz but mid- and high-frequency cetaceans are increasingly sensitive up to around 20kHz so although an airgun array has almost nothing above 10kHz, the balance between this and the increased sensitivity is not well understood. The detailed sections below attempt to throw some light on this balance.

EPBC Act Policy Statement 2.1 (Australia) www.environment.gov.au/epbc/

For proposed seismic surveys that can demonstrate through sound modelling or empirical measurements that the received acoustic signal at 1km will not likely exceed 160dB re 1muPa^2-s for 95% of the time, the following safety zones are recommended:

- Observation zone: 3+ km horizontal radius from the acoustic source,
- Low power zone: 1 km horizontal radius from the acoustic source,
- Shut-down zone: 500 m horizontal radius from the acoustic source,

The received acoustic signal in this case corresponds to the SEL in the table above at a mitigation radius of 1000m.

Joint Nature Conservation Committee Guidelines Aug 2010 (JNCC) (UK) jncc.defra.gov.uk

These guidelines primarily focus on mitigation measures for the prevention of injury whilst making the point that the onus is on the entity responsible for the activity to assess whether a disturbance offence is likely to occur. The mitigation zone is considered to be 500m.

The Southall criteria above may therefore be quoted for this mitigation zone radius.

Ambient noise

Note finally that some environmental regimes require that the array be below the expected environmental background noise at a certain range, for example, 150 km from the array. Ambient noise levels are often quoted from the work of Knudsen et. al (1948), "Underwater ambient noise", J. Mar. Res. 7(3), p. 410-429 and are approximately as follows:

- 100-1000Hz: 50-80 dB rel 1muPa^2/Hz
- 1000-10000Hz: 35-65 dB rel 1muPa^2/Hz

depending on sea state. The levels for this array can be found below in the section on directional exposure within specified depth although at this extreme range, travel path variations may necessitate sophisticated bathymetric modelling.

Some notes on the modelling algorithm

The Gundalf airgun modelling engine is the end-product of 15 years of state of the art research. It takes full account of all air-gun interactions including interactions between sub-arrays. No assumptions of linear superposition are made. This means that if you move sub-arrays closer together, the far-field signature will change. The effect is noticeable even when sub-arrays are separated by as much as 10m.

The engine is capable of modelling airgun clusters right down to the 'super-foam' region where the bubbles themselves collide and distort. It has been calibrated against both single and clustered guns for a number of different gun types under laboratory conditions and accurately predicts peak to peak and primary to bubble parameters across a very wide range of operating conditions.

In many cases, the predicted signatures are good enough to be used directly in signature deconvolution procedures.

Array summary

The following table lists the statistics for the array quoted in various commonly used units for convenience. Note that the rms value is computed over the entire modelled signature. Conservative error bounds for the main signature characteristics of peak to peak, primary to bubble and bubble period are also shown. These represent 95% confidence intervals for the Gundalf model against its calibration data.

Array parameters ...: (0-25000) Hz	
Number of guns	1
Total volume (cu.in).	60.0 (0.983 litres)
Peak to peak in bar-m.	6.21 +/- 0.621 (0.621 +/- 0.0621 MPa, ~ 236 db re 1 muPa. at 1m.)
Zero to peak in bar-m.	5.9 (0.59 MPa, 235 db re 1 muPa. at 1m.)
RMS pressure in bar-m.	0.213 (0.0213 MPa, 207 db re 1 muPa. at 1m.)
Primary to bubble (peak to peak)	19.3 +/- 13.6
Bubble period (s.)	0.184 +/- 0.0184
Maximum spectral ripple (dB): 10.0 - 50.0 Hz.	7.8
Maximum spectral value (dB): 10.0 - 50.0 Hz.	183
Average spectral value (dB): 10.0 - 50.0 Hz.	178
Total acoustic energy (Joules)	1263.0
Total acoustic efficiency (%)	7.4

Array geometry and gun contribution

The following table lists all the guns modelled in the array along with their characteristics. The last column is completed only if the array has actually been modelled during the interactive session and contains the approximate contribution of that gun as a percentage of the peak to peak amplitude of the whole array. Please note the following:-

