Vesterhav Syd
Offshore Wind Farm
EIA – Technical report

Modelling of underwater noise emissions during construction pile-driving work

Oldenburg, February 6th, 2020

Version 3 – final version

Contracting body: Vattenfall Vindkraft A/S
Jupitervej 6
2nd floor
6000 Kolding,
Denmark

Execution: Patrick Remmers, B. Eng.
Dr. Torben Wendt

itap GmbH
Institute for Technical and Applied Physics GmbH
Marie-Curie-Straße 8
D – 26129 Oldenburg

Scope of report: 59 pages

INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

Messstelle nach §29b BImSchG
für Geräusche und Erschütterungen

Sitz
itap GmbH
Marie-Curie-Straße 8
26129 Oldenburg

Amtsgericht Oldenburg
HRB: 12 06 97

Kontakt
Telefon (0441) 570 61-0
Fax (0441) 570 61-10
Mail info@itap.de

Geschäftsführer
Dipl. Phys. Hermann Remmers
Dr. Michael A. Bellmann

Bankverbindung
Raiffeisenbank Oldenburg
IBAN:
DE80 2806 0228 0080 0880 00
BIC: GENO DEF1 OL2

Commerzbank AG
IBAN:
DE70 2804 0046 0405 6552 00
BIC: COBA DEFF XXX

USt.-ID.-Nr. DE 181 295 042

Table of contents

1. Summary

In 2015, the Danish Energy Agency issued the tendering for Vesterhav Syd Offshore Wind Farm. In 2016 *Vattenfall Vindkraft A/S* was awarded the contract to construct and operate the wind farm. In December 2018, the Danish Energy Board of Appeal concluded that the Environmental Impact Assessment (EIA) of the project insufficiently addressed the potential impact from the actual project and as a consequence a new EIA based on the actual project design has to be carried out. This technical report on underwater noise modelling serves to inform the assessment of environmental impacts from underwater noise during the installation of monopile foundations at Vesterhav Syd Offshore Wind Farm.

The construction of Vesterhav Syd Offshore Wind Farm includes activities that emit noise levels that could potentially harm marine mammals and fish in the area. Installation of monopile foundations into the seabed by means of impact pile driving is regarded the most significant noise source during construction. Itap – Institute for Technical and Applied Physics GmbH was commissioned to carry out modelling of underwater noise during pile driving works for Vesterhav Syd Offshore Wind Farm.

Modelling scenarios, including pile diameter, hammer type and turbine locations, were defined to reflect the actual project to the highest extent possible, with the objective to determine expected noise levels, allowing for accurate impact assessment of the piling activities. Modelling included both cumulative and single strike Sound Exposure Levels as well as Peak Sound Pressure Levels. In addition to unweighted noise levels, hearing sensitivities of relevant species were taken into account. The present report does not include impact assessments of underwater noise emissions. This is treated in the EIA report for Vesterhav Syd Offshore Wind Farm.

A comparison with various sensation levels from the literature for all species (NMFS 2018 and Danish Energy Agency 2016) showed that all limit values for a permanent threshold shift can be met by using a standard noise mitigation system.

Oldenburg, February 6th 2020

Patrick Remmers, B. Eng.

Dr. Torben Wendt

2. Introduction

November 2012 the Danish Government pointed out six sites subject to pre-investigations prior to the development and production of a total of 450 MW wind power. One of these sites was Vesterhav Syd Offshore Wind Farm located approximately 4 km – 10 km off the coast of Jutland west of Hvide Sande. In 2013, Energinet.dk was commissioned by the Danish Energy Agency to provide assessments of potential impacts on the environment from the construction and operation of the wind farm. In September 2016, *Vattenfall Vindkraft A/S* was awarded the contract to construct and operate Vesterhav Syd Offshore Wind Farm. Following the issuing of the Construction License and Concession Agreement by the Danish Energy Agency in December 2016, the Danish Board of Appeal concluded that the environmental impact assessment of the project insufficiently addressed the potential impacts from the actual project. As a consequence, a second Environmental Impact Assessment should be carried out reflecting the actual project design to a higher degree. The objective of this technical report is to carry out modelling of underwater noise produced during construction of Vesterhav Syd Offshore Wind Farm and to inform the assessment of environmental impacts from underwater noise during construction. Within the Vesterhav Syd windfarm site, 20 wind turbines will be installed at monopile foundations.

The construction of the offshore wind farm involves activities that produce underwater noise. Installation of monopile foundations into the sea bed by means of impact pile driving is regarded the most significant noise source with the potential to harm marine mammals and fish in the area.

The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out modelling of underwater noise produced during construction of the offshore wind farm.

3. Objectives

The objective of the report is to use available knowledge about underwater sound propagation to determine the expected sound exposure into the North Sea as a result of pile driving operations during the construction of the Vesterhav Syd Offshore Wind Farm. Modelling will be based on the design for the actual project where available, while a worst case assumption will be applied for currently unspecified input. Modelling will extend to ranges where significant impact on marine mammals can occur.

4. Project description

The Vesterhav Syd Offshore Windfarm is located in the Danish North Sea approximately 4 km – 10 km off the coast of Jutland (Denmark) west of Hvide Sande (Figure 1). The water depth in the project area is between 20.37 m and 25.44 m (DVR90). Within the Offshore Wind Farm 20 wind turbines will be installed on monopile foundations with outer diameter of maximally 7 m. Monopile foundations consist of a single very large diameter steel pile that is driven into the seabed by an impact hammer. The larger the monopile, the more force is required to drive it into the seabed, and thus the higher the source level from the hammer blows.

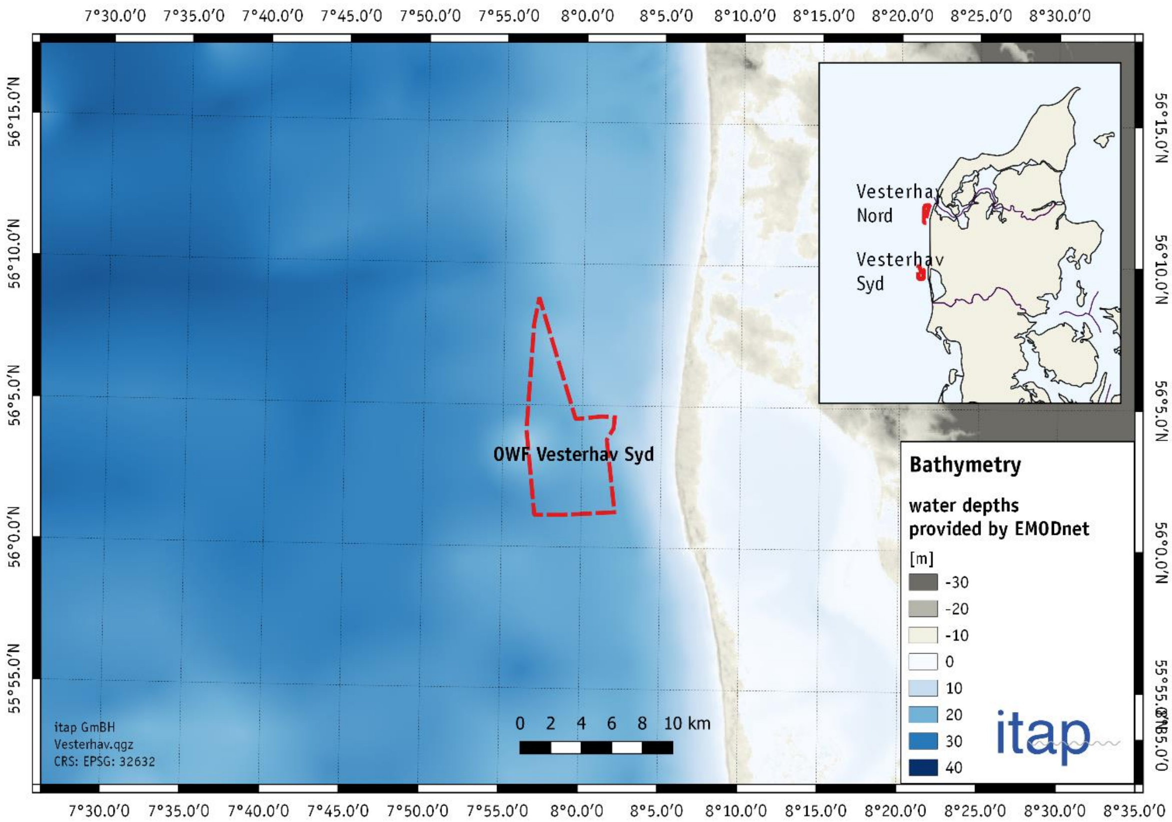


Figure 1: *Location of the Vesterhav Syd Offshore Wind Farm and bathymetry (provided by EMODDnet).*

It is proposed to install the monopiles with an IHC S-3000 Hydrohammer with a maximum possible blow energy of 3,000 kJ. For the underwater noise modelling, the following piling sequence of 7,305 blows is assumed, considering a 15 minutes long soft start interval and a 28 Minutes ramp up interval to get of maximum hammer energy. A 15 Minutes soft start is a common duration often used by installations in other windfarms. In some cases the duration is also laid down in building permits. The assumed piling sequence represent a realistic scenario as the detailed installation sequence is not known at this time. During actual installation the blow frequency will likely be considerably lower especially during the initial part of the installation.

Table 1: *Assumed piling sequence including soft start/ramp up with different blow frequencies [blows/min].*

percentual hammer energy	Number of blows	Blow frequency
10 %	5	25
15 minutes pile driving break		
10 %	400	25
20 %	100	25
40 %	100	50
60 %	100	50
80 %	100	50
100 %	6500	50

Within the Vesterhav Syd project area the uppermost surface layer of the semdiments consists of a mix of meltwater sand, gravel and clay with occasional occurrences of holocene clay in the South or neogene clay, silt and sand in the North. Figure 2 shows a geological cross section of the sediment within the Vesterhav Syd offshore windfarm.

