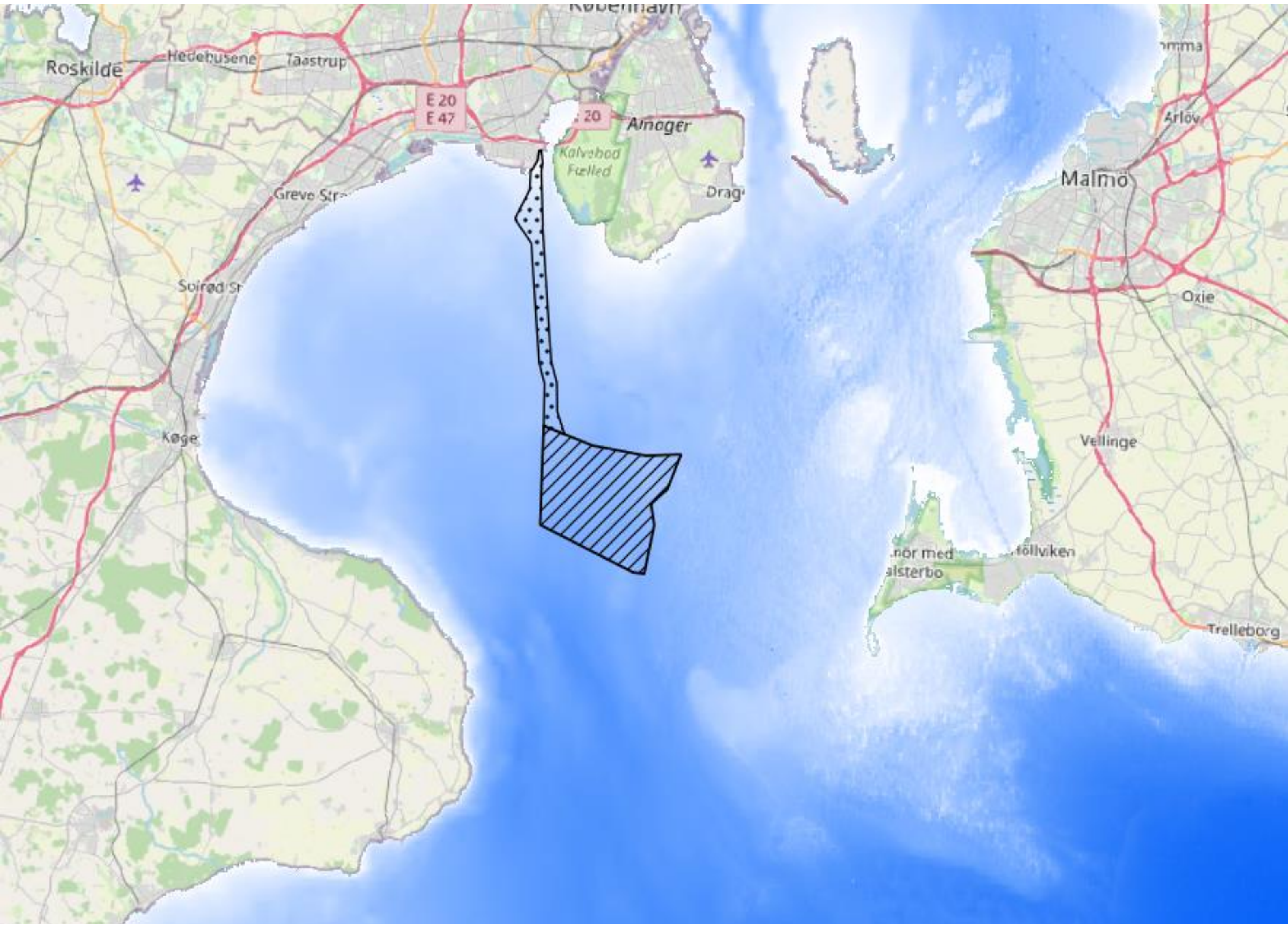

Aflandshage offshore wind farm

Underwater Noise Modelling for seismic survey activities

WAHA01-GEN-PRO-05-000024

HOFOR

Date: 13 December 2021

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1.0	06-12.2021	First Draft	MAM / KRHO	MAWI	LIE
2.0	10-12.2021	Final Draft; corrections in calculation method for PTS and TTS	MAM	MAWI	LIE

Contents

Summary

In connection with proposed seismic survey activities by HOFOR for the project Aflandshage offshore wind farm (OWF), NIRAS has carried out underwater sound propagation modelling.

The seismic survey activities, for which to calculate underwater noise emission, were specified by Rambøll, and include a sparker, boomer and a Sub-Bottom Profiler (SBP). The specifications included equipment types, source characteristics and source modelling method. 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 two equipment scenarios. The full setup (scenario 1) uses a sub-bottom profiler (Innomar SES-2000 Medium 100 parametric sub bottom profiler), a sparker (Geomarine GeoSource 800j) and a boomer (Applied Acoustics triple plate S-Boom). The second setup omits the sparker and boomer. All source specific characteristics (e.g. source level, frequency content, duty cycle and directivity) were specified by Rambøll, and 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, as well as TTS and PTS in seals.

The results showed minor 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 $SEL_{VHF,24h} = 140\ dB$	PTS $SEL_{VHF,24h} = 155\ dB$	TTS $SEL_{PW,24h} = 170\ dB$	PTS $SEL_{PW,24h} = 185\ dB$
Aflandshage OWF site	1: Sparker, SBP & Boomer	1	2450	1350-2700	750-1600	45-160	< 10
		2	2450	1375-2650	750-1575	45-170	< 10
	2: SBP	1	2450	1350-2700	750-1600	10-50	< 10
		2	2450	1375-2650	750-1575	10-40	< 10
Investigation corridor	2: SBP	3	2650	1425-2850	775-1725	10-60	< 10

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 the planned seismic survey activities by HOFOR for the project Aflandshage offshore wind farm (OWF). Aflandshage OWF is located in the Danish part of Øresund, approximately 20 km east of Køge and 12 km south from Søvang (Amager), as shown in Figure 1.1. Aflandshage OWF is located on the border to the Swedish part of Øresund, the red line in Figure 1.1, and just north of the Baltic Sea.

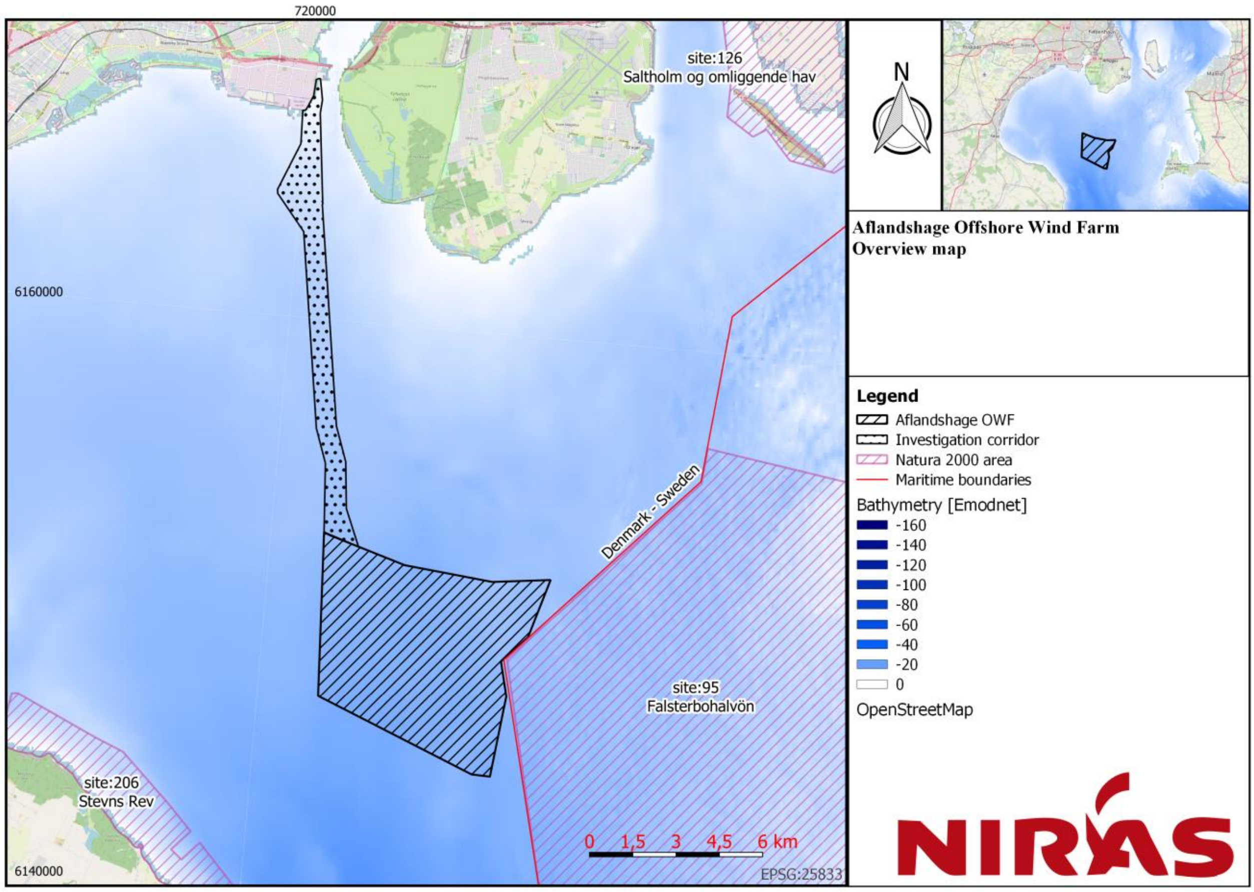

Figure 1.1: Overview map of Aflandshage OWF (black).

HOFOR plans to conduct seismic survey activities inside the OWF area, as well as in the investigation corridor. The seismic survey equipment, were specified by Rambøll, and include a sparker, boomer and a Sub-Bottom Profiler (SBP). All three equipment types are expected to be 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. Therefore detailed underwater noise modelling has been conducted for these three equipment types.

2 Purpose

The purpose of this report is to calculate and document the impact ranges for underwater noise emission, from the planned seismic survey activities, in relation to harbour porpoises and seals, in the Aflandshage OWF area and investigation corridors. The modelling covers impact ranges for avoidance behaviour, Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) and is calculated for two 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 sound pressure level 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 µPa.

When the SEL is used to describe the sum of noise from more than a single event/pulse, 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 3, 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.

$$r_i = \sqrt{\left(l_0 - ((i-1)\cdot \Delta t_i)\cdot v_{ship}\right)^2 + (d_0 + ((i-1)\cdot \Delta t_i)\cdot v_{receiver})^2} \qquad \textit{Equation 3}$$

By summing the pulses from the entire survey given the transmission loss for the survey area, Equation 4 gives the resulting SEL_{C24h}.

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

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).

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

3.2 Underwater noise impact criteria for marine mammals

The noise related impact ranges for both harbour porpoise and seal, is defined in relation to the PTS and TTS criteria, and is given in Table 3.1 along with avoidance behaviour for harbour 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 the offshore wind farm) 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 based on Table AE-1 in (NOAA, April 2018) to highlight the important species in the project area (NOAA, April 2018).

Hearing group	Representative species	Species specific weighted thresholds (Non-impulsive)		Species specific weighted thresholds (Impulsive)		
		$SEL_{C24h,<weighting>}$		$SEL_{C24h,<weighting>}$		$SPL_{RMS-fast,VHF}$
		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 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 behavioral 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 the 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 seals. 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, at the time of survey onset. This difference is because of the movement of vessel and marine mammal causing the vessel to gain on marine mammals 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 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.

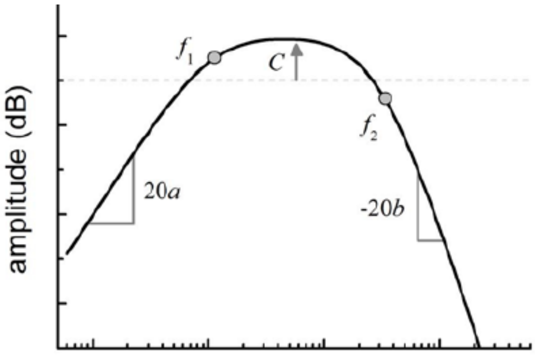

Figure 3.1: Illustration of the 5 parameters in the weighting function (NOAA, April 2018).

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_1 [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).

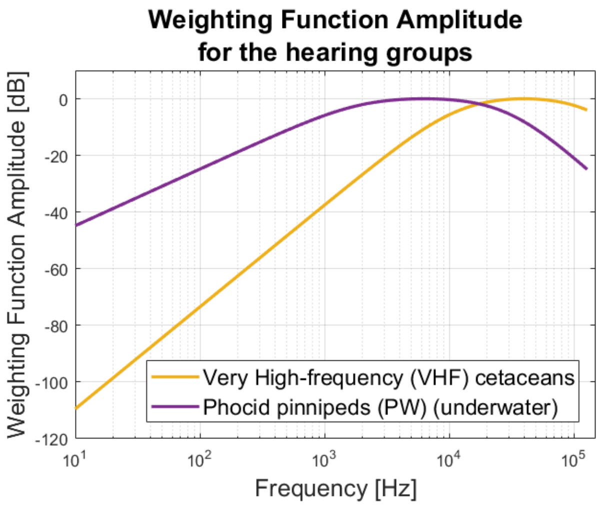

Figure 3.2: The weighting functions for the different hearing groups.

4 Proposed seismic survey equipment

HOFOR has requested, that the underwater sound propagation modelling is carried out using seismic survey equipment types specified by Rambøll, and that each source must be modelled according to specifications delivered by Rambøll. In the following, the specifications of the proposed seismic survey equipment is provided in detail, as well as the source modelling method.

The proposed setup, consists of a sub-bottom profiler (SBP), a sparker and a boomer, from here on referred to as Equipment scenario 1. It is specified by Rambøll, that this equipment scenario will be used during the seismic survey activities within the OWF area. Survey activities within the OWF area, will also include investigations only using the SBP. This setup is referred to as Equipment scenario 2. Rambøll has specified that survey activities in the investigation corridor, will be limited to the SBP (Equipment scenario 2). The two equipment scenarios are listed in Table 4.1.

Table 4.1: Overview of equipment scenarios, and equipment models specified by Rambøll.

Equipment Scenario	Equipment Types	Equipment models
1	Sub bottom profiler	Innomar SES-2000 Medium 100
	Sparker	GeoMarine Geo-Source 800J Sparker
	Boomer	Applied Acoustics triple plate S-Boom (1000 Joules)
2	Sub bottom profiler	Innomar SES-2000 Medium 100

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.