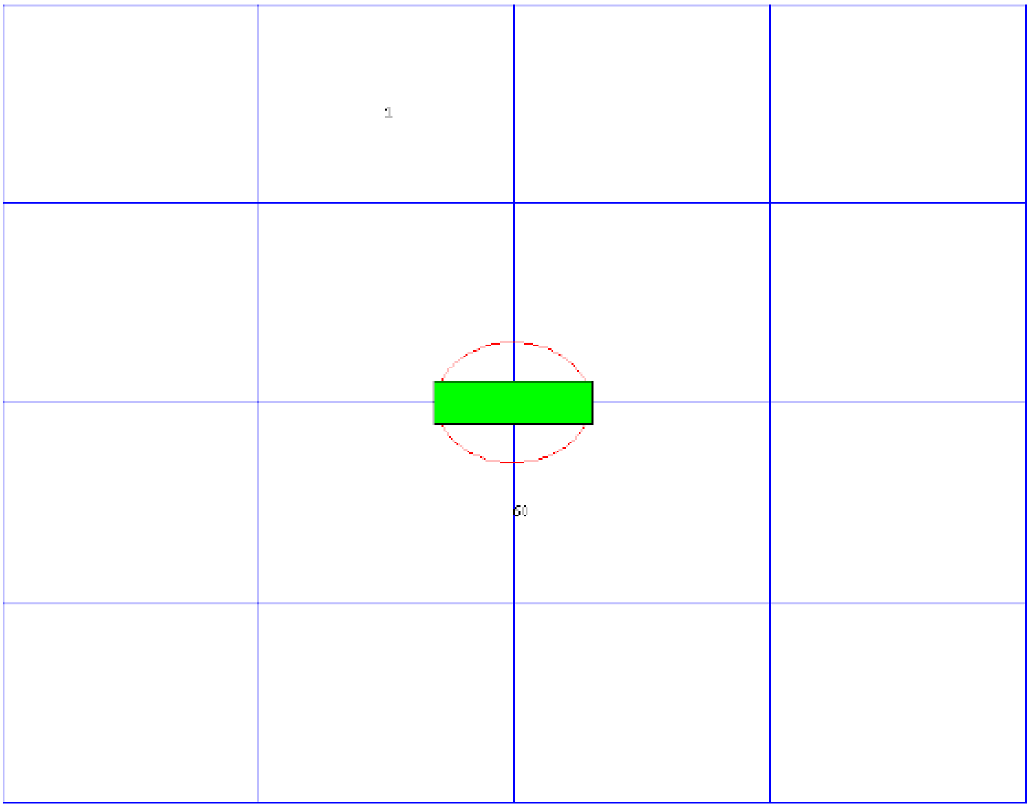
- The peak to peak varies only as the cube root of the volume for the same gun type so that even small guns contribute significantly. This is particularly relevant to drop-out analysis.
- The peak to peak can also be depressed due to clustering effects as reported by Strandenes and Vaage (1992), "Signatures from clustered airguns", First Break, 10(8).

Gun	Pressure (psi)	Volume (cuin)	Type	x (m.)	y (m.)	z (m.)	delay (s.)	sub-array	p-p contrib (pct.)
1	2500.0	G= 30.0, I= 30.0	GI-GUN	0.000	0.000	1.000	0.00000/(G->I internal)	1	100.0

The array is shown graphically below.

Hydrophone position: Infinite vertical far-field

<----- Direction of travel ----- --, 1 m. grid, plan view



The red circles denote the maximum radius reached by the bubble. Please note that pressure-field interactions take place over a much larger distance than this, (typically 10 times larger). However when bubbles touch or overlap, super-foam interaction can be expected. In this zone, significant peak AND bubble suppression will normally be observed.

Note also that a green rectangle represents a single gun and an orange rectangle indicates that the gun is currently dropped out. Where present, a yellow rectangle represents a vertical cluster (V.C.) of guns. Please see the geometry table above for more details. The small number to the above left of each gun is its reference number in this table. For clusters of guns, these reference numbers mirror the symmetry of the cluster.

Array azimuthal response

This section shows the azimuthal response of the array in various ways. Each of these is corrected using the user-defined spreading function. In reality, finding the correct spreading in any environment is an extraordinarily difficult problem but the real level is very likely to fall between these spherical and cylindrical spreading although in special cases, these limits can be exceeded at either end. In many environments, spreading close to spherical can be expected.

The user-specified spreading function is used for range-correction and was given as:- 19 log10(range)

A value of 10 log10(range) corresponds to cylindrical spreading whilst a value of 20 log10(range) corresponds to spherical spreading.

Losses due to anelastic reflection at the sea surface have been included. These are modelled internally by Gundalf using empirically observed sea-surface distortions when an airgun array fires. Such losses do not affect the direct arrival but do affect the ghost arrival.

Estimated Anelastic ghost reflection coefficient: -0.30

No allowance for species specific spectral weights was requested.