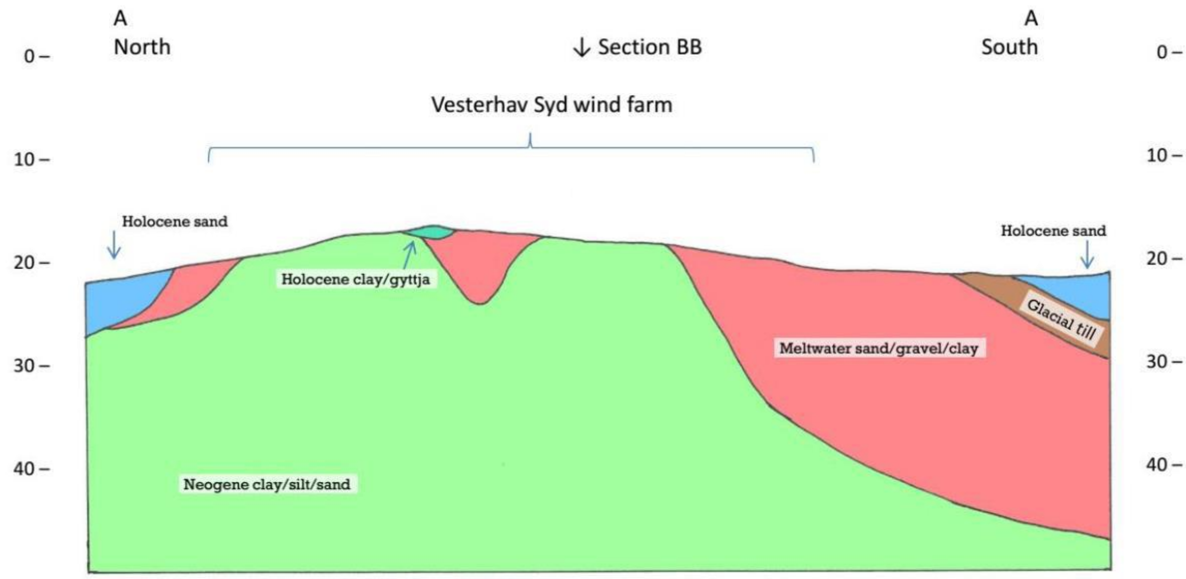


Figure 2: *Illustration of geological cross section Vesterhav Syd Offshore Wind Farm.*

5. Acoustic basics

Sound is a rapid, often periodic variation of pressure, which additively overlays the ambient pressure (in water the hydrostatic pressure). This involves a reciprocating motion of water particles, which is usually described by particle velocity *v*. Particle velocity means the alternating velocity of a particle oscillating about its rest position in a medium. Particle velocity is not to be confused with sound velocity c_{water}, thus, the propagation velocity of sound in a medium, which generally is c_{water} = 1,500 m/s in water. Particle velocity *v* is considerably less than sound velocity *c*.

Sound pressure *p* and particle velocity *v* are associated by the acoustic characteristic impedance *Z,* which characterizes the wave impedance of a medium as follows:

$$Z = \frac{p}{v}$$ Equation no. 1

In the far field, that means in a distance[1] of some wavelengths (frequency dependent) from the source of sound, the impedance is:

[1] The boundary between near and far field in hydro sound is not exactly defined or measured. It is a frequency-dependent value. In airborne sound, a value of $\geq 2\lambda$ is assumed. For underwater sound, values of $\geq 5\lambda$ can be found.

$$Z = \rho c$$ Equation no. 2

with ρ – density of a medium and c – sound velocity.

For instance, when the sound pressure amplitude is 1 Pa (with a sinusoidal signal, it is equivalent to a Sound Pressure Level of 117 dB re 1 µPa or a Peak Level of 120 dB re 1 µPa; see chapter 3.1), a particle velocity in water of appr. 0.7 µm/s is obtained.

In acoustics, the intensity of sounds is generally not described by the measurand sound pressure (or particle velocity), but by the level in dB (decibel) known from the telecommunication engineering. There are different sound levels, however:

- (Energy-) equivalent continuous Sound Pressure Level – SPL,
- Sound Exposure Level – SEL,
- Cummulative Sound Exposure Level - SEL_{cum}
- Peak Sound Pressure Level $L_{p,pk}$.

SPL and SEL can be specified independent of frequency, which means as broadband single values, as well as frequency-resolved, for example, in one-third octave bands (third spectrum).

In the following, the level values mentioned above are briefly described.

(Energy-) equivalent continuous Sound Pressure Level (SPL)

The SPL is the most common measurand in acoustics and is defined as:

$$SPL = 10\log\left(\frac{1}{T}\int_0^T \frac{p(t)^2}{p_0^2}\,dt\right) \text{ [dB]}$$ Equation no. 3

with

$p(t)$ - time-variant sound pressure,

p_0 - reference sound pressure (in underwater sound 1 µPa),

T - averaging time.

Sound Exposure Level (SEL)

For the characterization of pile-driving sounds, the SPL solely is an insufficient measure, since it does not only depend on the strength of the pile-driving blows, but also on the averaging time and the breaks between the pile-driving blows. The Sound Exposure Level – SEL is more appropriate and is defined as follows:

$$SEL = 10 \log \left(\frac{1}{T_0} \int_{T_1}^{T_2} \frac{p(t)^2}{p_0^2} dt \right) \text{ [dB]} \qquad \text{Equation no. 4}$$

with

T_1 and T_2 - starting and ending time of the averaging (should be determined, so that the sound event is between T_1 and T_2 ; Figure 3),

T_0 - reference 1 second.

Therefore, the Sound Exposure Level of a sound impulse (pile-driving blow) is the level (SPL) of a continuous sound of time duration of 1 s and the same acoustic energy as the impulse.

The Sound Exposure Level (SEL) and the Sound Pressure Level (SPL) can be converted into each other:

$$SEL = 10 \log \left(10^{SPL/10} - 10^{L_{hg}/10} \right) - 10 \log \frac{nT_0}{T} \text{ [dB]} \qquad \text{Equation no. 5a}$$

with

n - number of sound events, thus the pile-driving blows, within the time T,

T_0 - 1 s,

L_{hg} - noise and background level between the single pile-driving blows.

Thus, equation no. 5 provides the average Sound Exposure Level (SEL) of n sound events (pile-driving blows) from just one Sound Pressure Level SPL measurement. In case, that the background level between the pile-driving blows is significantly minor to the pile-driving sound (for instance > 10 dB), it can be calculated with a simplification of equation no. 5a and a sufficient degree of accuracy as follows:

$$SEL \approx SPL - 10 \log \frac{nT_0}{T} \text{ [dB]} \qquad \text{Equation no. 5b}$$

Cumulative Sound Exposure Level (SEL_{cum})

A value for the noise dose is the cumulative Sound Exposure Level (SEL_{cum}) and is defined as follows:

$$SEL_{cum} = 10\ \log_{10} \frac{E_{cum}}{E_{ref}}\ \text{[dB re 1 µPa]}$$ Equation no. 6a

With the cumulative sound exposure E_{cum} for N transient sound events with the frequency unweighted sound exposure E_n.

$$E_{cum} = \sum_{n=1}^{N} E_n$$

Equation no. 6b

and the reference exposure $E_{ref} = p_{ref}^2 \cdot T_{ref}$, in which p_{ref} is the reference sound pressure 1 µPa and T_{ref} the reference duration 1 s.

Peak Sound Pressure Level $L_{p,pk}$

This parameter is a measure for sound pressure peaks. Compared to Sound Pressure Level (SPL) and Sound Exposure Level (SEL), there is no average determination:

$$L_{p,pk} = 20 \log \left(\frac{|p_{pk}|}{p_0} \right)\ \text{[dB]}$$ Equation no. 7

with

p_{pk} - maximal determined positive or negative Sound Pressure Level.

An example is depicted in Figure 3. The Peak Sound Pressure Level ($L_{p,pk}$) is always higher than the Sound Exposure Level (SEL). Generally, the difference between $L_{p,pk}$ and SEL during pile-driving work is 20 dB to 25 dB. Some authors prefer the Peak-to-Peak value ($L_{pk,pk}$) instead of $L_{p,pk}$. A definition of this parameter is given in Figure 3. This factor does not describe the maximum achieved (absolute) Sound Pressure Level, but the difference between the negative and the positive amplitude of an impulse (Figure 3). This value is maximal 6 dB higher than the Peak Level $L_{p,pk}$.

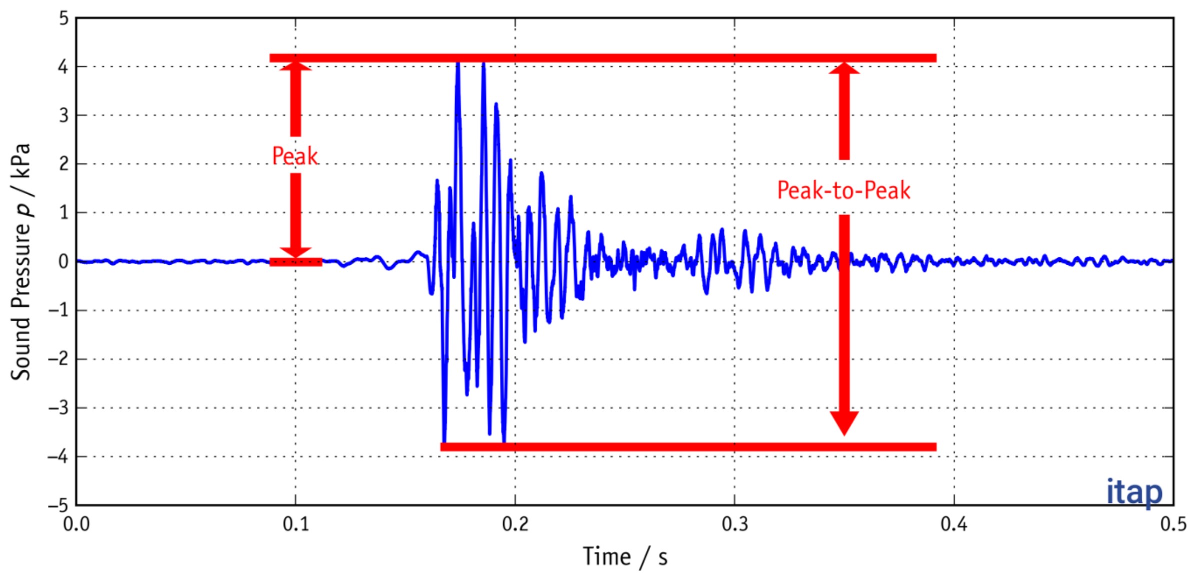


Figure 3: *Typical measured time signal of underwater sound due to pile-driving in a distance of several 100 m.*

6. Model approaches

6.1 Sound propagation in shallow waters

Impact of the distance

For approximate calculations it can be assumed, that the sound pressure decreases with the distance according to a basic power law. The level in dB is reduced about:

$$TL = k \cdot \log_{10}\left(\frac{r_1}{r_2}\right) \text{ [dB]} \qquad \text{Equation no. 8}$$

with

r_1 and r_2 - the distance to the source of sound increases from r_1 to r_2,

TL - Transmission Loss,

k - absolute term (in shallow waters, an often used value is $k = 15$, for spherical propagation, k = 20).