In Table 4.2, source characteristics specified by Rambøll are listed. It was specified by Rambøll, that the provided source levels are "apparent" source levels, meaning the equivalent source level @ 1m distance, if the equipment is modelled as a single point source with omnidirectional characteristics. This type of source model is typically used, where underwater noise measurements have been used to develop an empirical source model. It was also specified by Rambøll, that the frequency spectrum to be used, is as listed under "Primary Frequency Range", as a flat spectrum.

Table 4.2: Seismic survey equipment source characteristics as specified by Rambøll. Equipment scenario 1 comprise the SBP, Sparker and Boomer, while Equipment scenario 2 only comprise the SBP.

Type	Equipment model	Source Noise Level SPL_{RMS} (dB re 1 µPa @ 1m)	Primary Frequency Range (Hz)	Pulse Length	Sound Exposure Level (dB re 1 µPa^2/s @ 1m	Duty cycle over a 24 hour period
SBP	Innomar SES-2000 Medium 100	187 dB (apparent)	80k - 100k	0.1 – 2.5 ms	186 dB (apparent)	40 Hz
Sparker	GeoMarine Geo-Source 800J Sparker	189 dB (apparent)	200 - 3k	5 ms	178 dB (apparent)	0.41 Hz
Boomer	Applied Acoustics triple plate S-Boom (1000 Joules)	178 dB (apparent)	1k-4k	0.9 ms	162 dB (apparent)	3 Hz

4.1 Detailed Source Level and Frequency Spectrum

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 4.3. The detailed sound source levels are modelled in 1/3 octave bands, with a total amplitude as listed in Table 4.2, with a flat frequency spectrum within the primary frequency range, and zero outside, as specified by Rambøll. In addition to the modelled source spectrums, presented as "unweighted", the corresponding source levels in VHF and PW frequency weighting are also provided.

Table 4.3: Detailed source level information for the equipment.

Source		Innomar SES-2000			GeoMarine Geo-Source 800J			Applied Acoustics triple plate S-Boom (1000 Joules)		
Frequency weighting		Unweighted	VHF	PW	Unweighted	VHF	PW	Unweighted	VHF	PW
Source Level SEL @1m in 1/3octave bands [dB re. 1 µPa^{2}s]	200	0	0	0	166,9	104,2	148	0	0	0
	250	0	0	0	166,9	107,7	150	0	0	0
	315	0	0	0	166,9	111,3	151,9	0	0	0
	400	0	0	0	166,9	115,1	153,9	0	0	0
	500	0	0	0	166,9	118,6	155,8	0	0	0
	630	0	0	0	166,9	122,2	157,6	0	0	0
	800	0	0	0	166,9	125,9	159,4	0	0	0
	1k	0	0	0	166,9	129,4	161	153,5	116	147,6
	1,2k	0	0	0	166,9	132,8	162,4	153,5	119,4	149
	1,6k	0	0	0	166,9	136,6	163,8	153,5	123,2	150,4
	2k	0	0	0	166,9	140	164,8	153,5	126,6	151,4
	2,5k	0	0	0	166,9	143,4	165,6	153,5	130	152,2
	3,2k	0	0	0	166,9	146,8	166,2	153,5	133,4	152,8
	4k	0	0	0	0	0	0	153,5	136,9	153,2
	5k	0	0	0	0	0	0	0	0	0
	6,3k	0	0	0	0	0	0	0	0	0
	8k	0	0	0	0	0	0	0	0	0
	10k	0	0	0	0	0	0	0	0	0
	12,5k	0	0	0	0	0	0	0	0	0
	16k	0	0	0	0	0	0	0	0	0
	20k	0	0	0	0	0	0	0	0	0
	25k	0	0	0	0	0	0	0	0	0
	32k	0	0	0	0	0	0	0	0	0
	40k	0	0	0	0	0	0	0	0	0
	50k	0	0	0	0	0	0	0	0	0
	64k	0	0	0	0	0	0	0	0	0
	80k	183	181,7	165,6	0	0	0	0	0	0
	100k	183	180,7	162,1	0	0	0	0	0	0
	Broad-band	186,0	184,2	167,2	178,0	149,4	172,7	162,0	139,5	159,8

A further study into the source modelling methodology and/or the source levels and frequency spectrums used, was not carried out, as per agreement with HOFOR.

5 Description of activities

The seismic survey site for Aflandshage OWF is located in Øresund approximately 20 km east of Køge and 12 km south from Søvang (Amager). Aflandshage covers a 42 km^2 area. In Figure 5.1, the OWF site is shown with black outline. The black dotted area is the investigation corridor which goes from Avedøre Holme to the OWF.

According to received information, the seismic survey inside the OWF is scheduled for May to July, while the seismic survey in the investigation corridor is scheduled for March to May.

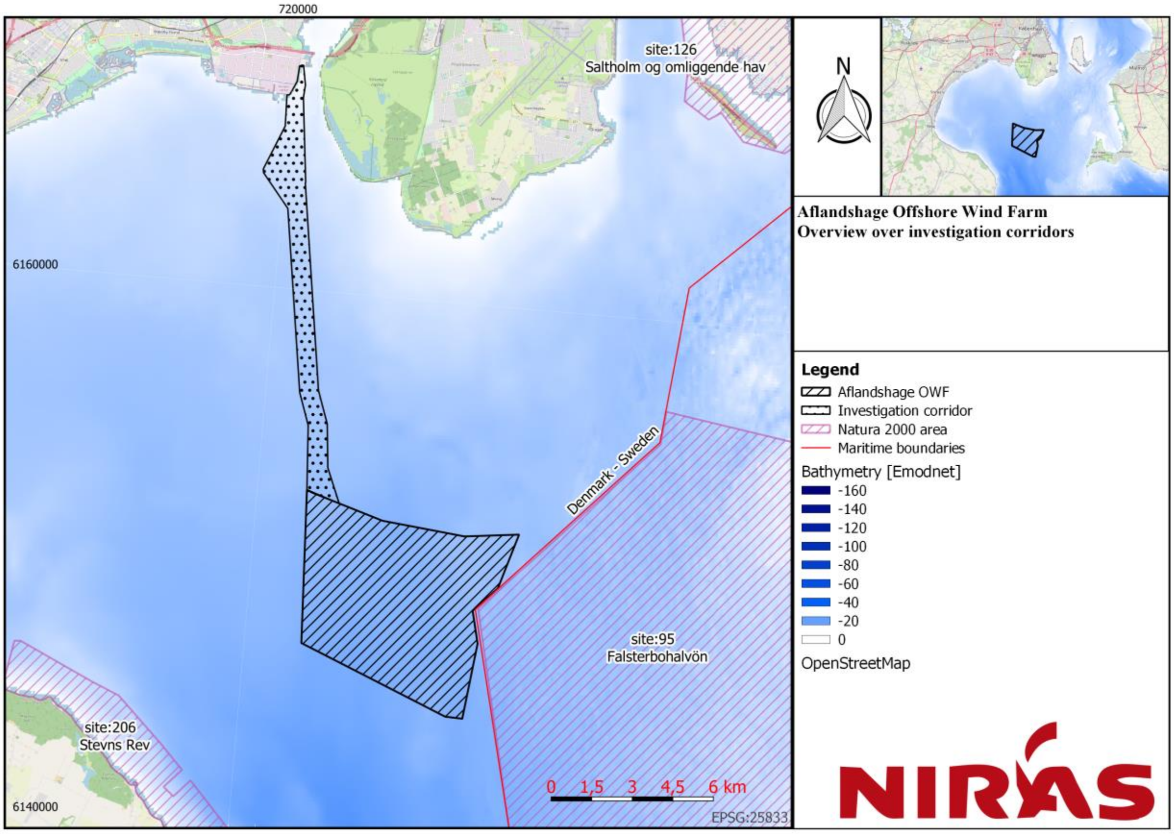

Figure 5.1: Survey site Aflandshage boundaries in black frames. The black dotted area indicates the investigation corridor.

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 [m/s].

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 waters of Kattegat, Skagerrak, Øresund 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):

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

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, 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 2.3.3, 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.

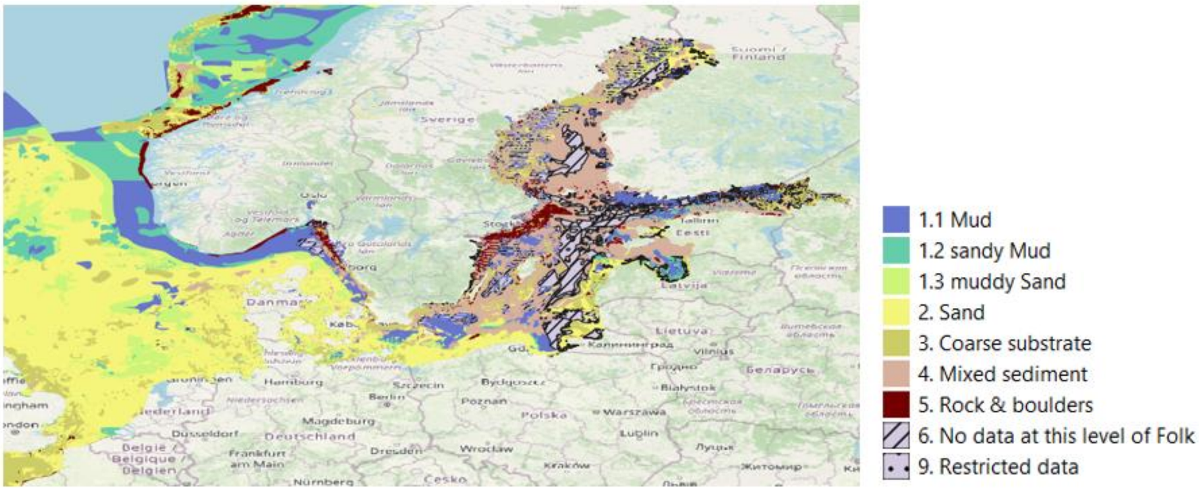

Figure 6.2: A section of the seabed substrate map, (Folk 7) (EMODnet, 2021).

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		1/3-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)	200 Hz	100 kHz

6.5.2 Bathymetry

The bathymetry implemented for this project, is shown in Figure 6.3, and includes the wind farm site and 30 km to each side (extracted from the bathymetry map in section Figure 6.1). In this area the bathymetry ranges from a depth of 50 m, indicated by the darker colours, to a depth of 0 m (land), indicated by the lighter colours.

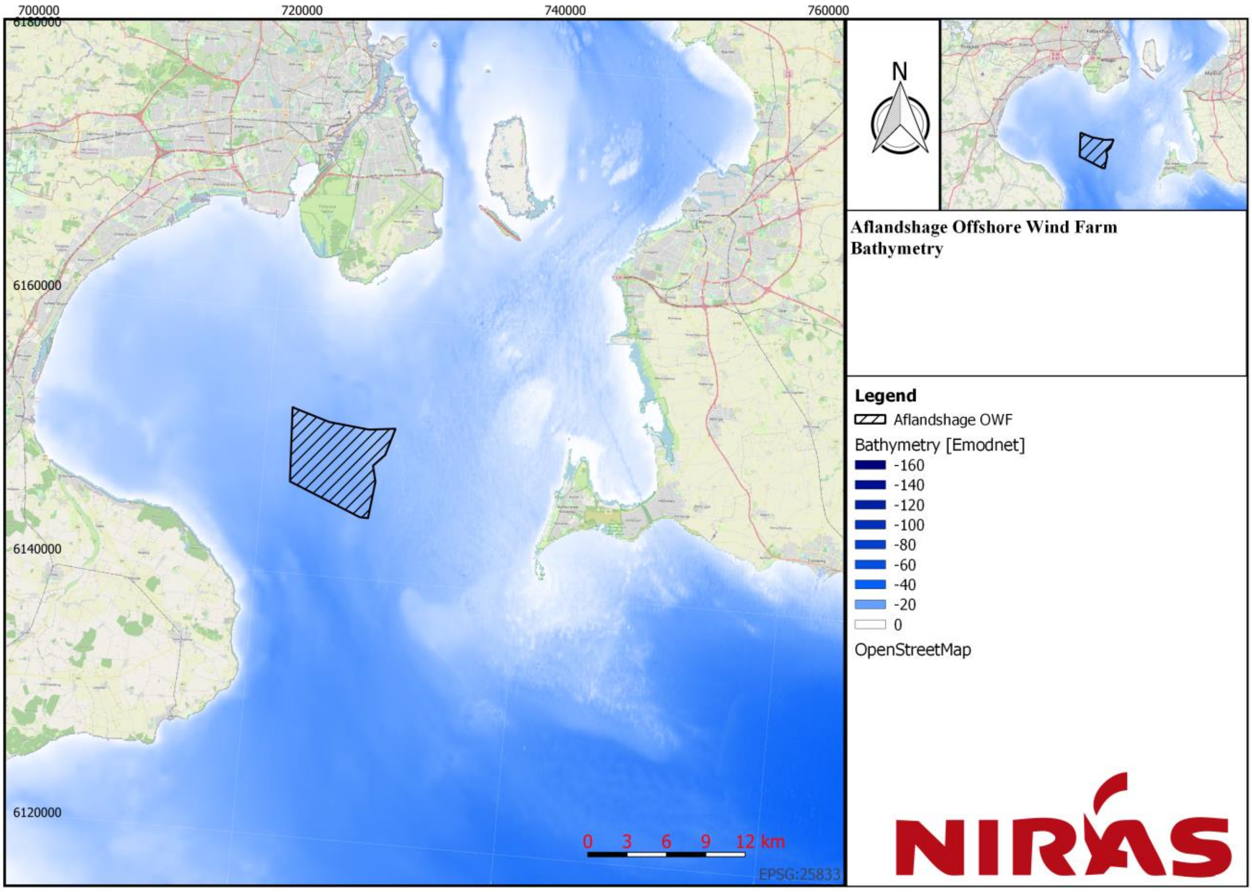

Figure 6.3: Bathymetry map for the Aflandshage site and surroundings.

6.5.3 Sediment

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.

For this project, the seabed substrate map from https://www.emodnet-geology.eu/ was studied in QGIS along with the GEUS "Pre-Quaternary surface topography of Denmark" map from www.geus.dk, and the book "Danmarks Geologi" chapter 4 to determine the sediment types and thicknesses for the site and surroundings. Additionally, geological modelling and sediment composition estimates, conducted and reported by GEO for the two sites, have also been used(GEO, 2019).

From the investigations, it was determined that the site and surroundings mostly have a top layer of mud and sand of varying thickness on average 5 metres. Patches of gravel, mixed boulders and other mixed sediments also occur. The lower half of the layer is however modelled using a more densely packed sediment type to account for the increased pressure on the lower sediment. Below this, is the chalk layer with thickness up to 1.5 km.