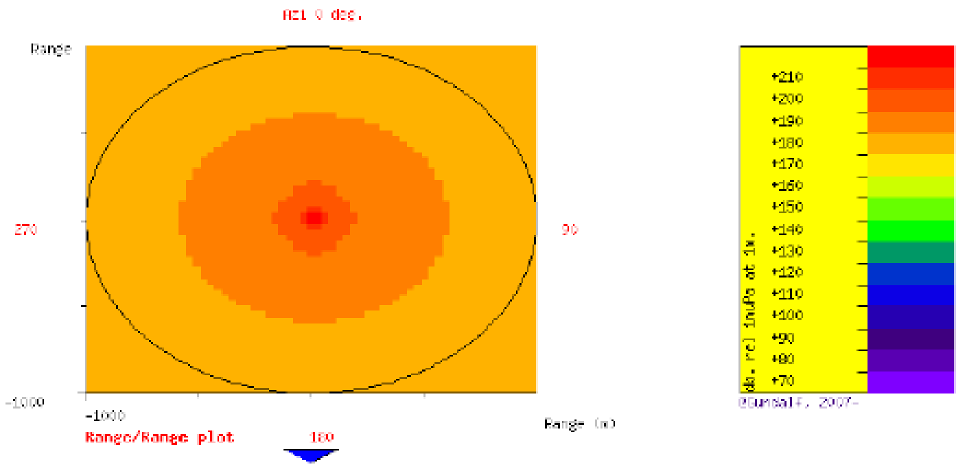
SPL/SEL within specified depth

This section shows the SPL (Sound Pressure Level) and SEL (Sound Exposure Level) as a function of direction for a supplied maximum depth. The displays show the view from above and contour the maximum value between the surface and the maximum depth given at each (x,y) position with the boat in the centre. These data are subject optionally to Cetacean or

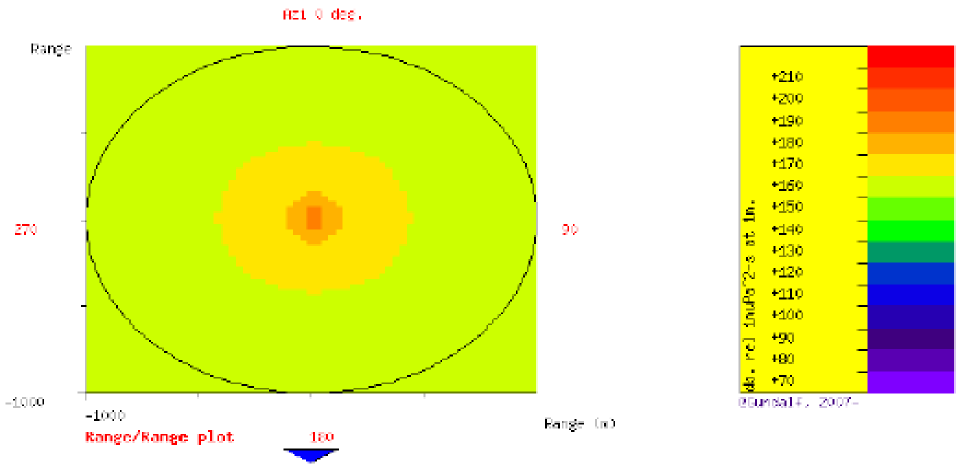
M-weighting functions and geometric spreading, all as specified elsewhere in this report. SPL is calculated peak to peak and SEL is calculated in a window between 5% and 95% of the total energy as recommended in Southall et. al. (2007). Array directivity means that this window varies significantly as a function of direction, implying that the commonly made assumption of 0.1s for airgun arrays is simply wrong. Gundalf therefore calculates this window explicitly for each angle of departure.

The specified depth was:- 20 m.

SPL to this depth, dB. rel. to 1 muPa at 1m.



SEL to this depth, dB. rel. to 1 muPa^2-s at 1m.



Swept area - pressure field

This section shows a cross-section underneath the ship at the stated bearing, of the radiation pattern of the array. The radiation pattern shown is the amplitude level in dB. relative to 1 muPa (rms) at 1m. In other words, the amplitude has been scaled by the rms value of the time signature measured over a window which exactly contains it, before the spectral values have been computed.

The user-specified spreading function is used for range-correction and was given as:- 19 log10(range)

A value of 10 log10(range) corresponds to cylindrical spreading whilst a value of 20 log10(range) corresponds to spherical spreading.