Often, the transmission loss is indicated for the distance $r_1 = 1$ m (fictitious distance to an assumed point source). This is used to calculate the sound power of a pile-driver in a distance of 1 m. Often, this is called source level. Equation no. 8 is then reduced to $TL = k \log (r/\text{meter})$. Additionally, it has to be considered, that the equation mentioned above is only valid for the far field of an acoustic signal, meaning in some distance (frequency dependent) to the source.

Additionally, the absorption in water becomes more apparent in distances of several kilometers and leads to a further reduction of sound pressure. This is considered with a constant proportional to the distance. Equation no. 8 expands to:

$$TL = k \cdot \log_{10} r + \alpha \cdot r \text{ [dB]}$$ Equation no. 9

For regions in the North Sea with water depths below 50 m the following equation no. 10 leads to realistic results compared with noise measurements in different regions in the North Sea. The example in the „Guideline for underwater noise – Installation of impact-driven piles“ (Danish Energy Agency, 2016) considered the same transmission loss.

$$TL = 14.72 \cdot \log_{10} r + 0.00027 \cdot r \text{ [dB]}$$ Equation no. 10

Thiele and Schellstede (1980) specified frequency dependent approximation equations for the calculation of sound propagation in different regions of the North Sea as well as for "rough" and "smooth" sea. For the installation of the foundations, a "smooth" sea is required. So, the following equation for shallow water and smooth sea (IIg) will be compared with measurement results from different offshore windfarms in the North Sea in Figure 4:

$$TL = (27 + 1.1F)(\log(R) + 3) + (0.7 + 0.135F + 0.013F^2)R \text{ [dB]}$$ Equation no. 11

with

F = *10 log(f/*[kHz]*)*,

R – distance.

Caused by the higher surface roughness of the sea and more inclusion of air in the upper sea layer due to the pounding of the waves the absorption in water is increasing. This would lead to slightly lower Sound Pressure Level in large distances. For distances below 10 km the impact is negligible.

In 2017 the transmission loss within the project areas Vesterhav Nord and Vesterhav Syd were made by measuring sparker impulses in different distances (Betke & Matuschek, 2017). During these measurements median transmission loss of $TL = 14.4 \cdot \log_{10} r$ was measured. The spreading of the result was characterised by the 25 % and 75 % quartiles of X, which are 12.8 and 15.0 for the k term. The determination of the absorption parameter α was not feasible due to the low signal-to-noise ratio of the sparker.

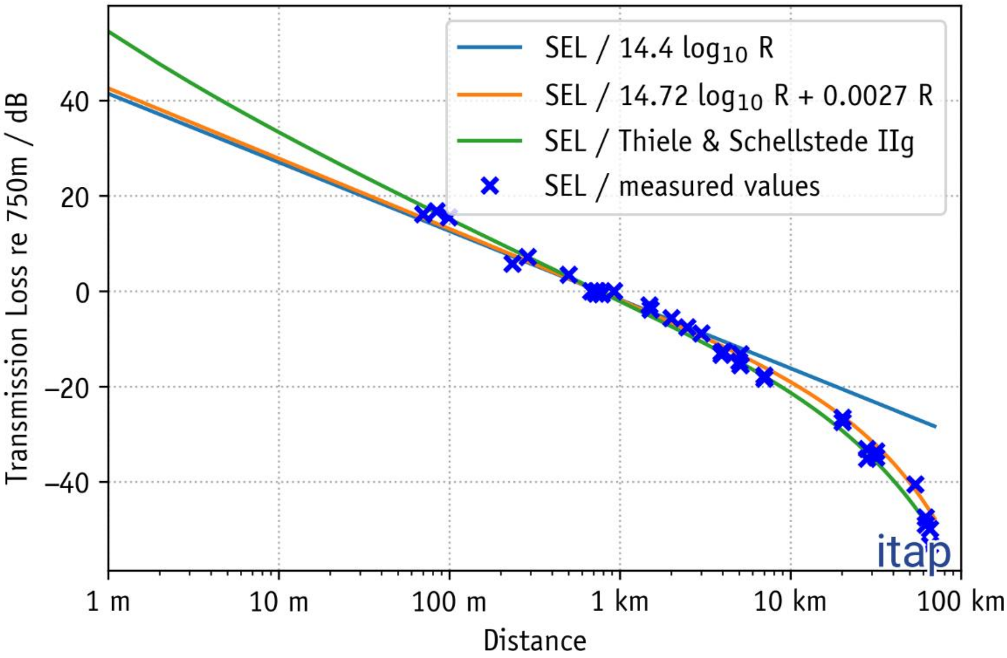


Figure 4: *Different predicted Transmission Loss (TL) curves according to the semi-empirical approach of Thiele und Schellstede (1980) (eq. 11) and eq. 10, compared with existing offshore measurement data. The measurement data comes from pile driving measurements from different offshore windfarms in the North Sea in Germany and the Netherlands. The water depth in all windfarms was below 50 m. IIg: shallow water, smooth sea and 14.4 log10(R): measured median TL in Vesterhav project areas, 14.72 log10(R) + 0.00027 R (eq 10).*

Equation No. 10 shows a high similarity and a high correspondence with the measured values of the Sound Exposure Level (SEL) during pile driving (see Figure 4) in different regions of the North Sea with comparable water depths. Only for distances less than 100 m, the equations differ from each other. So both equations, eq. 10 and eq. 11 are valid for the Vesterhav Nord project area. For modeling, equation no. 10 is considered since the absorption parameter α is not available for the measured transmission loss and the differences in the k term are within the variance of the measured site specific transmission losses (Betke & Matuschek, 2017). The transmission loss will be considered for each direction. Site specific changes in bathymetry, especially towards the shore, will be considered by the frequency dependent impact of water depth as described below.

Impact of water depth

Sound propagation in the ocean is also influenced by water depth. Below a certain cut-off frequency f_g, a continuous sound propagation is impossible. The shallower the water, the higher this cut-off frequency. The cut-off frequency f_g also depends on the type of sediment.

The lower limit frequency for predominantly arenaceous soil as a function of water depth is depicted in Figure 5. Moreover, the band widths of the lower cut-off frequency f_g at different soil layers, e. g. clay and chalk (till or moraine), are illustrated in grey (Jensen *et al.*, 2010). Sound around the cut-off frequency f_g is reduced or damped to a larger extent with an increasing distance to the sound source than it is calculated with equation 10.

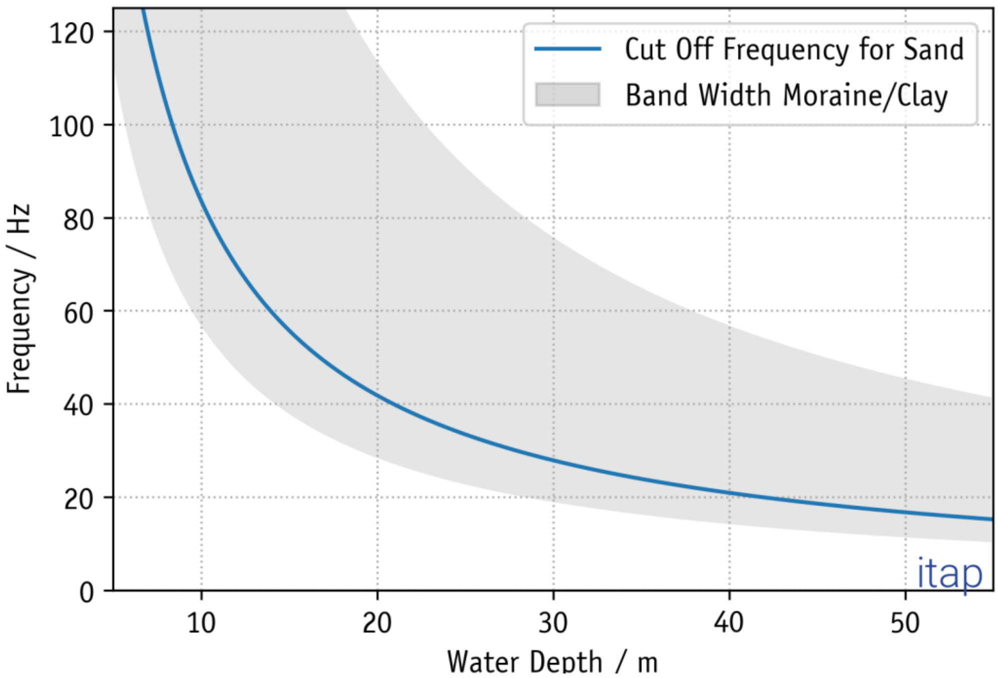


Figure 5: *Theoretical lower (limit) frequency fg for an undisturbed sound propagation in water as a function of the water depth for different soil stratifications (example adapted from Urick, 1983; Jensen et al., 2010; the example shows the possible range caused by different layers, the layer does not correspond to the layers in the construction field).*

6.2 Threshold level

The emission of underwater noise during pile driving is a human intervention in the marine environment which can have negative effects on the marine fauna. High sound pressure has the potential to harm marine mammals or fish potentially leading to behavioural disturbance, temporary hearing damage (TTS, Temporary Threshold Shift), permanent hearing damage (PTS, Permanent Threshold Shift) or even physical injury (cf. Table 2).

To assess the impact from underwater noise on marine mammals and fish, the threshold levels presented in Table 2 were modelled. For further details of the threshold levels, the reader is encouraged to consult the respective references provided in Table 2. Pertaining to threshold levels for auditory injury of marine mammals, both unweighted and frequency weighted threshold levels are modelled. The frequency weighting functions are based on the audiograms for generalized hearing groups according to the recommendations by the National Marine Fisheries Service (2018). By means of hearing group specific weighting functions, frequencies outside the optimal hearing range are given less weight than frequencies within the hearing range. Figure 6 shows the weighting functions provided by the National Marine Fisheries Service (2018) for high-frequency cetaceans (HF) (e. g. harbour porpoise, *Phocena phocena*), mid-frequency cetaceans (MF) (e. g. bottlenose, *Tursiops truncatus*, and white-beaked dolphin, *Lagenorhynchus albirostris*), low-frequency cetaceans (LF) (e. g. minke whale, *Balaenoptera acutorostrata*) and phocid pinnipeds (PW) (e. g. harbour seal, *Phoca vitulina*). For modelling of cumulative Sound Exposure Levels, an accumulation period of 24 hours as recommend by the National Marine Fisheries Service (2018) is applied.