The layer types were then translated into geoacoustic parameters, in accordance with Table 6.2, utilizing information from (Jensen, et al., 2011). For mixed layers, such as muddy sand, the geoacoustic profile was chosen to be 85% main layer and 15% of the secondary layer. It is recognized that this approach does not accurately reflect actual conditions, however it is not deemed possible to make a more accurate model without detailed seismic survey results, and even then, the results would only be applicable within the surveyed area. It must be recognized, that the level of knowledge available is very limited.

Table 6.2: Geoacoustic properties of sediment layers used in the environmental model.

Sediment	Sound Speed [m/s]	Density [kg/m³]	Attenuation factor [dB/λ]
Clay	1500	1500	0.2
Silt	1575	1700	1.0
Mud	1700	1500	1.0
Sandy mud	1690	1550	1.0
Sand	1650	1900	0.8
Muddy sand	1660	1850	0.8
Coarse substrate	1800	2000	0.6
Mixed sediment	1700	1900	0.7
Rock and boulders	5000	2700	0.1
Chalk	2400	2000	0.2

6.5.4 Sound speed profile

Figure 6.4 shows the extracted sound speed profiles at the available positions. Note that the layout of the sound speed profiles indicate their respective position geographically.

Based on Figure 6.4, March is identified as the “worst case” month (relatively low transmission loss) for the survey activities planned in the investigation corridors, while May is the “worst case” month during the seismic survey within the OWF area. In agreement with HOFOR, it was agreed to consider the worst case scenario, and carry out calculations for March in the investigation corridor, and May inside the OWF area. The sound speed profiles are shown for March and May only in Figure 6.5.

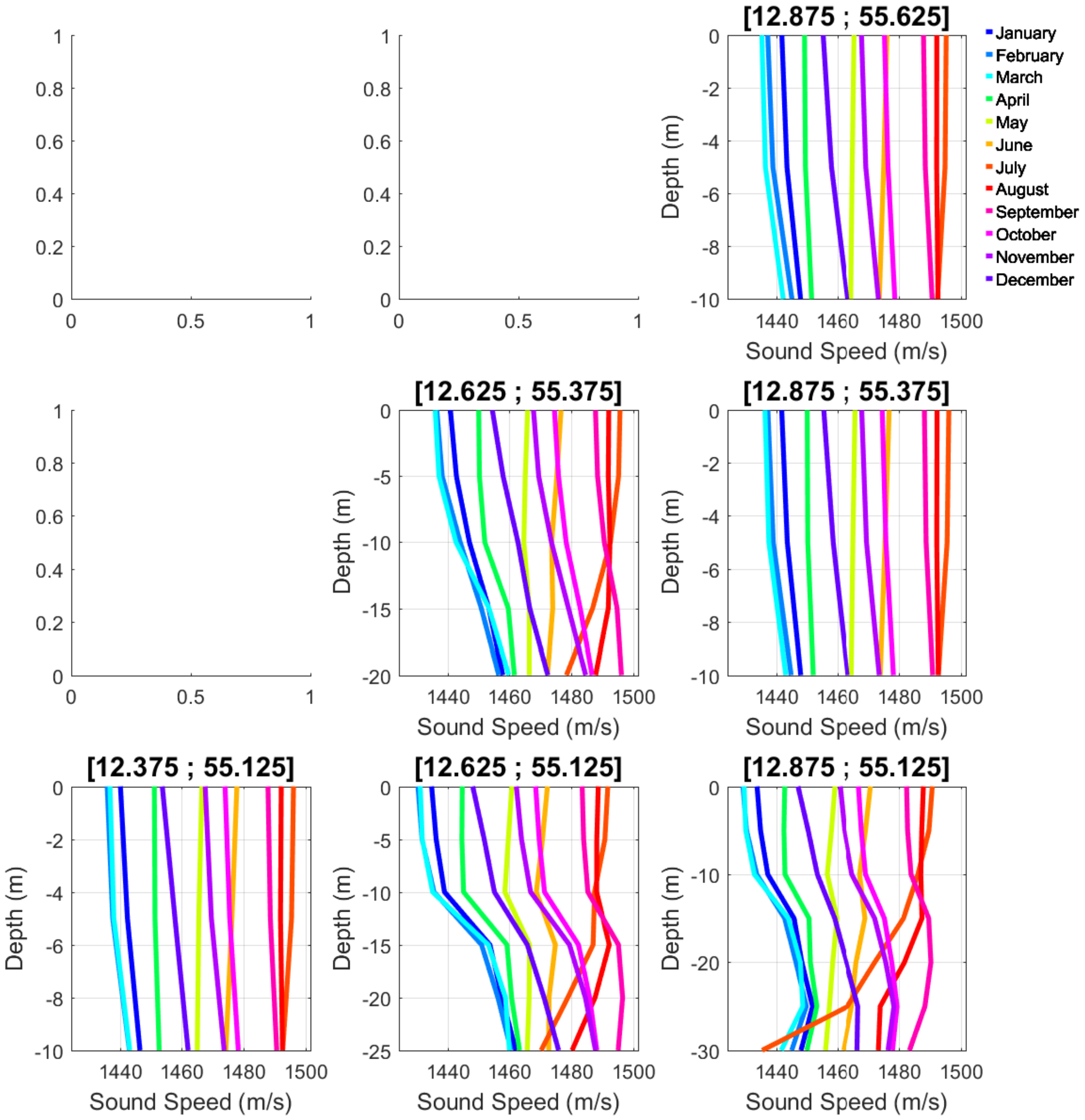

Figure 6.4: Historic averages for Sound Speed Profiles for the Aflandshage site for all months of the year.

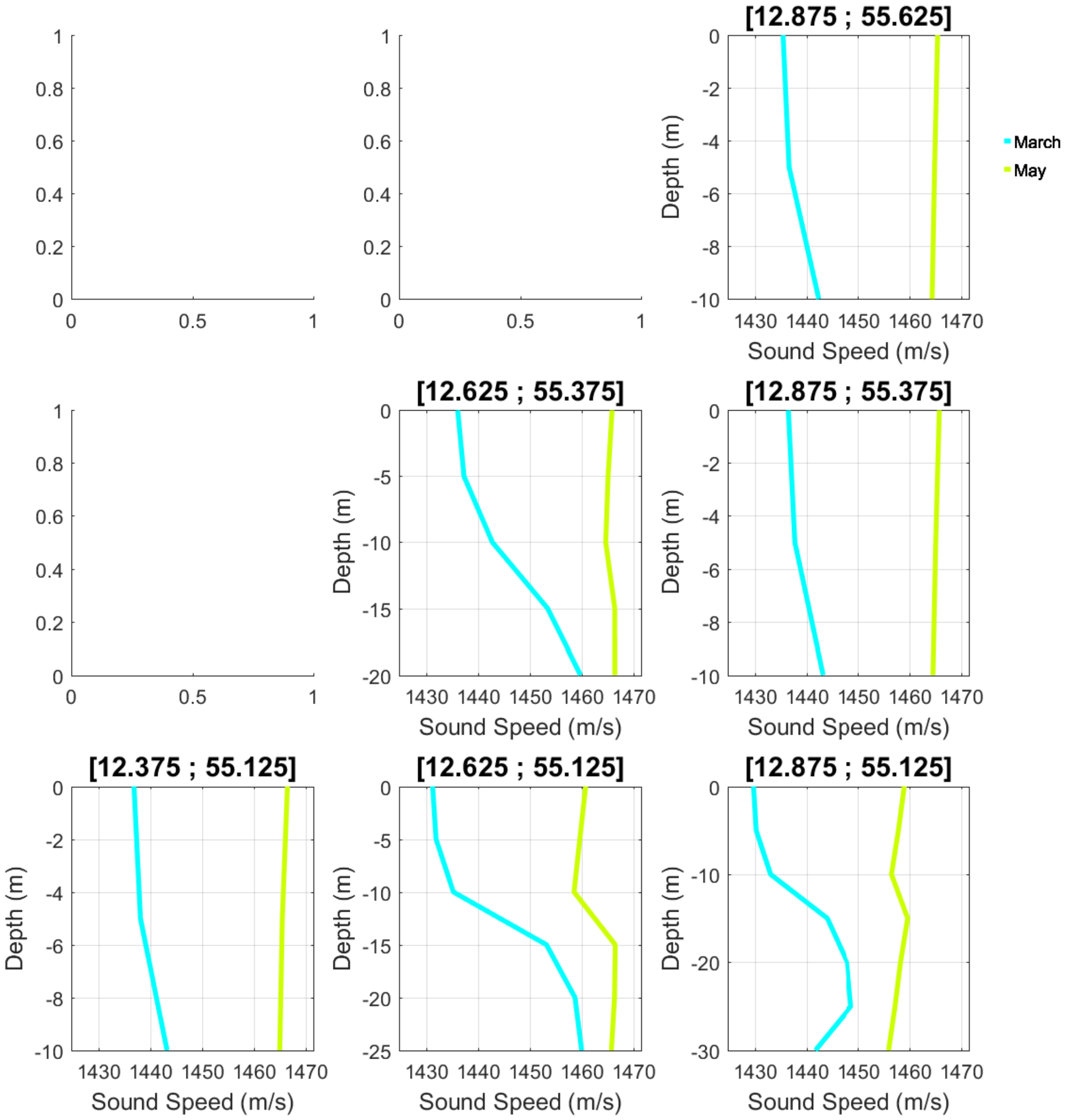

Figure 6.5: Historic averages for Sound Speed Profiles for the Aflandshage site for March and May months.

6.5.5 Salinity profile

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

Figure 6.7 shows the salinity profiles for March and May which were identified as the "worst case" months, according to the sound speed profiles, within the intended time frame for the investigations.

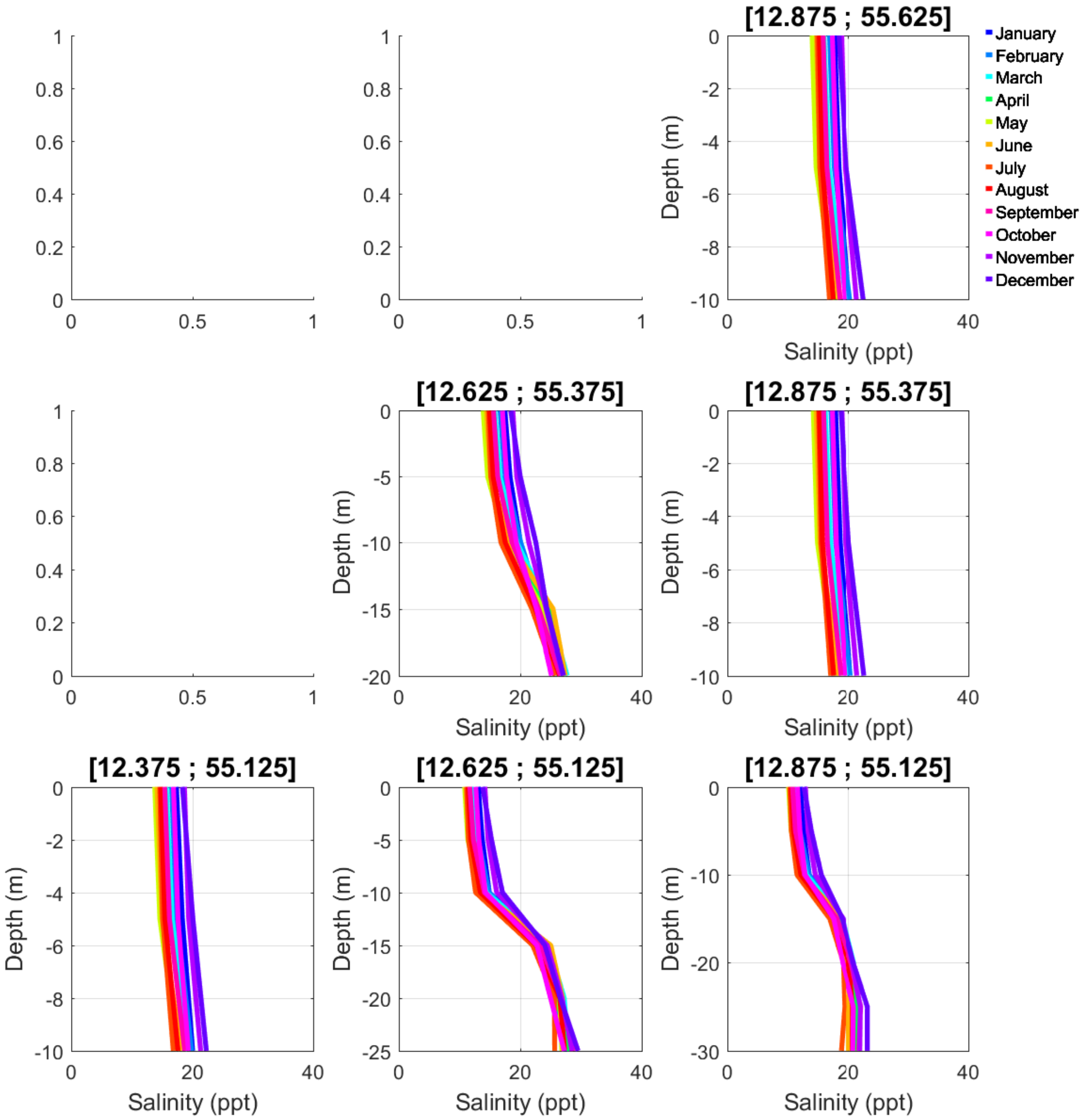

Figure 6.6: Historic averages for salinity profiles for the Aflandshage site for all months of the year.