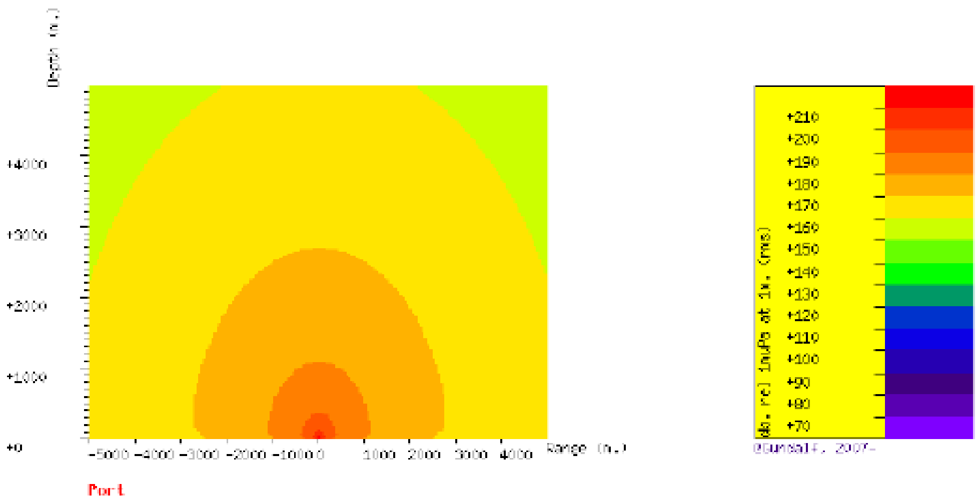
Absorption losses have been included as they can be significant in the higher frequencies. (At 25kHz, this is typically around 5 dB per km. and may be much higher.) The relationship due to Ross quoted in Richardson et. al. (1995), p.73 has been used.

Losses due to anelastic reflection at the sea surface have been included. These are modelled internally by Gundalf using empirically observed sea-surface distortions when an airgun array fires. Such losses do not affect the direct arrival but do affect the ghost arrival.

Estimated Anelastic ghost reflection coefficient: -0.30

No allowance for species specific spectral weights was requested.

Range-depth contours of exposure: 0 - 25000 Hz. , bearing = 90 degrees



The following table computes the area in sq.m. for which the sound level exceeds the stated value. These data can be used to compute the total swept volume in a survey which exceeds specified levels and thereby compute the total number of mammals expected to be affected given the density of mammals in the survey area.

RMS pressure level (dB. ref 1 muPa at 1m.): 0 - 25000 Hz.	Swept area (km. sq.)
220	0.002
210	0.003
200	0.023
190	0.229
180	1.938
170	11.605
160	43.709
150	50.000

Swept area - particle velocity field

This section shows a cross-section underneath the ship at the stated bearing, of the rms particle velocity field of the array. It is believed that hearing in fish may be responsive to the particle velocity field and some recent experiments have attempted to measure the auditory response of different species of fish as a function of both pressure and particle velocity, (see for example, Popper et. al. (2005), 'Effects of exposure to seismic airgun use on hearing of three fish species', J. Acoust. Soc. Am. 117 (6), June 2005).

It should be noted that this is an over-estimate as fish appear to be much less sensitive to frequencies much above 1-2kHz whereas this is a broadband calculation.

The standard ANSI unit for acoustic particle velocity is dB. relative to 1nm/s (nanometre/s).

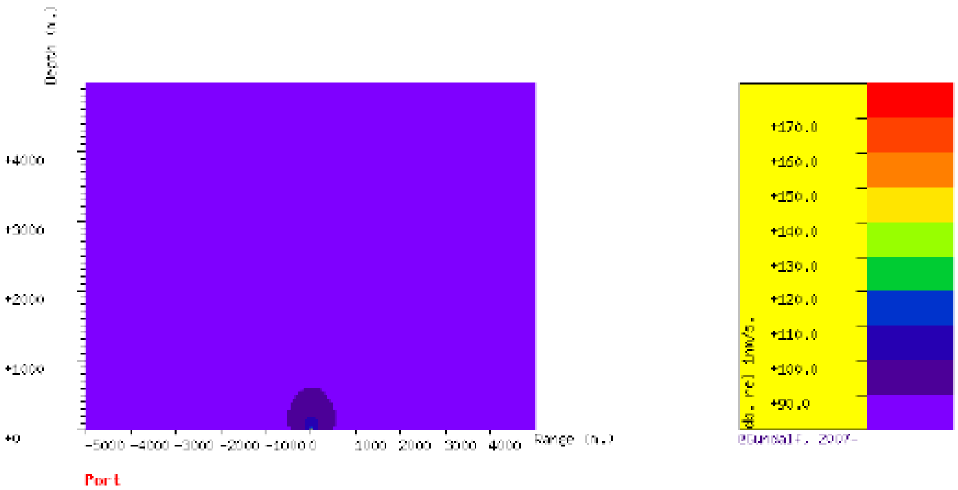
The user-specified spreading function is used for range-correction and was given as:- 19 log10(range)

A value of 10 log10(range) corresponds to cylindrical spreading whilst a value of 20 log10(range) corresponds to spherical spreading.