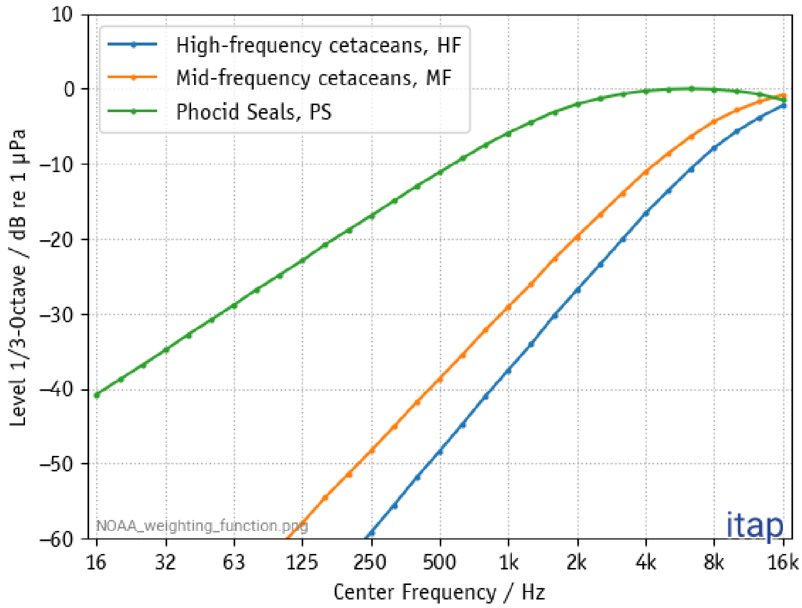


Figure 6: *Weighting functions for high- and mid-frequency cetaceans HF and MF and phocid seals according to NMFS (2018).*

Table 2: *Noise modelling threshold criteria. PTS: Permanent Threshold Shift; TTS: Temporary Threshold Shift.*

Receptor	Impact type	Range [km]	metric	Criteria [dB]	References
Phocid seals	PTS		$L_{p,pk}$	218	NMFS 2018
			$SEL_{cum, PS}$	185	
			SEL_{cum}	200	Skjellerup *et al*. 2015
	TTS		$L_{p,pk}$	212	NMFS 2018
			$SEL_{cum, PS}$	170	
			SEL_{cum}	176	Skjellerup *et al*. 2015
	Disturbance		SEL_{SS}	142	Russel *et al*. 2016
		20 km for 24 hrs	-	-	Tougaard & Michaelsen 2018
Mid-frequency cetaceans	PTS		$L_{p,pk}$	230	NMFS 2018
			$SEL_{cum, MF}$	185	
	TTS		$L_{p,pk}$	224	
			$SEL_{cum, MF}$	170	
	Disturbance	20 km for 24 hrs	-	-	Tougaard & Michaelsen 2018
High-frequency cetaceans	PTS		$L_{p,pk}$	202	NMFS 2018
			$SEL_{cum, HF}$	155	
	TTS		$L_{p,pk}$	196	
			$SEL_{cum, HF}$	140	
	Disturbance		SEL_{SS}	140	Dähne *et al*. 2013
		20 km for 24 hrs	-		Tougaard & Michaelsen 2018
Harbour porpoise	PTS		SEL_{cum}	190	Danish Energy Agency 2016
	TTS			175	
Fish, Adults	Mortal injury		$L_{p,pk}$	207	Andersson *et al*. 2016
			SEL_{cum}	204	
	Recoverable injury		$L_{p,pk}$	207	Popper *et al*. 2014
			SEL_{cum}	203	
	TTS		SEL_{cum}	185	
Fish eggs and larvae	Mortal injury		$L_{p,pk}$	217	Andersson *et al*. 2016
			SEL_{cum}	207	

6.3 Model description

The (standard-) model of the *itap GmbH* is an empirical model, i. e. it is based on measured values for the Sound Exposure Level (SEL) and for the Peak Sound Pressure Level ($L_{p,pk}$) of previous projects. Therefore, this sort of model is an "adaptive" model, which becomes more "precise" with increasing input data.

The emitted sound level depends on many different factors, such as e. g. wall thickness, blow energy, diameter and soil composition (soil resistance) and water depth. But since all parameters mentioned might interact with each other, it is not possible to make exact statements on the impact of a single parameter. In a first step, only one parameter, the "pile diameter", is considered.

Figure 7 shows sound levels measured during pile-driving construction works at a number of windfarms plotted over the input parameter "pile diameter". The bigger the sound-emitting surface in the water, the bigger also the sound entry. This means, the evaluation-relevant level values increase with increasing pile surface, thus the diameter of the pile. It should also be noted that the relationship is not linear.

The model uncertainty is ± 5 dB, just taking into account the input parameter „pile diameter", and is based on the scatter of the actual existing measuring results from Figure 7 that is probably due to further influencing factors, such as e. g. blow energy and reflecting pile skin surface.

The following comparison between the predicted values and the actually later measured level values was covered adequately in any case by the specified model uncertainty (± 5 dB). In most cases, the model slightly overestimated the level value in 750 m distance (not published data). Therefore, an application in the present case is possible from a practical point of view. So the model is likely to be conservative.

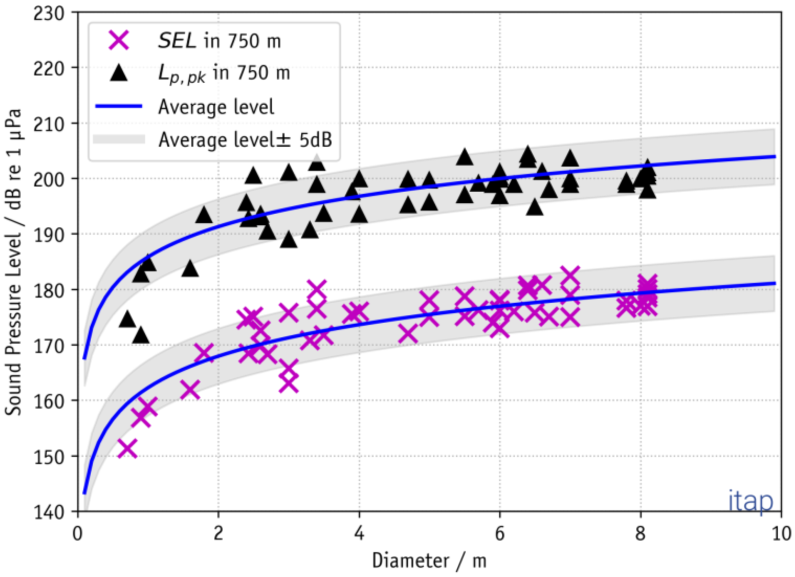


Figure 7: *Measured Peak Sound Pressure Level ($L_{p,pk}$) and broad-band Sound Exposure Levels (SEL_{05}) at pile-driving construction works at a number of OWFs as function of the pile diameter.*

Moreover, in this model, additions resp. deductions for very high and very low maximum blow energies are used in a second step. Considering the actually applied maximum blow energy resp. the maximum blow energy estimated in the model, normally, differences between the model and the real measuring values of about 2 dB were obtained. In the majority of cases, the model slightly overestimated the level value at a distance of 750 m with the input data "pile diameter" and "maximum blow energy".

Within the scope of a master's thesis at the *itap GmbH*, it it was established, that the impact of the blow energy used is on average about 2.5 dB per duplication of blow energy (Gündert, 2014). This finding resulted from investigations at different foundations, at which the variations of the blow energy during pile-driving (penetration depth) were statistically compared to corresponding level changes (each from soft-start to maximum blow energy).

Therefore, this additional module for the existing model of the *itap GmbH* is able to predict the evaluation-relevant level values for each single blow with given courses of blow energy. The model uncertainty of this statistic model (*itap GmbH* basic model + extension) is verifiably ± 2 dB; a slight overestimation of this model could be proven as well.

Gündert (2014) shows that the blow energies used and the penetration depth influence the resulting sound pollution significantly with a significant correlation of penetration depth and blow energy used. Considering the influencing factors "pile diameter", "maximum blow energy" and "penetration depth", a model uncertainty of ± 2 dB in the range of measurement inaccuracy could be achieved. The biggest amount of the measured variances could thus be traced back to the three influencing factors mentioned above.

Since an exact modeling of the blow energy to be applied over the entire penetration depth (per blow) is not possible without further “uncertainties”, additions and deductions for the maximum blow energy are considered.

Based on experiences of the last few years and the findings from the master’s thesis, it can be assumed, that the model uncertainty can be minimized significantly in due consideration of the above mentioned additions and deductions.

6.4 Determination of the source and propagation level

The Sound Exposure Level (SEL) varies in the course of a pile-driving and depends on, as mentioned before, several parameters (e. g. reflecting pile skin surface, blow energy, soil conditions, wall thickness, etc.). The applied model just considers the pile diameter as influencing parameter in a first step. To get a statistically valid result of the loudest expected blows, the empirical model for this model is based on the 95 % percentiles of the Sound Exposure Level (SEL) during one pile installation.

6.4.1 Blow energy

The evaluation-relevant level values (Sound Exposure Level and Peak Level) increase with growing blow energy. Based on the experiences of previous construction projects, a starting point for the determination of the influence parameter “maximum blow energy” is assumed. Assuming this, additions resp. deductions of 2.5 dB per doubling/halving for higher resp. lower maximum blow energies are estimated in the model.

6.4.2 Hydro hammer

Currently, the influence of different hydro hammer types are not taken into account, since too many influencing parameters and factors exist, e. g. anvil design, contact area between hammer and pile, pile-gripper or pile-guiding frame. Theoretical studies point out that the influence of different hammer types could be in a range of 0 dB to max. 3 dB. Additionally, no valid empirical data regarding different hammer types currently exist. Therefore, the *itap* model is focusing on the worst case (loudest possible) scenario. In case new and statistically valid results for the influencing factor hammer type will be available within the project duration, these findings will be taken into account.

6.4.3 Ground couplings

The influence of different ground conditions is currently still subject to research. However, it can be assumed, that the used blow energy will also increase with growing soil resistance (SRD-value) of a soil layer. As in the construction field there is a sandy underground and the measurement data shown in chapter 6.3 Figure 7 were largely determined on sandy and medium-tight, argillaceous underground, it can be assumed, that the sound emissions to be expected are the same as the regression line shown in Figure 7. For this reason, in the model, a frequency-independent safety margin for the soil conditions (ground coupling) is not necessary.