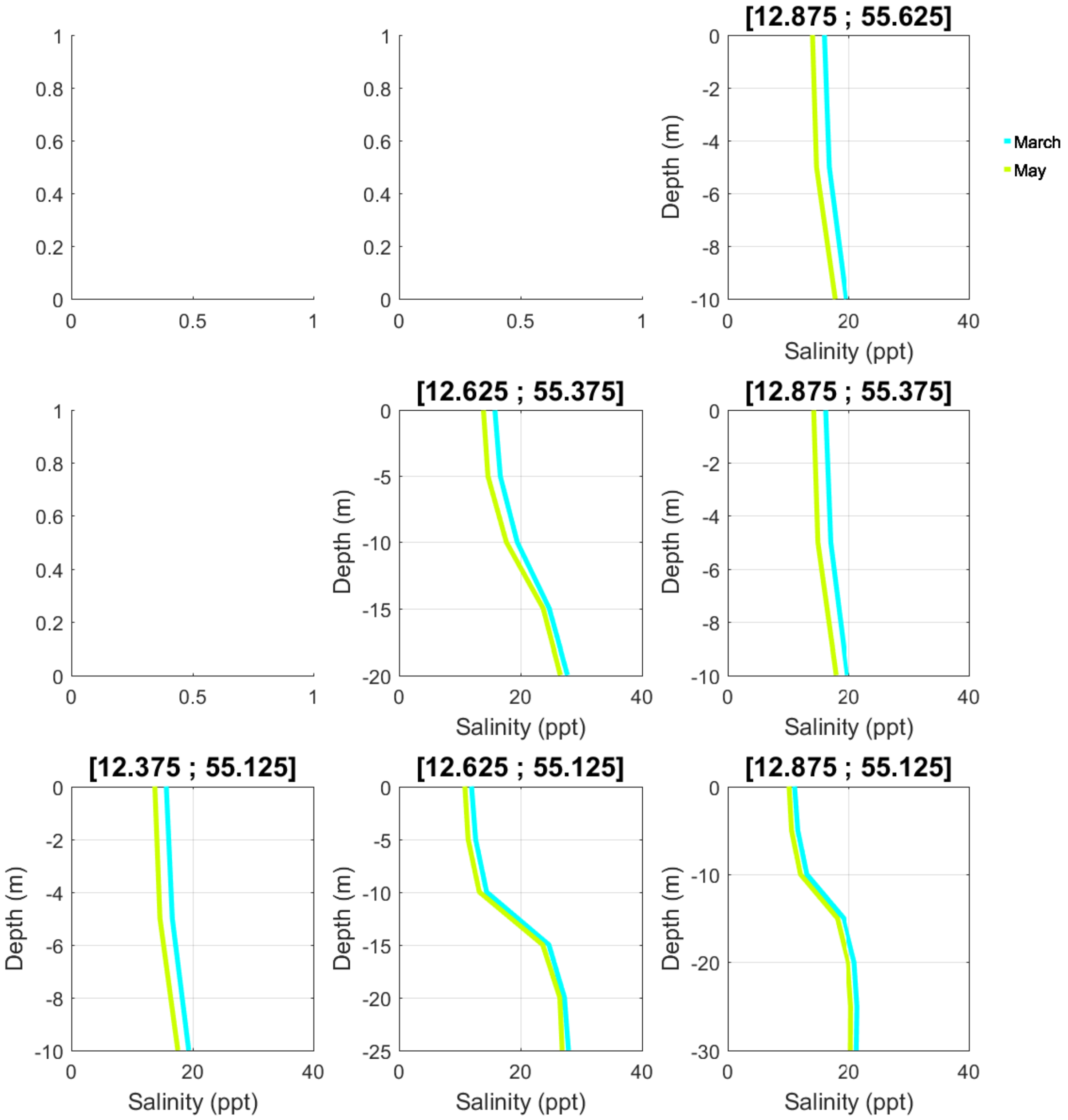

Figure 6.7: Historic averages for salinity profiles for the Aflandshage site for March and May months.

6.5.6 Temperature profile

Figure 6.8 shows the extracted temperature profiles at the available positions. Note that the layout of the sound speed profiles indicate their respective position geographically.

Figure 6.9 shows the temperature profiles for March and May which were identified as the "worst case" months, according to the sound speed profiles, within the intended time frame for the investigations.

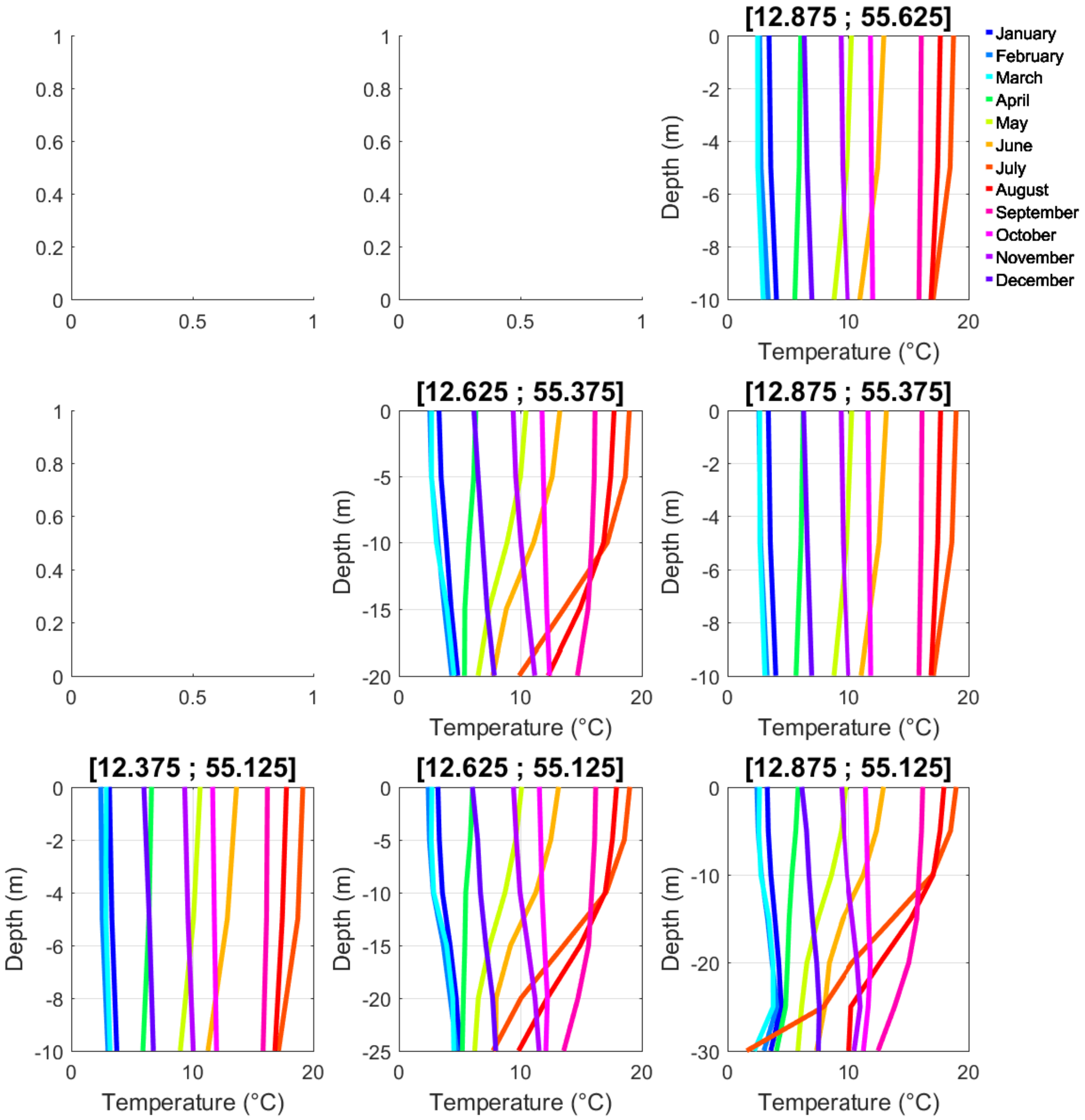

Figure 6.8: Historic averages for temperature profiles for the Aflandshage site for all months of the year.

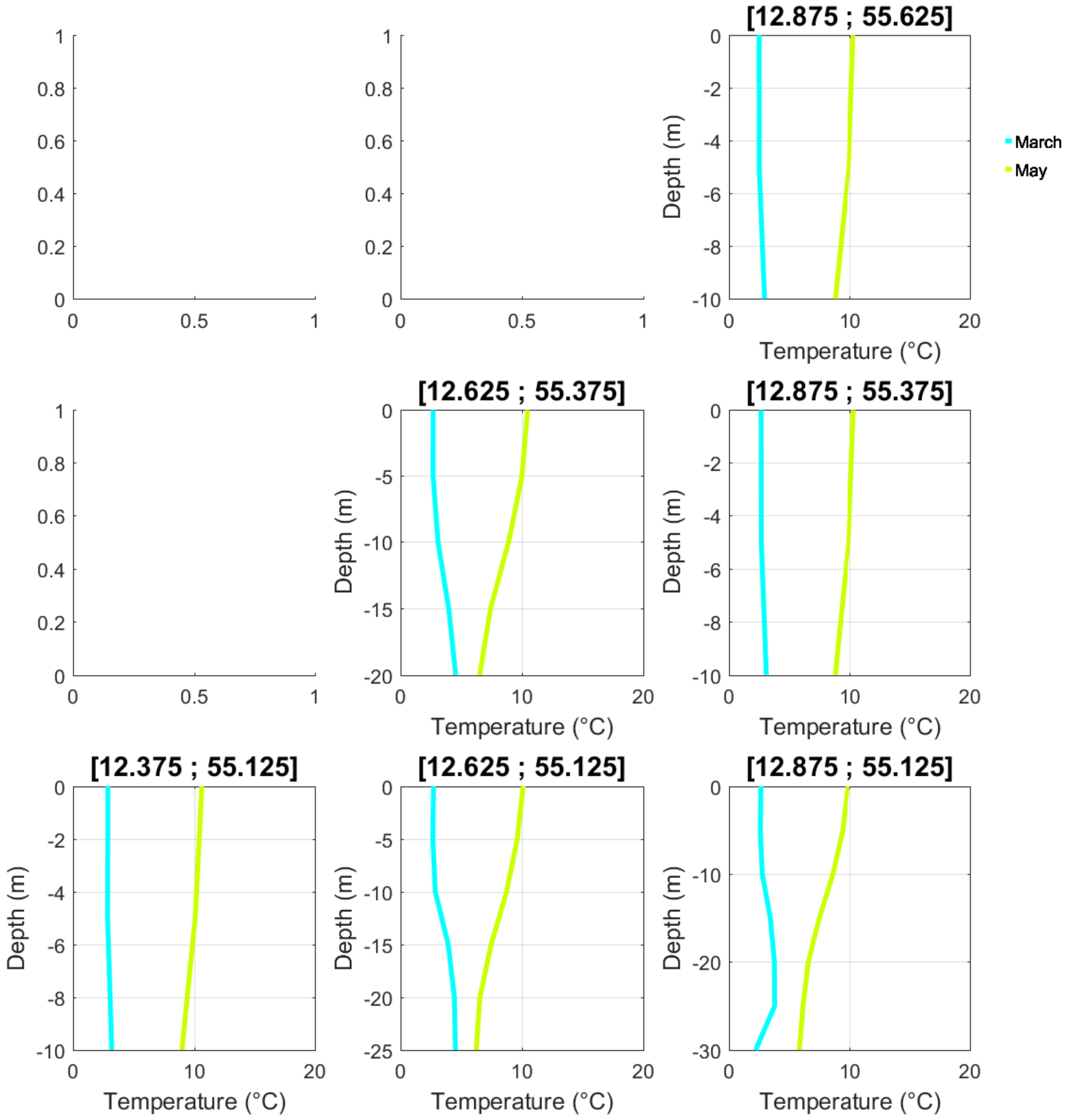

Figure 6.9: Historic averages for temperature profiles for the Aflandshage site for March and May months.

6.6 Source modelling

In order to determine 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 SBP system as well as the sparker and boomer. For equipment scenario 2, only the SBP 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 outfitted with the equipment listed in section 4, some of it mounted on the vessel itself, some of it towed behind the vessel. For cumulative sound levels, used to determine threshold distances for PTS and TTS effects, a 24 hour continuous survey period is considered. The underwater noise emission is calculated in 180 transects (angles), resulting in a 2° resolution. The modelling method for cumulative sound levels is summarized in Table 6.3.

Table 6.3: Technical specification for cumulative sound level 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)	

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

6.6.1 Source positions

Figure 6.10 shows the investigation corridor provided by HOFOR, indicated by the black dotted areas, along with the surrounding Natura 2000 areas, shown in pink. In order to represent seismic survey activities within both the OWF area and investigation corridor, three source positions were selected for underwater sound propagation modelling. Two positions were chosen within the OWF area (Position 1 and 2), representing possible survey starting positions for the OWF area surveys. Position 1 was also chosen because it has the lowest bathymetry within the OWF area, and position 2 because it has the deepest. Both positions were also chosen due to their proximity to the Natura 2000 area "Falsterbohalvön". Position 3 is placed at a representative location within the investigation corridor, where the bathymetry is average.

All positions are shown in Figure 6.10 as yellow stars. With the selected source positions, it is expected that the results will be representative for any position within the OWF area and corridors.

For estimating the impact on the specific Natura 2000 areas, the worst case underwater noise propagation has been used and the impact range contours have been moved to the position within the site that will cause the largest overlap between the Natura 2000 area and the impact ranges.

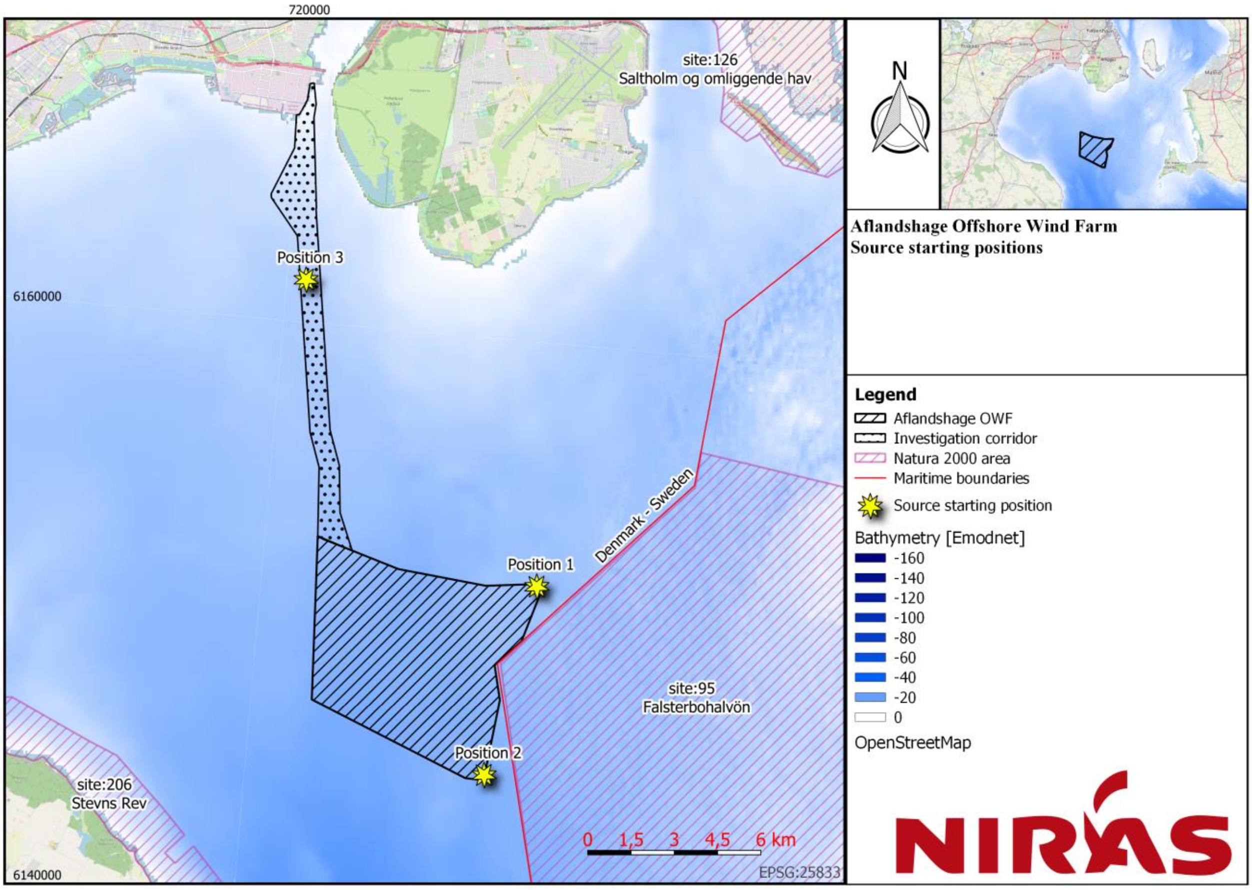

Figure 6.10: Overview over the selected source positions indicated by the yellow stars.