Losses due to anelastic reflection at the sea surface have been included. These are modelled internally by Gundalf using empirically observed sea-surface distortions when an airgun array fires. Such losses do not affect the direct arrival but do affect the ghost arrival.

Estimated Anelastic ghost reflection coefficient: -0.30

Range-depth contours of exposure for particle velocity: 0 - 25000 Hz. , bearing = 90 degrees



Total high frequency energy

The total quantity of acoustic energy emitted into the higher frequency bands is of relevance to echo-locators such as odontocete. Airgun arrays are not very rich in such frequencies but for convenience, the total energy budget in Joules is given here along with the total contribution above 10kHz where echo-location is primarily located.

The total average energy flux per shot is also given at the stated radius in Joules / m^2. For comparison, humans begin to experience pain at around 9 Joules / m^2 / s.

Total acoustic output (joules)	Total acoustic output (joules) above 10kHz	Total acoustic efficiency (%)	Average energy flux per shot (Joule/m^2) at 1000 m.
1262.972	73.91	7.45	0.000201

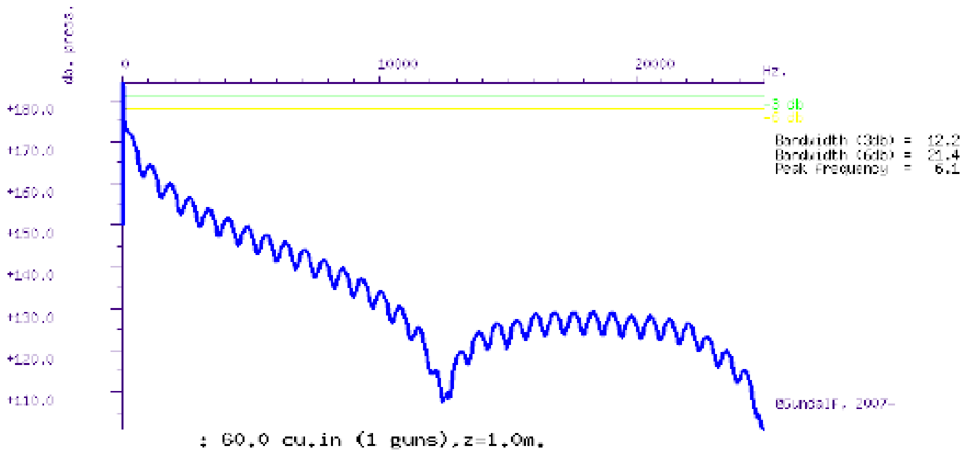
Related measurements which are sometimes quoted refer to the array output in units of 1muPa^2-s. For the specified range, the received acoustic energy per shot across the full signature bandwidth is a maximum of

132.0 dB rel. 1muPa^2-s.

Array amplitude spectrum

The following table shows the broadband amplitude spectrum of the vertically travelling far-field signature of the array corrected back to 1m.

Amplitude spectrum. Amplitude Units are dB. relative to 1 muPa / Hz. at 1m.



Modelling summary

The following table lists the modelling parameters for the array quoted in various commonly used units for convenience.

Signature parameters ...	
Output sample interval (s.)	0.00002
Number of samples in signature	16384
Duration of signature (s.)	0.328
Modelling sample interval (s.)	0.0005
Observation point	Infinite vertical far-field
Bubble search start time (s.)	0.03998 (Auto)
Filter parameters ...	
Signature filtering details	OFF
Q filtering	OFF
Wiener deconvolution	OFF
Sea Surface parameters ...	
Source ghost	ON
Reflection coefficient	-0.30
Source ghost estimation method	Anelastic
Streamer 1 ghost	OFF
Streamer 2 ghost	OFF
Physical parameters ...	
Sea temperature (C)	10.0
Velocity of sound in water (m./s.)	1496.0
Expected dominant frequency in signature (Hz)	20.0
Observed wave height (m)	0.0
Gun controller parameters ...	
RMS gun controller variation (s.)	0.0

Product code : GDF8.1Optimiser

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Maximum users : 1