6.4.4 Spectrum of piling noise

The estimations of the broad-band Sound Exposure Level (SEL)- and Peak Sound Pressure Level ($L_{p,pk}$)-value shown in chapter 8.1 below are based on the broad-band measuring data of different studies (Figure 7). However, sound propagation in the sea is highly frequency-dependent; see chapter 6.1. For this reason, estimations of the frequency composition of the respective source levels[2] have to be made for the calculations.

Figure 8 shows the spectral distribution of the Sound Exposure Levels (SEL), which have been determined during pile-driving works at different piles (gray lines). The spectra determined at different distances as well as at different blow energies and pile diameters run similarly. The frequency spectrum shows a maximum within the range 160-250 Hz. At frequencies above approx. 250 Hz the level decrease gradually, while for frequencies lower than approx. 60 Hz, a steep decrease in levels is observed. The cutoff frequency for the steeply fall off at low frequencies depends on water depth. The deeper the water, the lower the cutoff frequency. For the water depths in the project area between 20 m and 26 m, the cutoff frequency will be within 32 Hz and 42 Hz.

From measurements collected over the last two years, it has become apparent, that the pile hammer type as well as the pile diameter can have an influence on the piling noise spectrum to be expected. By trend, the local maximum shifts in case of larger pile hammer types and

[2] "Source level" means the Sound Exposure Level (SEL) or Peak Level at a fictive distance 750 m to an imagined point source of sound.

larger pile diameters to lower frequencies. At present, however, these influencing factors cannot be estimated with statistical validity.

In detail, the spectral course of a piling noise event is not exactly predictable according to the present state of knowledge. Thus, for the modelling, an idealized model spectrum for the Sound Exposure Level will be extracted from the measured data of comparable construction projects. The shape of this idealized 1/3-octave-spectrum is shown in Figure 8 in red colour. The frequency-dependent amplitudes are measured in a way that the sum level of this spectrum in 750 m distance corresponds to the source levels determined before. Since 2016, the model of the *itap GmbH* calculates the evaluation-relevant level values on the measured Sound Exposure Level (5 % percentile level, SEL_{05}) and the Peak Level ($L_{p,pk}$).

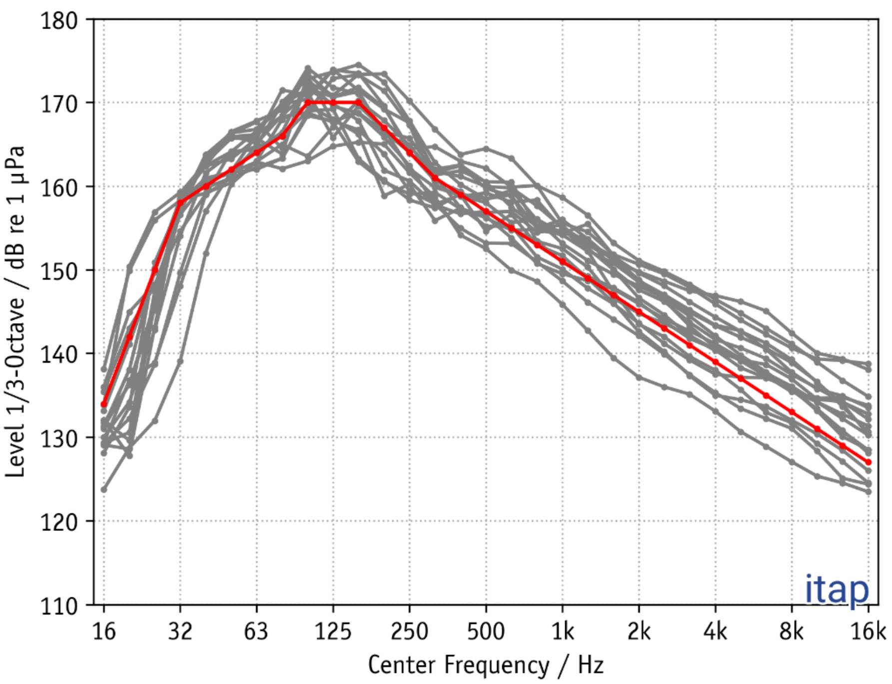


Figure 8: *The model spectrum (red) estimated for the prognosis of the piling noise, based on different measuring data (grey: measuring data) for monopiles.*

6.4.5 Water depth

Sound propagation in the sea is also influenced by the water depth. Below a certain cut-off frequency, however, a continuous sound propagation is not possible. The shallower the water, the higher this frequency is. Figure 5 in chapter 6.1 shows the cut-off frequencies for an undisturbed sound propagation. For the modeling, all frequencies below this cut-off frequency will decrease with 12 dB/octave. Decisive is the minimum water depth between source and receiver. The used bathymetry data were provided from EMODnet. The water depth in the project area is between 20.37 m and 25.44 m. This results to cut-off frequencies of 41 Hz for 20.31 m and 33 Hz for 25.44 m.

6.4.6 Transmission loss

For modeling, equation no. 10 is considered. Equation no. 10 shows a high level of agreement with the measurements in the Vesterhav Nord project area (Betke & Matuschek, 2017) and also takes account of the absorption in water. The impact of the absorption parameter α is increasing with the distance, so it becomes more relevant for larger distances. By modeling the transmission loss via such a propagation function, a plain wave in water is assumed. This is only the case in a few meters distance from the pile, when the directly emitted sound from the pile is superimposed with the first reflections from water surface and sediment. Below 50 m from the pile no plain wave field has formed within the water column, the noise level will be below the level calculated with equation no. 10. In the model the noise level will be constant over the first 50 m from the pile.

For the considered piling sequence (see Table 1) and a fleeing speed of 1.5 m/s, the SEL_{cum} increases by 1.3 dB by setting the α – parameter from 0 to 0.00027 assuming 1,300 m start distance. For 200 m start distance the difference will 0.6 dB. The cumulative Sound Exposure Level (SEL_{cum}) increases by $\leq$ 0.2 dB by considering a k term of 14.72 instead 14.4 for both start distances.

6.4.7 Model requirements

The empirical pile-driving model fulfill the national guidelines from regulators in Germany (BSH, 2013) and Denmark (Danish Energy Agency, 2016) for pile-driving predictions including required outputs. International guidelines or standards do not exist today. Other nations do also not have fixed guidance for the predictions; typically, the requirements on the predictions will be defined separately for each construction project. This model has already been applied in other countries, like Germany, Denmark, Netherlands, United Kingdom, Belgium, France, USA, Australia and Taiwan.

6.5 Calculation procedure

In the following subsections, the different calculation procedures/steps and sub-model runs are described in detail.

6.5.1 Step 1: Peak Level and broad-band Sound Exposure Level at 750 m

The *itap* model predicts the Sound Exposure Level (SEL) and the Peak Level ($L_{p,pk}$) based on the empirical data base in a specified distance of 750 m distance to the source after the requirements of the German measurement guidance (BSH, 2011) and the international standard (ISO 18406). The model results depends on the following parameter:

(i) the pile diameter,
(ii) the maximum blow energy (worst-case-scenario),
(iii) the water depth and
(iv) the safety margins for e. g. coupling effects, acoustic connections (coupling effects) between pile and Jacket-structure.

6.5.2 Step 2: Frequency dependency of the source level and transmission loss

Estimations about the broad-band Sound Exposure Level (SEL) and the Peak Sound Pressure Level ($L_{p,pk}$) value are based on measured broad-band data from different studies. Sound propagation in the ocean, however, is frequency-dependent, as discussed in chapter 6.1.

The spectral approaches for the piling noise at 750 m will be determined from empirical data (see chapter 6.4.4) and an approach for the transmission loss (TL) will be defined. The selection of the spectral shape based on empirical data and the amplitude will be adapted to the predicted broad-band Sound Exposure Level (SEL). The Sound Exposure Level (SEL) is an energetic value, where the energy is distributed over different frequency windows. For a broad-band presentation, only one frequency window over the whole frequency domain is used. In contrast, the Peak Sound Pressure Level ($L_{p,pk}$) represented the maximum Sound Pressure during one blow, which is independent of the frequency. So the $L_{p,pk}$ is only a single-number value.

For the transmission loss a theoretical approach will be indentified, which was validated with existing measuring data form the project area.

6.5.3 Step 3: Cumulative SEL

The cumulative Sound Exposure Level (SEL_{cum}) is a value for the noise dose, a marine mammal (e. g. a harbor porpoise) is exposed to. This value is the sum of the energy of all blows for one single foundation a marine mammal is exposed to within 24 hours (National Marine Fisheries Service, 2018), moving with a constant speed, increasing its distance with e. g. 1.5 m/s (Danish Energy Agency, 2016). In order to determine the impact ranges for certain sensation level values, the cumulative Sound Exposure Level (SEL_{cum}) will be calculated as a function over the start distance.

To predict the cumulative Sound Exposure Level (SEL_{cum}), assumptions about the piling sequence have to be made. Therefore the piling sequence in chapter 2 will be considered. This sequence represents a conservative scenario considering a very fast ramp up compared to actual installations and the maximum possible blow energy over all 6500 blows. The installations will not apply 100% hammer energy for 6500 blows in reality.

6.5.4 Step 4: Impact ranges

For the Threshold Level listed in Table 2 chapter 6.2 impact ranges will be calculated where these level are reached. All calculations will be done in 1/3 octave frequency resolution, considering these acoustic filters (according to MNFS, 2018, see Figure 6 chapter 6.2) in frequency domain. The cumulative Sound Exposure Level (SEL_{cum}) represents not a distance. The impact distances refer to the distance from the pile at which the animal risk PTS when moving at a constant speed of 1.5 m/s away from the pile during the installation.

6.5.5 Step 5: Noise maps

Based on the source level and defined transmission loss approaches, the specified noise metrics will be calculated as a function of distance and direction. In case of cumulative Sound Exposure Level (SEL_{cum}) the distance refers to the start distance. The results will be plotted in coloured noise maps.

The key output will be coloured noise maps for the NMFS weighted or unweighted Sound Exposure Level (SEL) as well as approximations of the distances, in which the defined SEL- or Peak Sound Pressure Level ($L_{p,pk}$) will be predicted.