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 two positions within the OWF area for each of the two equipment setup scenarios, and in one position within the investigation corridor for equipment scenario 2 (SBP only).

7.1 Impact distances

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 seals 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 avoidance (negative phonotaxy) behaviour as described in section 3.2.1.

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 (Position 3) and may (Position 1 and 2).

Area	Equipment scenario	Position	Threshold distance [m]				
			Harbour porpoise			Seal	
			Avoidance Behavior $SPL_{RMS-fast,VHF} = 100\ dB$	TTS $SEL_{VHF,24h} = 140\ dB$	PTS $SEL_{VHF,24h} = 155\ dB$	TTS $SEL_{PW,24h} = 170\ dB$	PTS $SEL_{PW,24h} = 185\ dB$
Aflandshage OWF site	1: Sparker, SBP & Boomer	1	2450	1350-2700	750-1600	45-160	< 10
		2	2450	1375-2650	750-1575	45-170	< 10
	2: SBP	1	2450	1350-2700	750-1600	10-50	< 10
		2	2450	1375-2650	750-1575	10-40	< 10
Investigation corridor	2: SBP	3	2650	1425-2850	775-1725	10-60	< 10

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.

It should be noted, that impact distances for scenario 1 and scenario 2 are identical for positions 1 and 2. This is due to the sparker and boomer having an insignificant effect on the overall noise levels with the frequency weightings applied, compared to the effect of the SBP.

It should be noted, that the impact distances for the investigation corridor (position 3), scenario 2 are slightly higher than position 1 and 2. This is due to the differences in the local environmental conditions, and that the model for position 3 assumes the month of March, whereas position 1 and 2 are modelled for the month of May.

The impact ranges are also presented as direction specific contour maps, for PTS, TTS and behaviour effects. Contour maps are only presented for 1 equipment scenario per position, as the different scenarios showed insignificant variation. Maps for phocid pinniped impact ranges are not shown as the distances are too short. The following contour maps are presented in the report and appendices:

- Figure 7.1: TTS and PTS with VHF-weighting in position 1
- Figure 7.2: Avoidance behaviour in harbour porpoise in position 1.
- In Appendix 1, noise contour maps for position 1
- In Appendix 3 noise contour maps for position 2
- In Appendix 5 noise contour maps for position 3

In addition to the impact distance results in Table 7.1, calculations of worst case area of effect are given as the total area affected by noise over the threshold limits, see Table 7.2.

Table 7.2: Area affected for TTS, PTS and avoidance behaviour impact threshold criteria.

Area	Position	Equipment scenario	Area of threshold effect [km^2]						
			Harbour porpoise					Seal	
			Avoidance Behaviour $SPL_{RMS-fast,VHF} = 100\ dB$			TTS $SEL_{VHF,24h} = 140\ dB$	PTS $SEL_{VHF,24h} = 155\ dB$	TTS $SEL_{PW,24h} = 170\ dB$	PTS $SEL_{PW,24h} = 185\ dB$
			SBP	Sparker	Boomer				
Aflandshage OWF site	1	1	18	11	2	8.8	2.8	< 0.1	< 0.1
		2	18	11	2	8.8	2.8	< 0.1	< 0.1
	2	1	18	10	2	8.9	2.8	< 0.1	< 0.1
		2	18	10	2	8.9	2.8	< 0.1	< 0.1
Investigation corridor	3	1	-	-	-	-	-	-	-
		2	20	-	-	9.9	3.3	< 0.1	< 0.1

Calculation of overlap with the nearby Natura 2000 areas was also carried out, for the worst case positions. From Figure 6.10 it can be seen that the Natura 2000 site called "Falsterbohalvön" is the only nearby Natura 2000 area, where underwater noise from the survey can cause underwater noise levels above impact thresholds. To assume the absolute worst case, the noise contour maps have been shifted to where overlap with the Natura 2000 area would be largest. The presented overlap area is thus only to be considered from a worst case perspective. The worst case positions are shown as "W.C. Px" in Appendix 2 and Appendix 4, where "x" indicates which position the noise contours originate from. The worst case overlap is summarized in Table 7.3.

Table 7.3: Affected Natura 2000 area for TTS, PTS and avoidance behaviour impact threshold criteria for VHF-weighting.

Area	Position	Affected Natura 2000 area									
		Avoidance Behaviour $SPL_{RMS-fast,VHF} = 100\ dB$						TTS $SEL_{VHF,24h} = 140\ dB$		PTS $SEL_{VHF,24h} = 155\ dB$	
		SBP		Sparker		Boomer					
		[km^2]	[%]	[km^2]	[%]	[km^2]	[%]	[km^2]	[%]	[km^2]	[%]
Falsterbohalvön (423 km^2)	1	8	1.9	5	1.2	1	0.2	2.8	0.7	0.8	0.2
	2	7	1.7	4	0.9	0	0.0	3.1	0.8	0.9	0.2

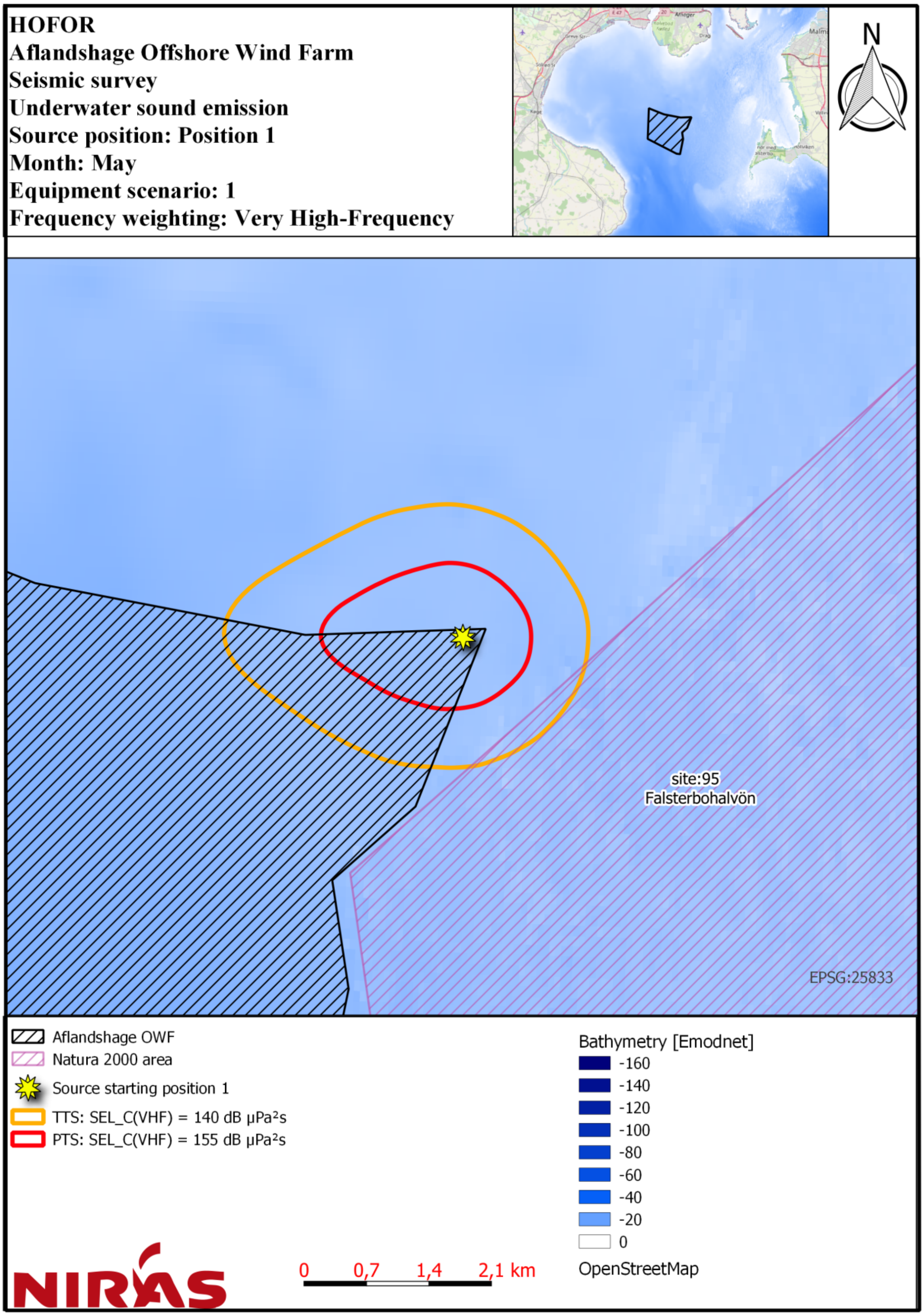

Figure 7.1: Noise contour map for position 1, showing impact distances for TTS and PTS with VHF-weighting for the month of May.

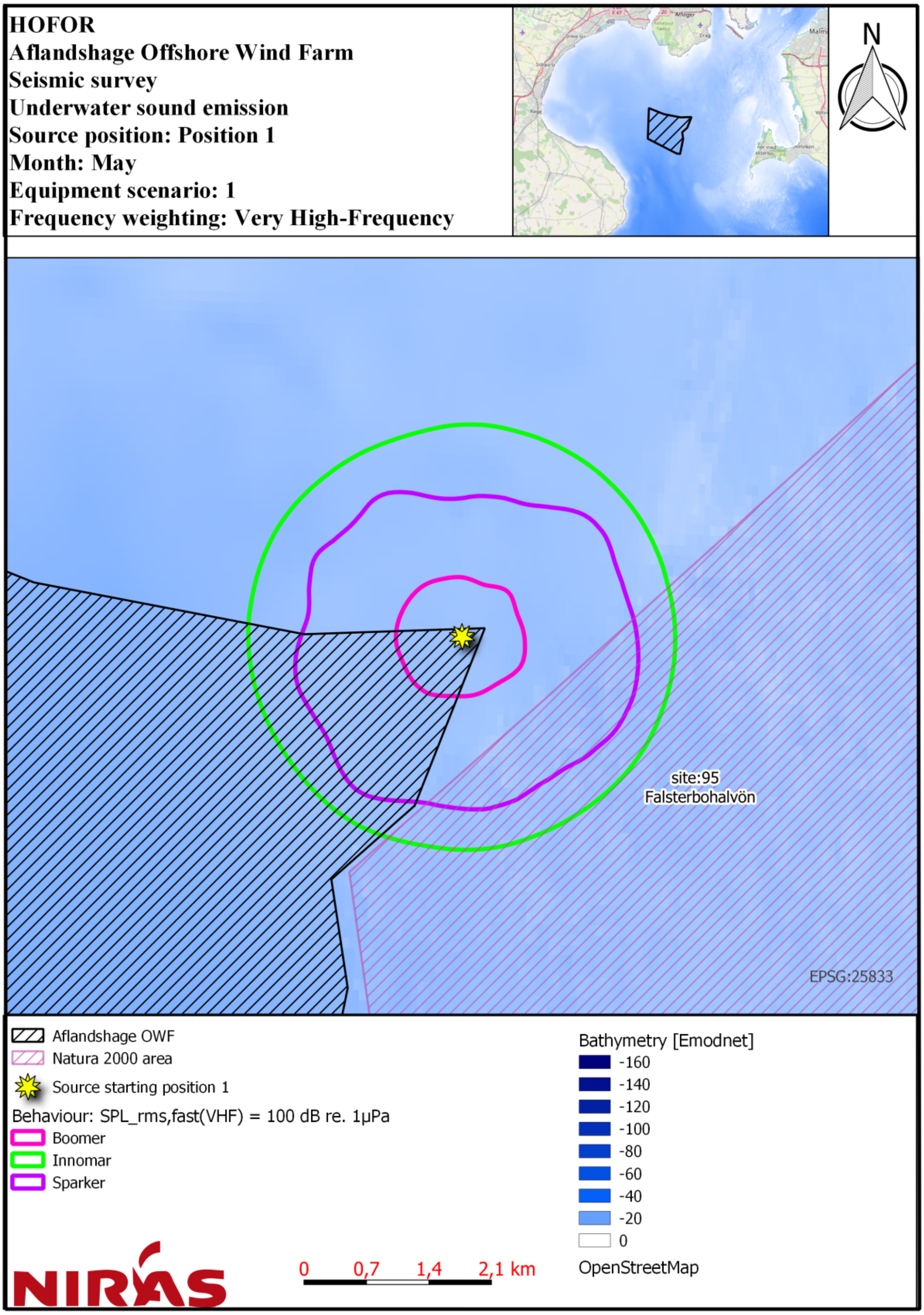

Figure 7.2: Noise contour map for position 1, showing impact distances for avoidance behaviour with VHF-weighting for the month of May.

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

Sound propagation modelling was carried out for two positions within the Aflandshage OWF area for two equipment setup scenarios, and in one position within the investigation corridor for equipment scenario 2 (SBP only), based on source characteristics and source modelling method specified by Rambøll.