6.6 Possible sources of error

Both, the modelling of "source strength" or "source level" of the pile-driving sound and the pile-driving analysis for the determination of the maximum blow energies as well as the modeling of sound propagation under water (for instance the transmission loss according to Danish Energy Agency (2016) or Thiele & Schellstede; chapter 6.1) involve a certain degree of uncertainty and thereby the derivative of calculated/predicted level values as well as their effect radian.

Measurements from completed construction projects (unpublished data from the construction monitoring in 2010 to 2018 by the *itap GmbH*) with large monopiles show, that the measured SEL at the end of the pile-driving sequence stays constant or decreases by up to 25 % despite an increase of the blow energy, i. e. it does not increase. One possible explanatory approach for this is the high penetration depth of the monopiles and the resulting elevated stiffness of the pile to be driven.

Occasionally, however, the Sound Exposure Levels steadily increased until the maximum penetration depth was reached (at simultaneous increase of the blow energy). This is why always the maximum blow energy is applied for all calculations.

By determining the source level just with the input parameter "pile diameter", an uncertainty of +/- 5 dB arises (Figure 7). In step 2, assumptions for the second relevant effective parameter "maximum blow energy" are made and additions and deductions are considered based on an initial value.

By considering the effective parameter "maximum blow energy" the uncertainty is clearly reduced. The comparison of the prognosis with real measuring data from 2012 until now shows an uncertainty of ± 2 dB (not published data from different projects) for the Sound Exposure Level in a distance of 750 m to the piling event with the tendency, that the prognosis model with the input data "pile diameter" and "maximum blow energy" slightly overestimates the level values in most cases.

7. Modelling scenarios

7.1 Existing conditions

The water depths in the project area varies between 20.37 m and 25.44 m (DVR90). The model will be performed for the three locations with the maximum water depths see Table 3. At these locations the highest noise level are expected since the parameter with the highest impact, the pile diameter as well and conservative piling sequence for this model, are the same for all foundations and the only varying parameter is the water depth. The sediment layer will be considered as described in Figure 2 chapter 2. Differences in soil resistance (SRD-value) of the soil layer also result in different blow energies which are taken into account in the model by considering a conservative piling sequence. Further significant impacts of the sediment are not to be expected for the existing sediment layer.

For the project area a good intermixing of the water without a distinct sound velocity profile can be assumed. This leads to a constant sound velocity over the whole water depth (see salinity forcast on www.fcoo.dk). For the model an average sound velocity of 1,480 m/s is assumed. The sound velocity in water depends on salinity and temperature and has a minor impact to the cutoff-frequency caused by water depth (Urick, 1983; Jensen *et al.*, 2010).

The model do not consider any background level. Especially when considering a scenario including a mitigation system some results can be below the background level. During the Transmission Loss Measurements (Betke & Matuschek, 2017) the background level was below 100 dB in intervals without disturbance of the seismic survey vessel and the vessel used to deploy the hydrophones.

Table 3: *Coordinates and water depth for considered turbine positions in Vesterhav Syd Offshore Wind Farm.*

Name	Location (WGS 84)	Water depth [m]
VHS 12	56° 4,169′ N 007° 57,215′ E	25.44
VHS 13	56° 3,799′ N 007° 57,217′ E	24.31
VHS 15	56° 3,061′ N 007° 57,219′ E	24.19

7.2 Acoustically relevant input data

The following input data will be considered for the model:

Input data for the foundations

- Foundation type:	monopile,
- Pile diameter:	7 m,
- Water depth:	between 20.37 m and 25.44 m, for the noise maps the bathymetry provided from EMODDnet is considered
- Water condition:	good intermixing of the water without a distinct sound velocity profile,
- Maximum blow energy:	3,000 kJ.

Model assumption to calculate the source level:

- Input parameter #1:	pile diameter,
- Input parameter #2:	blow energy: initial value (model internal parameter) 2,400 kJ; 2.5 dB addition or deduction per duplication or halving of blow energy,
- Soil conditions:	no additions,
- Pile surface:	decreasing, no additions or deductions,
- Penetration depth:	no additions or deductions (see possible impact in chapter 6.4.3),
- Transmission loss:	site specific transmission according to equation no. 10.

8. Modeling Results

8.1 Calculated Level Values

Considering the model approaches in chapter 6 and the piling sequence described in chapter 4, the following levels are expected in 750 m distance (Table 4 and Table 5 and Figure 9 to Figure 11) for all the locations. The main difference between the three locations is the water depth. The resulting cutoff frequencies for low frequencies caused by water depth differ by 2 Hz. At VHS 12 is the cutoff frequency 33 Hz at VHS 15 35 Hz. So the difference is no longer representable within a 1/3 octave accuracy. A distinction between the foundations can be omitted in the following. The expected Sound Exposure Level (SEL) over the time is presented in Figure 9. Figure 10 shows the calculated Sound Exposure Level (SEL) using 3,000 kJ blow energy as a function over the distance. In the noise map below the unweighted cumulative Sound Exposure Level (SEL_{cum}) is given for location VHS12 as an example. The areas for different SEL values are shown in different colours. The Noise Maps for all scenarios are attached in the Annex.

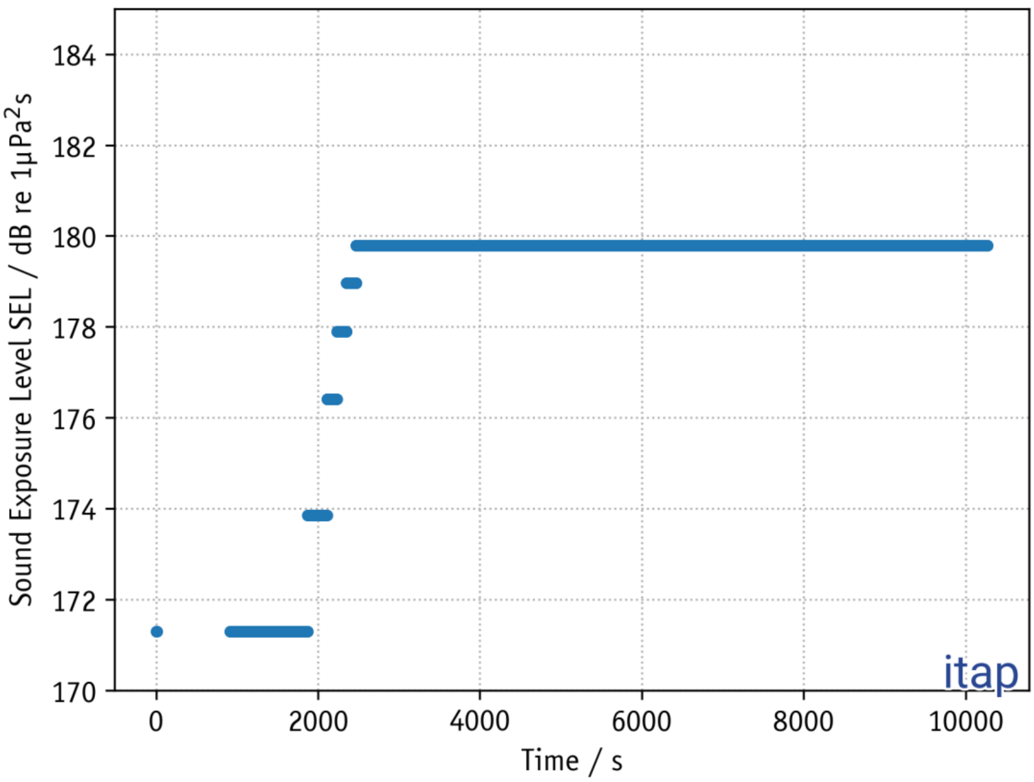


Figure 9: *Expected Sound Exposure Level (SEL) in 750 m distance to the pile for the location VHS12, VHS13 and VHS15.*

Table 4: *Calculated level of the Sound Exposure Level (SEL) and the peak Level ($L_{p,pk}$) in 1 m and 750 m distance for different weightings.*

MNFS weighting	SEL in 1 m distance	$L_{p,pk}$ in 1 m distance	SEL in 750 m distance	$L_{p,pk}$ in 750 m distance
No	222	245	180	203
Mid frequency cetaceans	184	245	141	203
High frequency cetaceans	179	245	137	203
phocid seals	203	245	161	203

Table 5. *The cumulative Sound Exposure Level for different receptors.*

Receptor	MNFS weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
Phocid seals	PW	200	1.5	183
Mid-frequency cetaceans	MF	1.300	1.5	162
High-frequency cetaceans	HF	1.300	1.5	157
Harbour porpoise	No	1.300	1.5	200
Adult Cod	No	1	0.9	206
Juveline Cod	No	1	0.38	212
Herring	No	1	1.04	205
Fish eggs and larvae	No	1	0	236

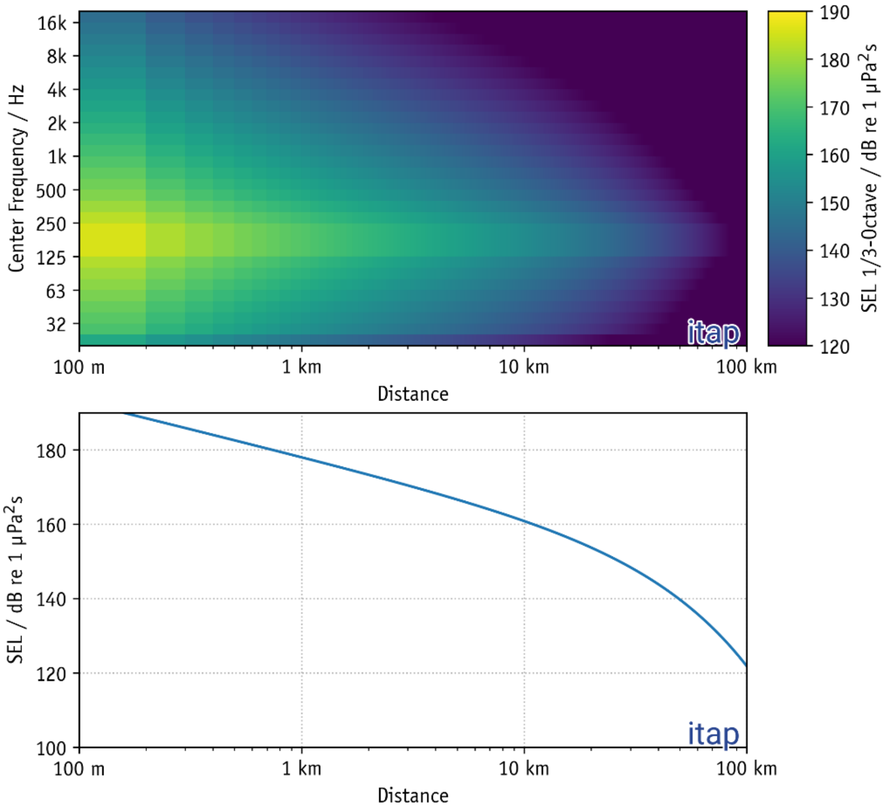


Figure 10: *Predicted SEL (unweighted) of sounds due to driving monopiles with a diameter of 7 m at maximum blow energy of 3,000 kJ as function of distance. The spectrogram on top shows the SEL divided in 1/3-octave components. On the y-axis the frequency is listed and on the x-axis the distance is shown. The value of the unweighted SEL in every 1/3 octave band is marked by different colours, yellow for high levels and blue for low levels. The diagram below shows the broad-band values SEL.*