9.1 Conclusions for the Aflandshage OWF area

For harbour porpoise, it is concluded that all equipment scenarios cause the same impact distances with regards to Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS). This is due to the Sub Bottom Profiler (SBP) system being the dominant noise source. For harbour porpoise, avoidance behaviour is likely to occur within a 2.45 km radius from the survey vessel. TTS is considered unlikely to occur in harbour porpoise located further than 2.7 km from the survey vessel at the onset of seismic survey activities, while for PTS, the distance is 1.6 km.

For seals, where PW weighting is applied, the sparker source is identified to have the highest impact. While PTS in seals is unlikely to occur beyond 10 m regardless of the equipment scenario. The impact distance for TTS varies significantly with the equipment scenarios, with a likely impact range of up to 170 m for equipment scenario 1 (all sources active) and up to 50 m for equipment scenario 2 (SBP only).

It should be noted, that the impact distances mentioned here 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 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.

9.2 Conclusions for the investigation corridors

In the investigation corridor, results show similar, albeit a bit higher impact distances for PTS and TTS, compared to positions within the OWF area. PTS is likely to occur in harbour porpoise at distances out to 1725 m from the survey vessel at the onset of seismic survey activities, while for TTS, the distance is 2850 m. The slightly higher impact distances, compared to the OWF area positions, is attributed to the water depth at the source location and surrounding area, combined with the differences in seabed sediment and sound speed profile. For avoidance behaviour, the distances are also comparable to those found within the site positions, however with slightly higher distance of 2.65 km.

For seals, where PW weighting is applied, PTS is unlikely to occur beyond 10 m. The impact distance for TTS is likely to be up to 60 m.

It should be noted, that the impact distances mentioned here 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 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.

10 References

EMODnet, 2021. [Online]
Available at: https://www.emodnet-bathymetry.eu/data-products
[Accessed 2021].

Erbe, C., 2011. *Underwater Acoustics: Noise and the Effects on Marine Mammals.* s.l.:jasco.

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

Jakob Tougaard, K. B., 2018. *Practical implementation of auditory time and frequency weighting in marine bioacoustics.* s.l.:Department of Bioscience, Aarhus University, Denmark.

Jensen, F. B., Kuperman, W. A., Porter, M. B. & Schmidt, H., 2011. *Computational Ocean Acoustics, 2nd edition.* s.l.:Springer.

Jensen, F. B., Kuperman, W. A., Porter, M. B. & Schmidt, H., 2011. *Computational Ocean Acoustics, 2nd edition.* s.l.:Springer.

Martin, B., Morris, C. & O'Neill, C., 2019. *Sound exposure level as a metric for analyzing and managing underwater.* s.l.:s.n.

Nielsen, B. et al., 2011. *Marin råstof- og naturtypekortlægning i Kattegat og vestlige Østersø.* s.l.:s.n.

NOAA, 2019. *WORLD OCEAN ATLAS 2018 (WOA18).* [Online].

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

Porter, M., 2011. *The BELLHOP Manual and User's Guide: PRELIMINARY DRAFT.* s.l.:Heat, Light and Sound Research Inc. La Jolla, CA, USA.

Sopher, D., Erlströmb, M., Bell, N. & Juhlin, C., 2016. *The structure and stratigraphy of the sedimentary succession in the Swedish sector of the Baltic Basin: New insights from vintage 2D marine seismic data.* s.l.:s.n.

Southall, B. L. et al., 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals 45(2)*, pp. 125-232, DOI 10.1578/AM.45.2.2019.125.

Sveegaard, S., Teilmann, J. & Tougaard, J., 2017. *Marine mammals in the Swedish and Danish Baltic Sea in relation to the Nord Stream 2 project. Expert Assessment*, s.l.: Aarhus University, DCE - Danish Centre for Environment and Energ, 68 pp. Scientific Report from DCE - Danish Centre for Environment and Energy No. 237. http://dce2.au.dk/pub/SR237.pdf.

Tougaard J, W. A. M. P., 2015. Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises.. *MarPollutBull*, pp. 90:196-208.

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

Tougaard, J., 2016. *Input to revision of guidelines regarding underwater noise from oil and gas activities - effects on marine mammals and mitigation measures.*, s.l.: Aarhus University. DCE - Danish Centre for Environment and Energy No. 202. http://dce2.au.dk/pub/SR202.pdf.

Wunderlich, J., 2016. *Innomar's SES-2000 Parametric SBPs and Marine Mammals. Technical Note TN-01*, s.l.: Innomar Technologie GmbH.

Appendix 1

Underwater Sound Emission – Position 1

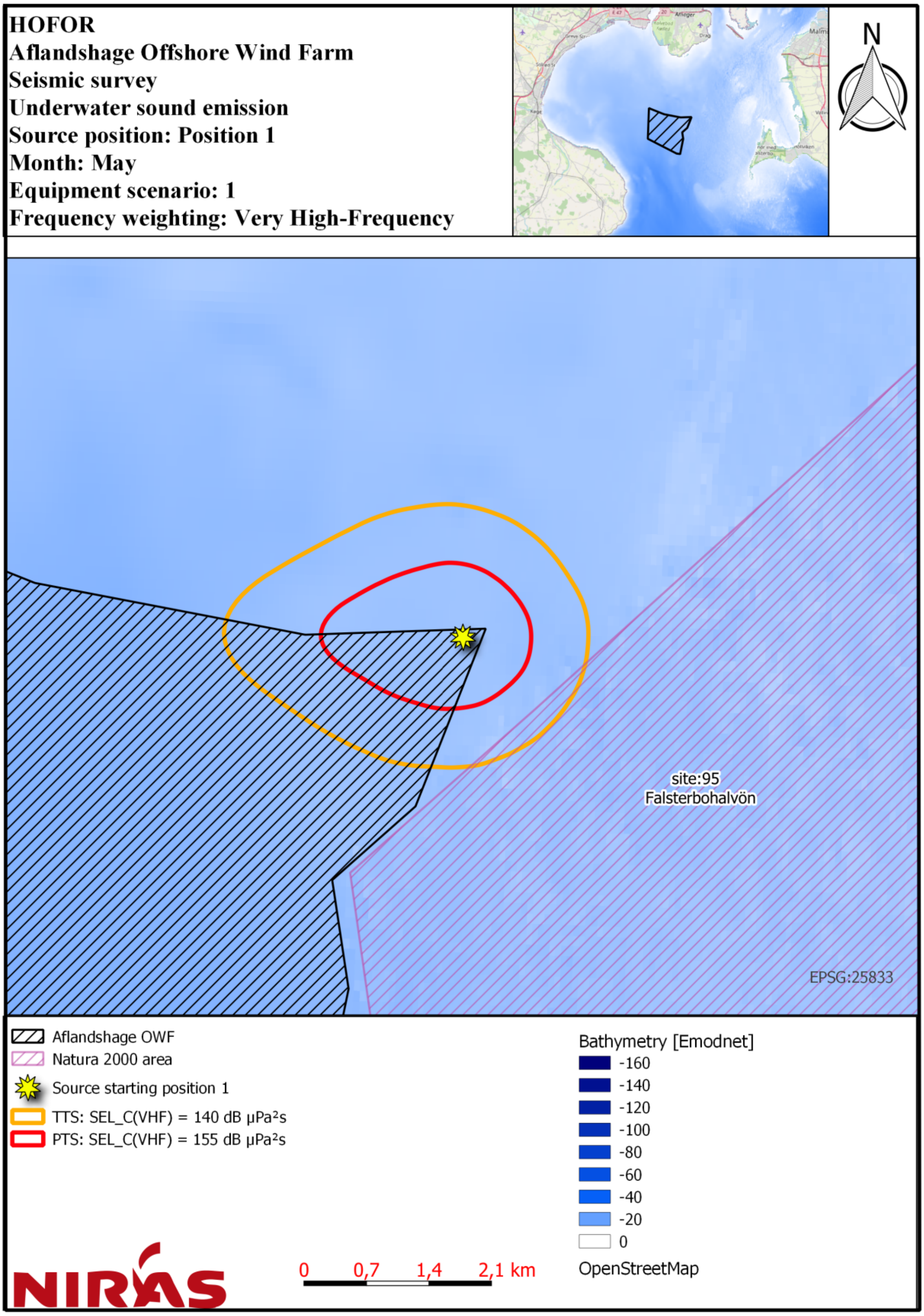

Figure 10.1: Noise contour map for position 1, showing impact distances for TTS and PTS with VHF-weighting for the month of May

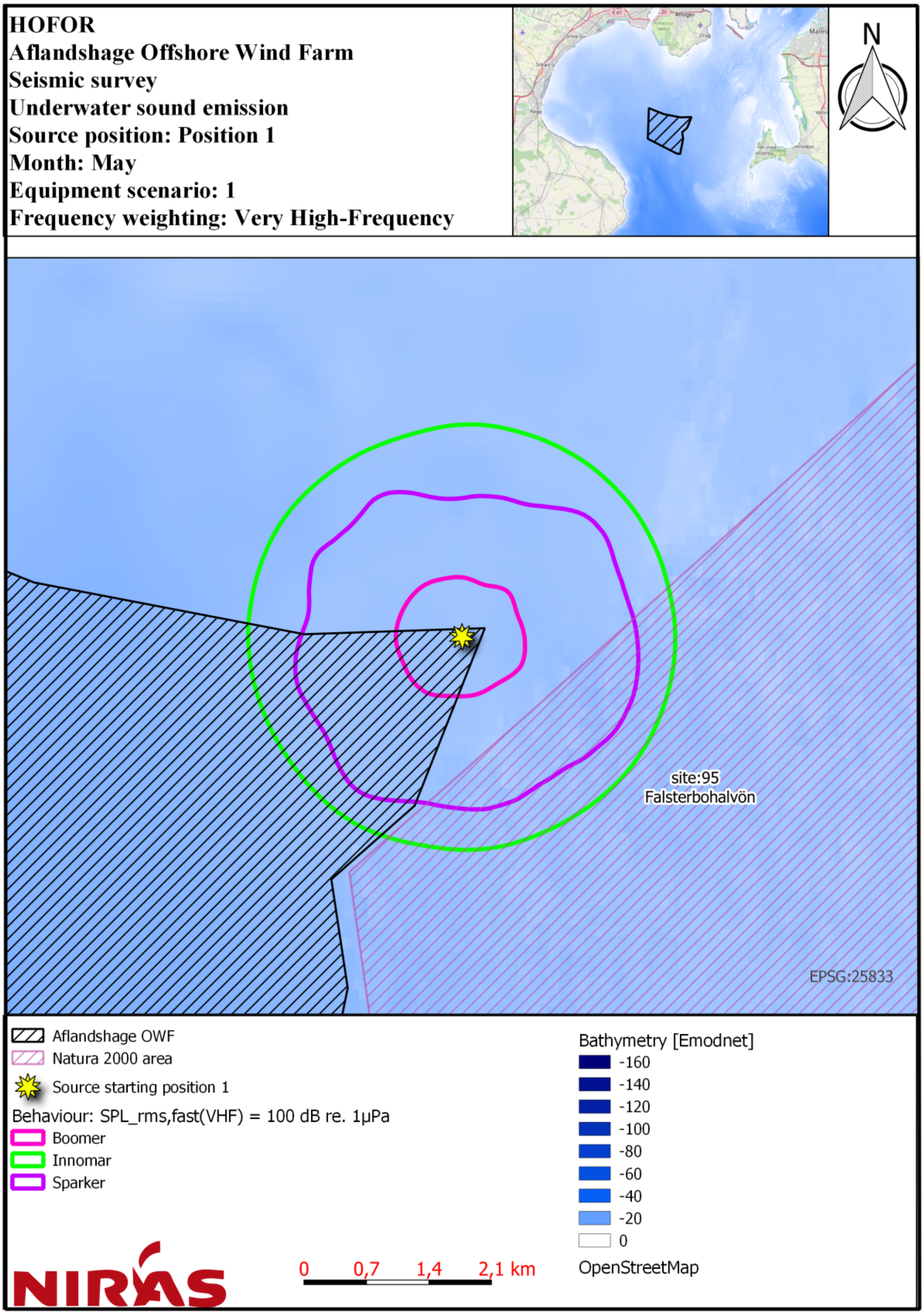

Figure 10.2: Noise contour map for position 1, showing impact distances for avoidance behaviour with VHF-weighting for the month of May.

Appendix 2

Affected Natura 2000 area – Position 1

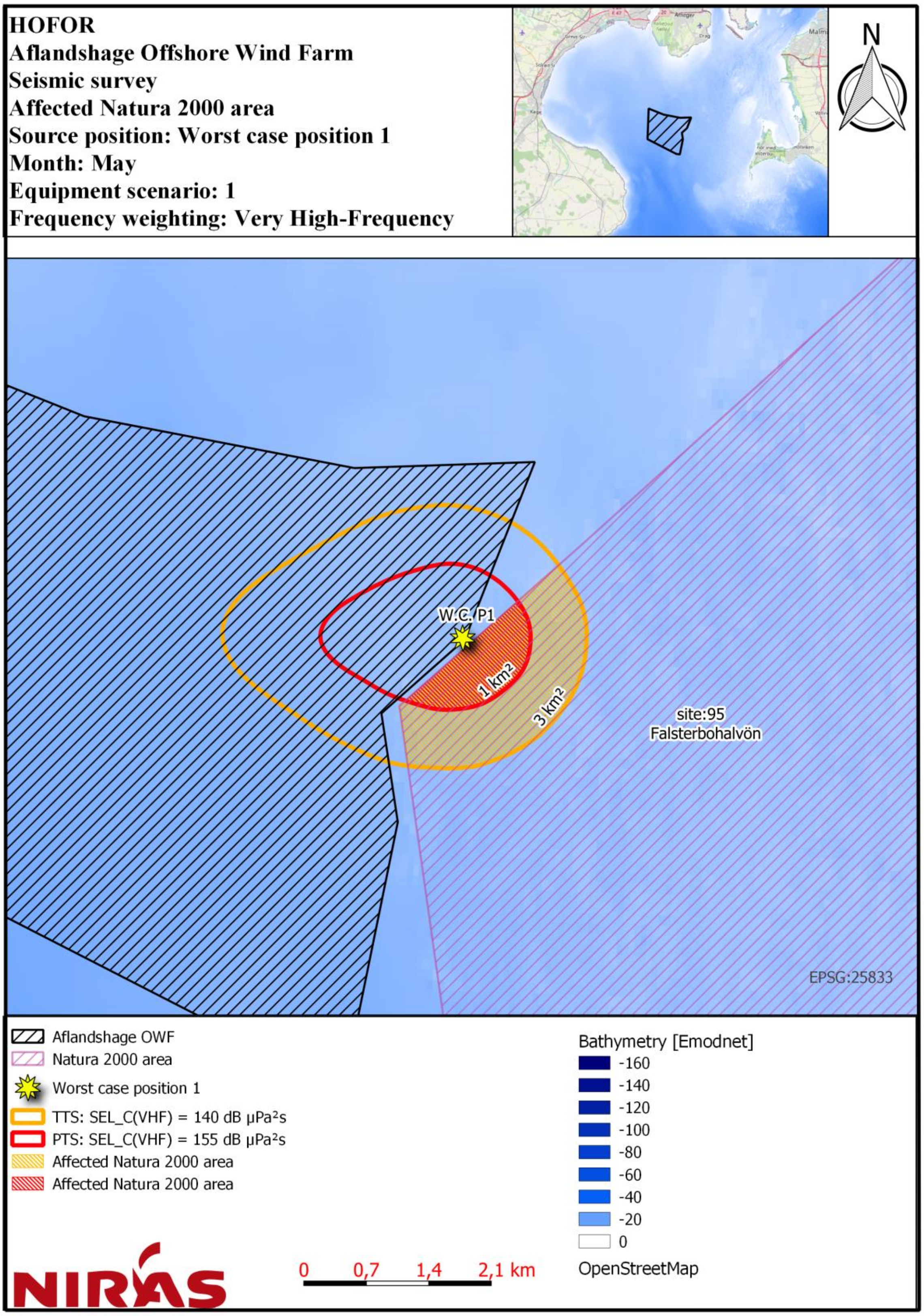

Figure 10.3: Noise contour map for worst case position 1, showing impact distance for TTS and PTS with VHF-weighting, and affected Natura 2000 area for the month of May.