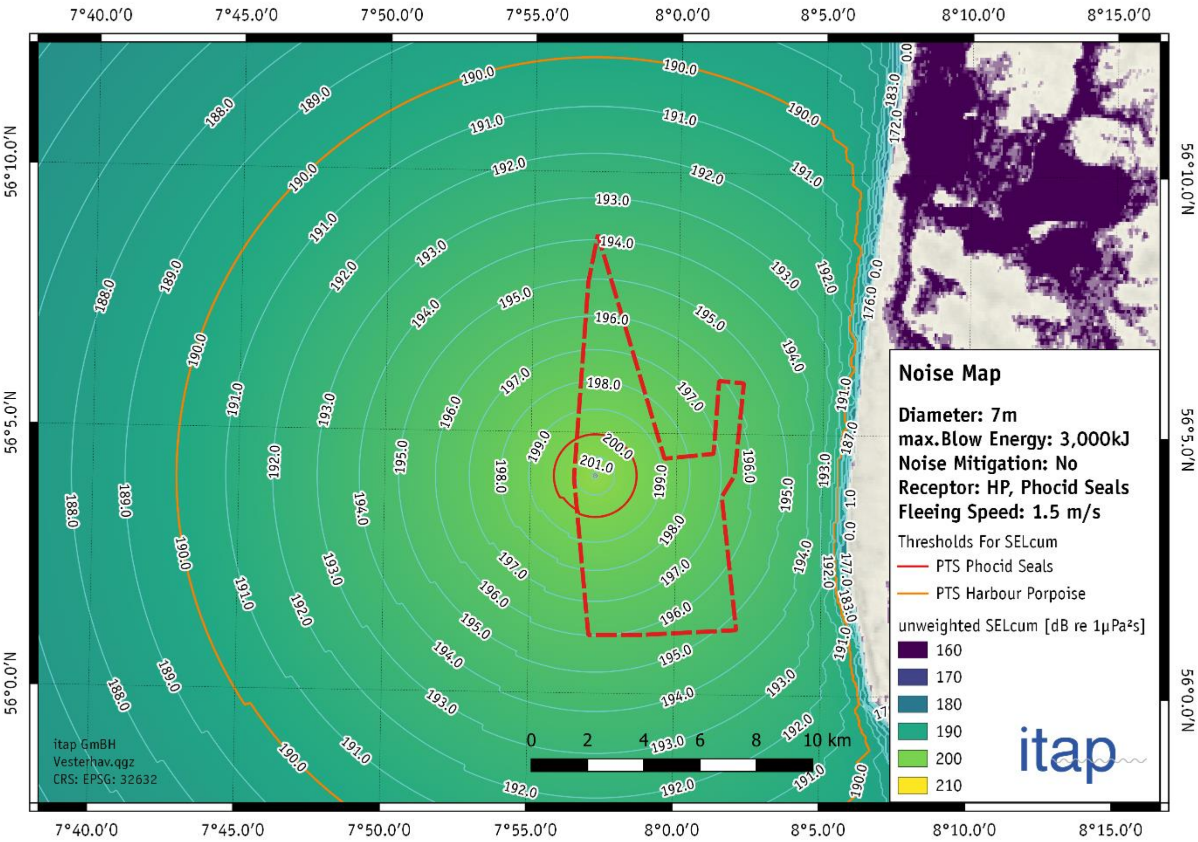


Figure 11: *Noise map for the unweighted SEL_{cum} during the installation of the 7 m monopile foundation at VHS12 with a maximum blow energy of 3,000 kJ.*

8.2 Distances to threshold level

For the threshold levels in chapter 6.2, the following impact ranges are expected in which these values are reached. In Table 7 the exceedance of the threshold level for each receptor is presented.

Table 6: *Distance to thresholds.*

Receptor	Impact type	metric	Criteria [dB]	Range [km] No NMS
Phocid seals	PTS	$L_{p,pk}$	218	0.002
1.5 m/s fleeing speed		SEL_{cum}	200	1.517
		$SEL_{cum, mpw}$	185	0.021
	TTS	$L_{p,pk}$	212	0.005
		SEL_{cum}	176	46.271
		$SEL_{cum, mpw}$	170	16.915
	Disturbance	SEL	142	44.188
Mid-frequency cetaceans	PTS	$L_{p,pk}$	230	0.011
1.5 m/s fleeing speed		$SEL_{cum, mmf}$	185	-
	TTS	$L_{p,pk}$	224	0.028
		$SEL_{cum, mmf}$	170	0.004
High-frequency cetaceans	PTS	$L_{p,pk}$	202	0.838
1.5 m/s fleeing speed		$SEL_{cum, mhf}$	155	3.199
	TTS	$L_{p,pk}$	196	2.037
		$SEL_{cum, mhf}$	140	28.778
	Disturbance	SEL	140	49.1
Harbour porpoise	PTS	SEL_{cum}	190	14.987
1.5 m/s fleeing speed	TTS	SEL_{cum}	175	48.868
Adult Cod	Mortal injury	$L_{p,pk}$	207	0.391
0.9 m/s fleeing speed		SEL_{cum}	204	1.004
	Recoverable injury	$L_{p,pk}$	207	0.391
		SEL_{cum}	203	1.638
	TTS	SEL_{cum}	185	28.116
Juveline Cod	Mortal injury	$L_{p,pk}$	207	0.391
0.38 m/s fleeing speed		SEL_{cum}	204	3.389
	Recoverable injury	$L_{p,pk}$	207	0.391
		SEL_{cum}	203	4.109
	TTS	SEL_{cum}	185	31.119
Herring	Mortal injury	$L_{p,pk}$	207	0.391
1.04 m/s fleeing speed		SEL_{cum}	204	0.473
	Recoverable injury	$L_{p,pk}$	207	0.391
		SEL_{cum}	203	1.069
	TTS	SEL_{cum}	185	27.338
Fish eggs and larvae	Mortal injury	$L_{p,pk}$	217	0.083
0 m/s fleeing speed		SEL_{cum}	207	3.749

Table 7: *Exceedance of threshold level for different receptor.*

Receptor	Impact type	metric	Criteria [dB]	Level [dB]	Exceedance [dB]
Phocid seals	PTS	$L_{p,pk}$	218	211	-
1.5 m/s fleeing speed		SEL_{cum}	200	200	-
		$SEL_{cum,\ mpw}$	185	183	-
	TTS	$L_{p,pk}$	212	211	-
		SEL_{cum}	176	200	24
		$SEL_{cum,\ mpw}$	170	183	13
	Disturbance	SEL	142	188	46
Mid-frequency cetaceans	PTS	$L_{p,pk}$	230	199	-
1.5 m/s fleeing speed		$SEL_{cum,\ mmf}$	185	162	-
	TTS	$L_{p,pk}$	224	199	-
		$SEL_{cum,\ mmf}$	170	162	-
High-frequency cetaceans	PTS	$L_{p,pk}$	202	199	-
1.5 m/s fleeing speed		$SEL_{cum,\ mhf}$	155	157	2
	TTS	$L_{p,pk}$	196	199	3
		$SEL_{cum,\ mhf}$	140	157	17
	Disturbance	SEL	140	176	36
Harbour porpoise	PTS	SEL_{cum}	190	200	10
1.5 m/s fleeing speed	TTS	SEL_{cum}	175	200	25
Adult Cod	Mortal injury	$L_{p,pk}$	207	220	13
0.9 m/s fleeing speed		SEL_{cum}	204	206	2
	Recoverable injury	$L_{p,pk}$	207	220	13
		SEL_{cum}	203	206	3
	TTS	SEL_{cum}	185	206	21
Juveline Cod	Mortal injury	$L_{p,pk}$	207	220	13
0.38 m/s fleeing speed		SEL_{cum}	204	212	8
	Recoverable injury	$L_{p,pk}$	207	220	13
		SEL_{cum}	203	212	9
	TTS	SEL_{cum}	185	212	27
Herring	Mortal injury	$L_{p,pk}$	207	220	13
1.04 m/s fleeing speed		SEL_{cum}	204	205	1
	Recoverable injury	$L_{p,pk}$	207	220	13
		SEL_{cum}	203	205	2
	TTS	SEL_{cum}	207	205	-
Fish eggs and larvae	Mortal injury	$L_{p,pk}$	217	220	3
0.0 m/s fleeing speed		SEL_{cum}	207	236	29

9. Noise mitigation

The piling noise during installation has impacts on marine mammals. In order to reduce the impact ranges it is possible to prolong the ramp-up. Piling breaks at the beginning of piling will increase the distance of the animals to the pile for the following blows, so that that the impact to the cumulative Sound Exposure Level (SEL_{cum}) is decreasing. For example a break of 30 Minutes after the fifth blow within the considered piling sequence would lead to a 4 dB lower SEL_{cum} value for a Harbour porpoise starting at 1.300 m distance with a constant speed of 1.5 m/s. To archive noise reductions of 14 dB and more the use of noise mitigation systems is recommended.

At present, noise reductions for the SEL of up to 15 dB are possible by using a single noise mitigation system. By the combination of two noise mitigation systems, it was possible to achieve noise reductions of more than 20 dB in the past. All previously used noise mitigation systems show variances on average of ± 2 dB (Bellmann, 2014). This was found during a pile-driving at one location (usually several thousands of blows per location), as well as at the comparison of several locations with and without noise mitigation system.

Furthermore, the sound reduction of each noise mitigation system is highly frequency-dependent and thus, the resulting (broad-band) sound reduction depends on the spectral composition of the piling noise without the application of a noise mitigation measure.