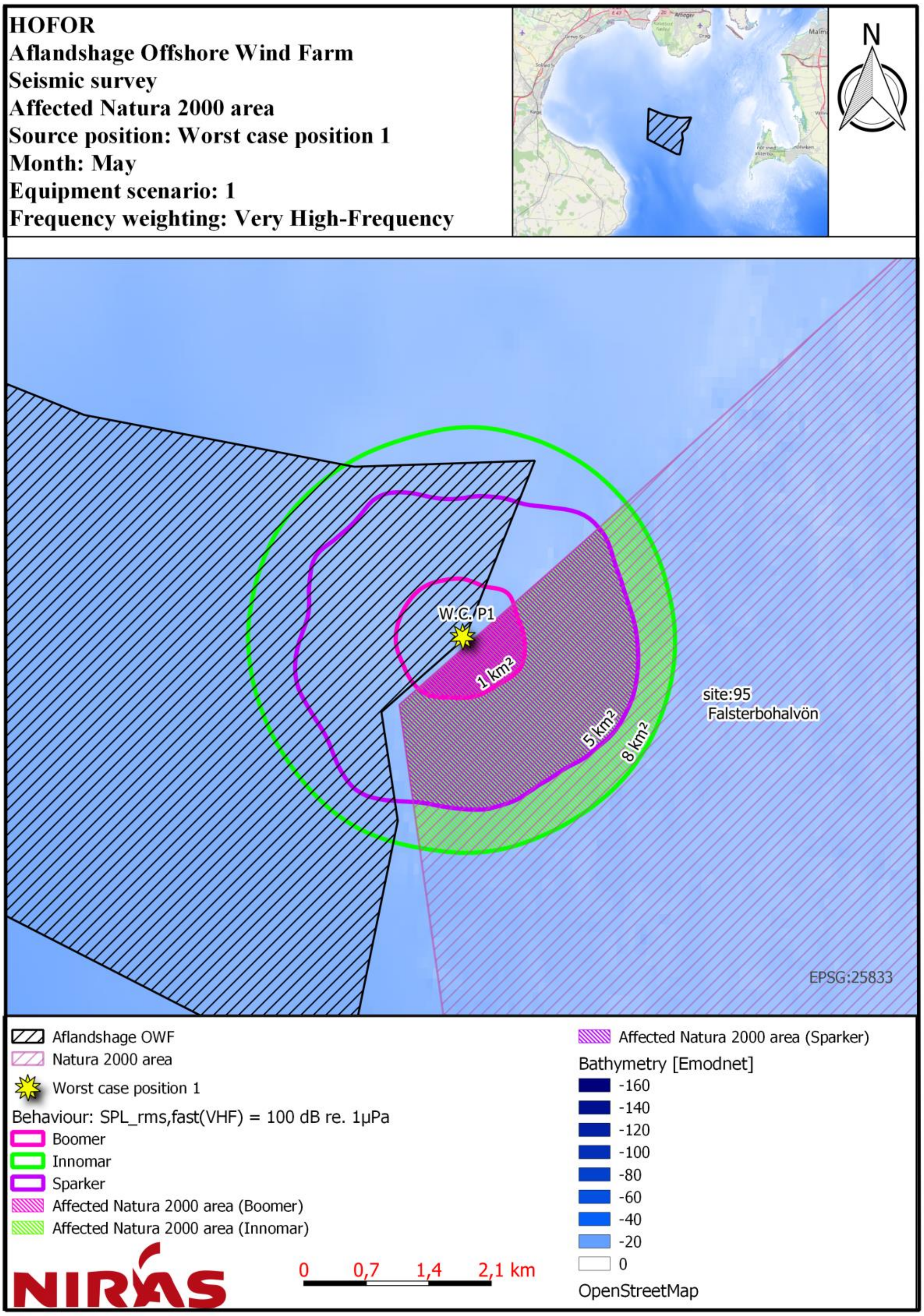

Figure 10.4: Noise contour map for worst case position 1, showing impact distance for avoidance behaviour with VHF-weighting, and affected Natura 2000 area for the month of May.

Appendix 3

Underwater Sound Emission – Position 2

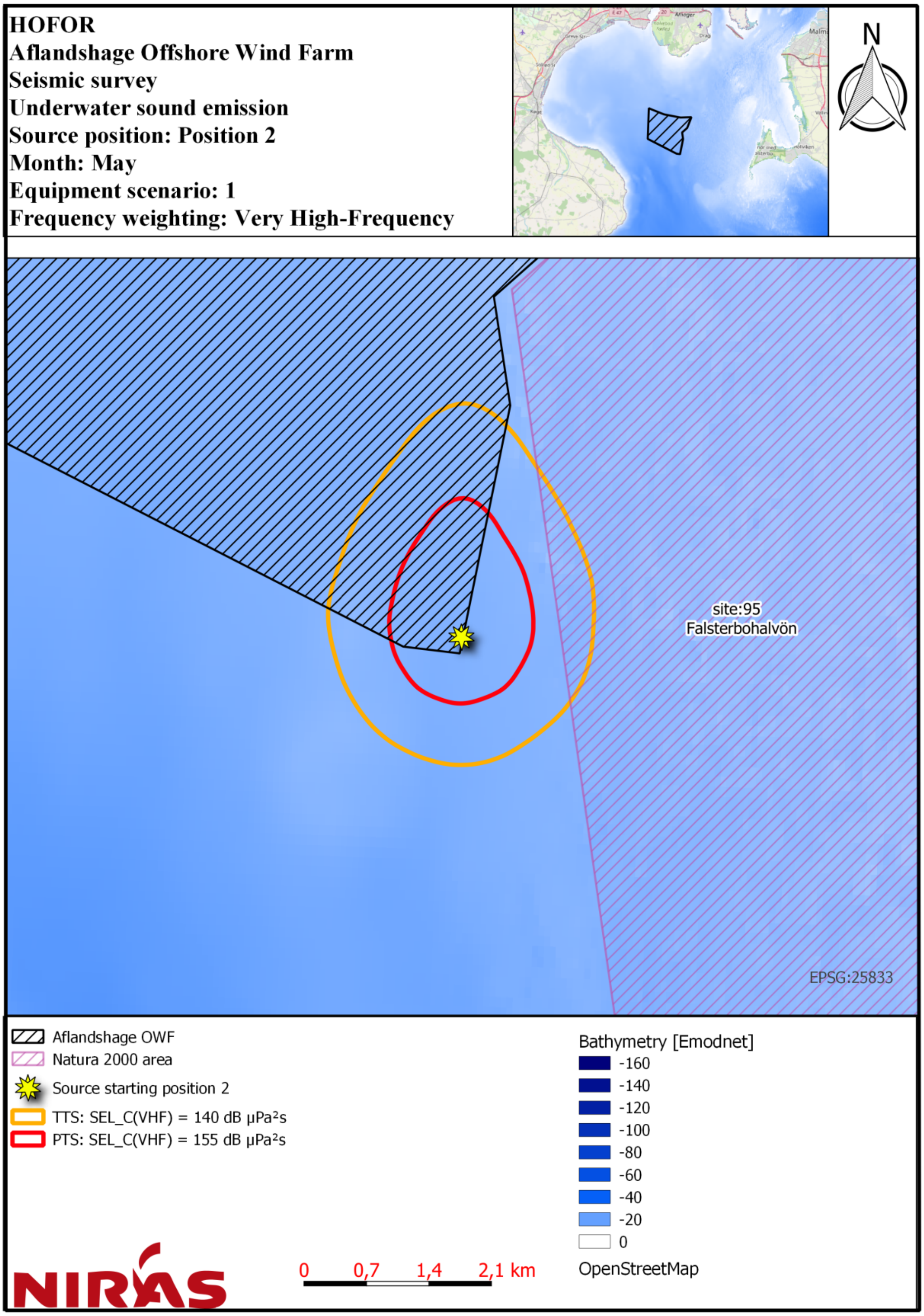

Figure 10.5: Noise contour map for position 2, showing impact distances for TTS and PTS with VHF-weighting for the month of May.

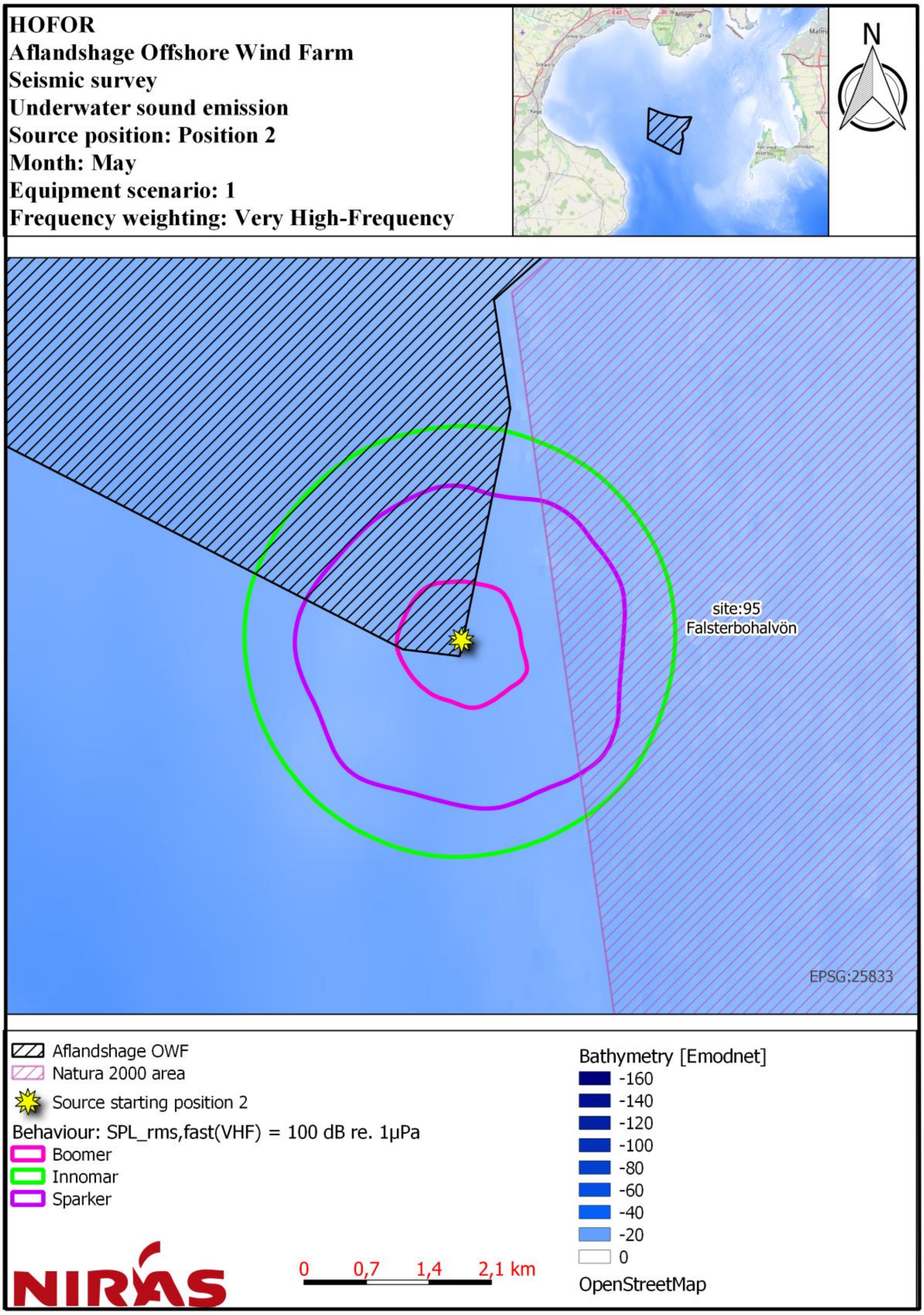

Figure 10.6: Noise contour map for position 2, showing impact distances for avoidance behaviour with VHF-weighting for the month of May.

Appendix 4

Affected Natura 2000 area – Position 2

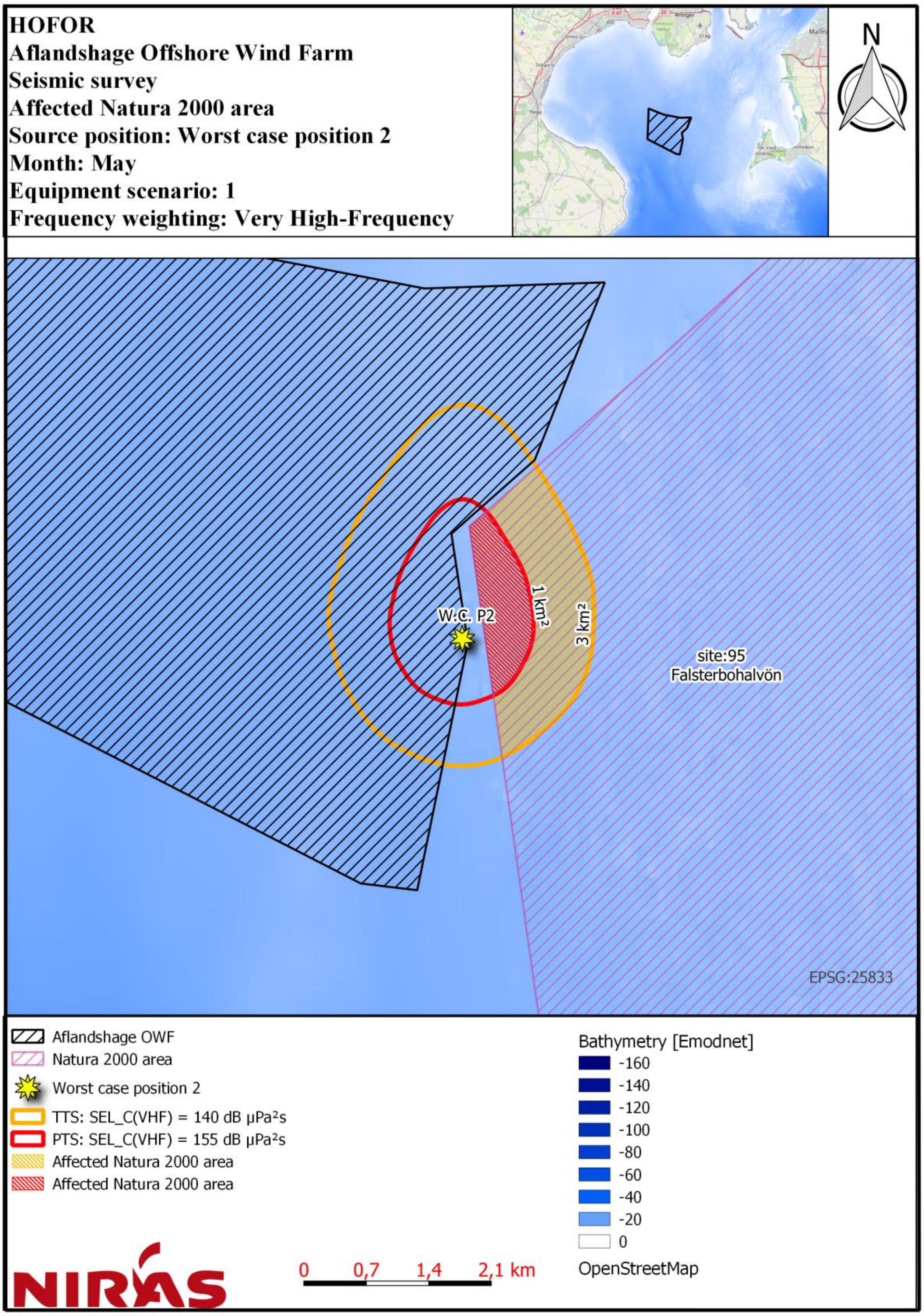

Figure 10.7: Noise contour map for worst case position 2, showing impact distance for TTS and PTS with VHF-weighting and affected Natura 2000 area for the month of May.

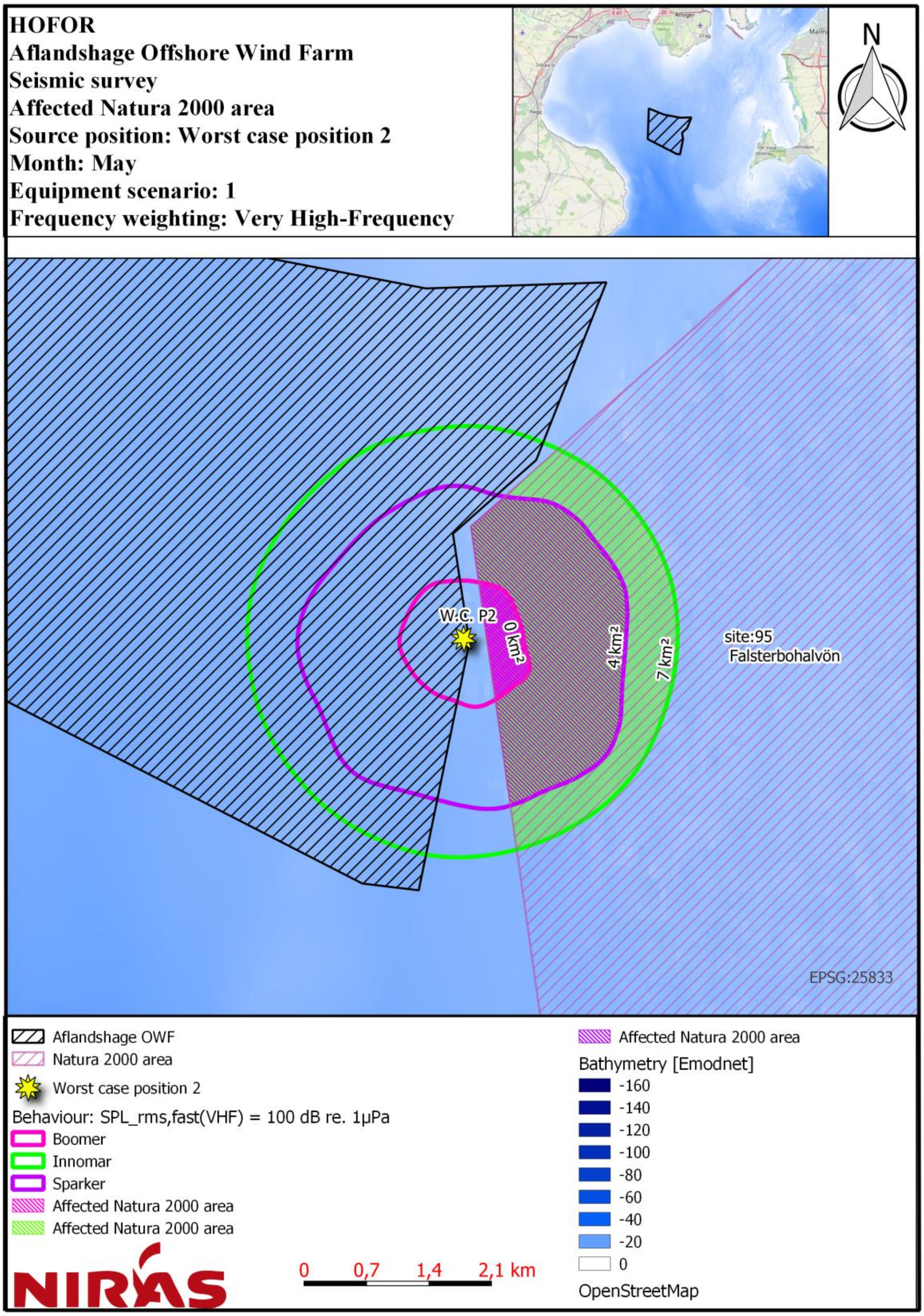

Figure 10.8: Noise contour map for worst case position 2, showing impact distance for avoidance behaviour with VHF-weighting and affected Natura 2000 area for the month of May.

Appendix 5

Underwater Sound Emission – Position 3

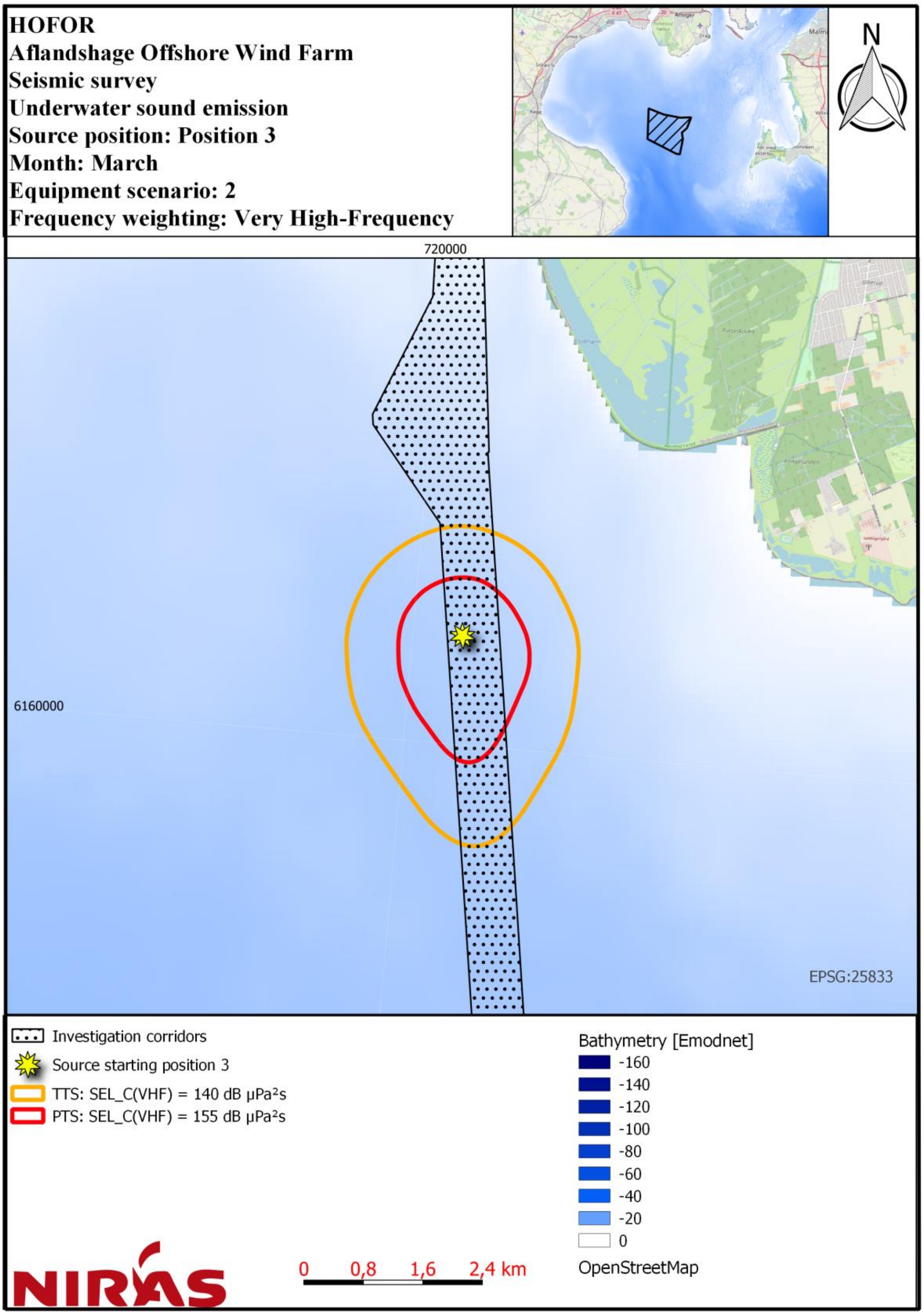

Figure 10.9: Noise contour map for position 3, showing impact distances for TTS and PTS with VHF-weighting for equipment scenario 2 (SBP only) for the month of March

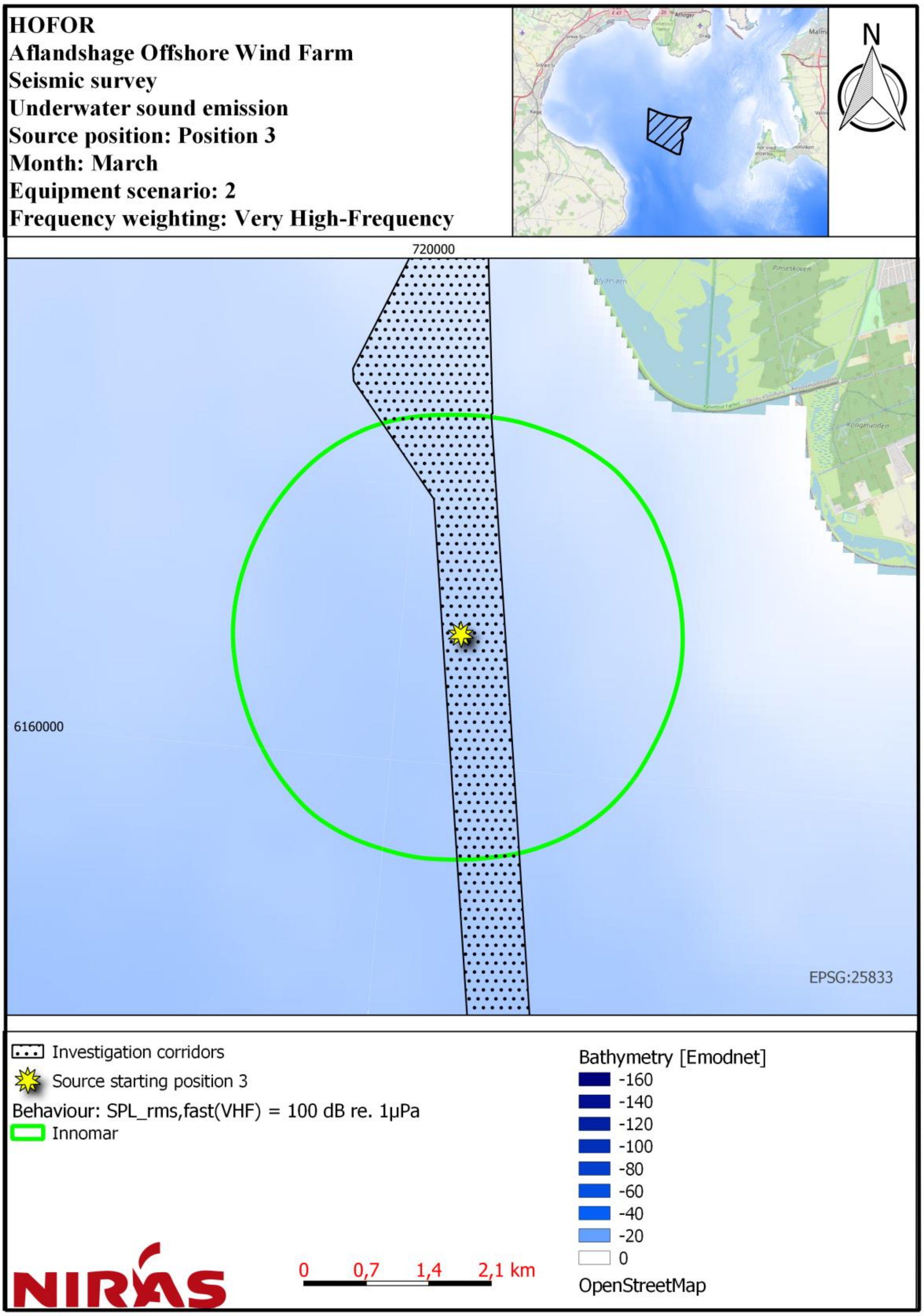

Figure 10.10: Noise contour map for position 3, showing impact distances for avoidance behaviour with VHF-weighting for equipment scenario 2 (SBP only) for the month of March.