One of the most practicable and most frequently used (> 600 applications) noise mitigation system is the double Big Bubble Curtain. Additionally, two funded RD-projects were conducted to understand the main influencing factors of a Big Bubble Curtain on the overall noise reduction (Nehls & Bellmann, 2015; Bellmann *et al.*, 2018).

At present, noise reductions for the unweighted Sound Exposure Level (SEL) and cumulative Sound Exposure Level (SEL_{cum}) of up to 18 dB (maximum measured noise reduction) are possible by using a "Double Big Bubble Curtain" (DBBC) in the North Sea at water depths to 40 m. The averaged noise reduction of an optimized DBBC mostly ranged between 15 dB and 16 dB. But the usage of single and double Big Bubble Curtains shows partly high variances in noise reduction (Bellmann, 2014; Bellmann *et al.*, 2018 and Bellmann *et al.*, 2015). The most variances could be traced back to technical problems or dysfunctions of the respective noise mitigation system or the application of not project-specific optimized system configurations of the applied BBC-system.

The noise reduction of bubble curtains is increasing with the frequency. Figure 12 shows the expected noise reduction considering the weighting functions according to the National Marine Fisheries Service (2018). The expected values presented in Figure 12 are theoretical values without considering the background level.

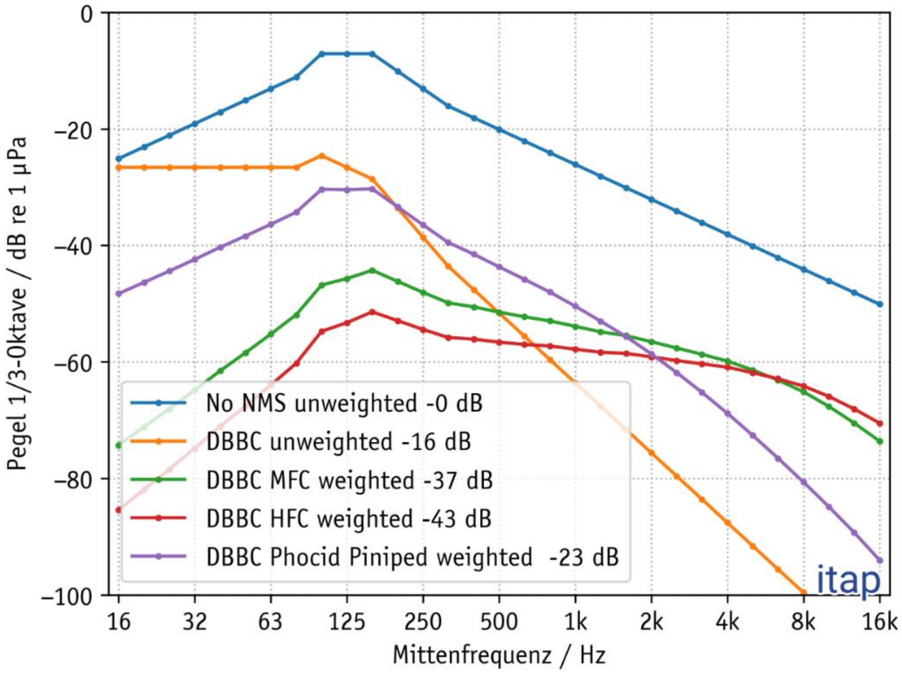


Figure 12: *Expected noise reduction of a double Big Bubble Curtian (DBBC) for different weighting functions.*

The noise reduction of Big Bubble Curtains depends on many factors like water depth, current, used hole configuration in the applied nozzle hoses on the seabed and compressed air supply. It is important to enhance the Big Bubble Curtain system configuration to the local project-specific conditions (Bellmann, *et al.*, 2018). Decisive for a successful application are:

(i) a sufficient amount of compressed air and
(ii) a complete wrapping of the pile by the bubble curtain.

The required air volume depends on the water depth due to the static pressure of the surrounding water. In the North Sea (where the most BBC applications took place), an applied air volume of $\geq$ 0.5 $m^3/(min*m)$ is currently state-of-the-art for water depths of up to 40 m. In order to enable a complete wrapping of the pile, a sufficient distance of the Big Bubble Curtain nozzle hoses to the pile is required. This distance depends on the local current and the water depth (drifting effects). Means by setting up the BBC system configuration, the water depth and the current, but also the type of installation vessel (DP, anchor moored floating vessel of jack-up barge) shall be considered by designing the overall length of the applied nozzle hoses and the layout shape used.

The physical and technical limitation of a nozzle hose with a diameter of typically 100 mm is an overall length for a single BBC of 1,000 m based on experiences and a flow-dynamic BBC model (Nehls & Bellmann, 2015).

Bigger diameters than 100 mm are currently under investigation to prolong the overall nozzle hose length and to increase the air volume, but no validated experiences with these new system configurations currently exist. Currently, the best practice is to use an elliptical layout shape of the nozzle hose to keep the length of the hoses as short as possible (< 1,000 m) and to provide a maximum air volume per meter nozzle hose by typically 20 to 24 compressors used for a double Big Bubble Curtain. The longer side of the elliptic shape is aligned in flow (current) direction.

Another important influencing factor on the overall noise reduction is the water depth. Furthermore, the sound reduction of each noise mitigation system is highly frequency-dependent and thus, the resulting (single-number) sound reduction depends on the spectral composition of the piling noise, without the application of a noise mitigation measure. By using $\geq 0.5\ m^3/(min*m)$, the resultant noise reduction increases by several decibels towards shallow water. Experiences with not optimized Big Bubble Curtain system configurations showed an influence of up to 3 dB between 40 m and 10 m water depth.

For illustrative purposes, the minimum DBBC system specifications from already closed pile-driving projects is listed (Bellmann *et al.*, 2018):

- hole size (diameter) and hole spacing: 1 – 2 mm every 20 – 30 cm,
- applied air volume: $\geq 0.5\ m^3/(min*m)$,
- distance of the nozzle hoses: $\geq$ a water depth between 1^{st} and 2^{nd} BBC,
- BBC shall surround the foundation structure completely and shall have a minimum distance to the structure of 30 to 40 m,
- typical nozzle hose diameter is currently 100 mm, which limits the overall length of a single BBC to 1,000 m due to air flow dynamic boundaries,
- regular maintenance of the applied nozzle hoses,
- no turbulence-producing obstacles in the nozzle hoses,
- the overall life-time of each nozzle hose is limited (currently best practice < 80 - 100 applications).

In order to comply with the Threshold level for permanent threshold shifts for marine mammals a minimum noise reduction of 10 dB is required (see Table 7). This noise reduction can be archived with different noise mitigation systems and combinations, see **Fehler! Ungültiger Eigenverweis auf Textmarke.**. For illustrative purposes a Big Bubble Curtain (BBC) with a minimum required noise mitigation of 10 dB has been considered for the modelled mitigated scenarios. The resulting impact ranges are compared with the impact ranges without noise mitigation in Table 9.

Table 8: *Summary of the available and assessed noise mitigation systems incl. the (broadband) insertion loss of the best available system configurations (based on Bellmann, 2014 with unpublished evaluation from projects between 2014 - 2018).*

No.	Noise Mitigation System	∆SEL [dB]
1	Single Big Bubble Curtain - BBC (> 0,3 m^3/(min*m), water depth < 25 m)	11 ≤ 14 ≤ 15
2	Double Big Bubble Curtain - DBBC (> 0,3 m^3/(min*m), water depth < 25 m)	14 ≤ 17 ≤ 18
3	Single Big Bubble Curtain - BBC (> 0,3 m^3/(min*m), water depth ~30 m)	8 ≤ 11 ≤ 14
4	Single Big Bubble Curtain - BBC (> 0,3 m^3/(min*m), water depth ~40 m)	7 ≤ 9 ≤ 11
5	Double Big Bubble Curtain - DBBC (> 0,3 m^3/(min*m), water depth ~ 40 m)	8 ≤ 11 ≤ 13
6	Double Big Bubble Curtain - DBBC (> 0,4 m^3/(min*m), water depth ~ 40 m)	12 ≤ 15 ≤ 18
7	Double Big Bubble Curtain - DBBC (> 0,5 m^3/(min*m), water depth > 40 m)	~ 15 – 16
8	IHC-NMS	10 ≤ 13 ≤ 17
9	Optimised BBC+ HSD (> 0,4 m^3/(min*m), water depth ~30 m)	15 ≤ 16 ≤ 20
10	Optimised DBBC + HSD (0,48 m^3/(min*m), water depth 20 to 40 m, Baltic Sea)	15 ≤ 23 ≤ 28
11	Optimised DBBC + HSD (> 0,5 m^3/(min*m), water depth < 45 m, North Sea)	~ 18 - 19
12	IHC-NMS + opt. single BBC (> 0,3 m^3/(min*m), water depth < 25 m)	17 ≤ 19 ≤ 23
13	IHC-NMS + opt. single BBC (> 0,4 m^3/(min*m), water depth ~ 40 m)	~ 17 - 18
14	IHC-NMS + opt. double BBC (DBBC) (> 0,5 m^3/(min*m), water depth ~ 40 m)	18 ≤ 19 ≤ 20

Table 9: *Comparision of impact ranges for different criteria using no noise mitigation (NMS) and a Big Bubble curtain. Please note that the model calculates the noise reduction of the Bubble Curtain (DBBC) from the first meter. In reality, the Bubble Curtains are laid at a distance of a few meters (typically between 80 m and*

150 m). If the presented ranges are smaller, the threshold is complied with the beginning of the Bubble Curtain.

Receptor	Impact type	metric	Criteria [dB]	Range [km]	
				No NMS	10 dB BBC
Phocid seals	PTS	$L_{p,pk}$	218	0.002	-
		SEL_{cum}	200	1.517	0.003
1.5 m/s fleeing speed		$SEL_{cum,\ mpw}$	185	0.021	-
	TTS	$L_{p,pk}$	212	0.005	-
		SEL_{cum}	176	46.271	22.105
		$SEL_{cum,\ mpw}$	170	16.915	0.019
	Disturbance	SEL	142	44.188	22.241
Mid-frequency cetaceans	PTS	$L_{p,pk}$	230	0.011	0.002
1.5 m/s fleeing speed		$SEL_{cum,\ mmf}$	185	0	0
	TTS	$L_{p,pk}$	224	0.028	0.006
		$SEL_{cum,\ mmf}$	170	0.004	-
High-frequency cetaceans	PTS	$L_{p,pk}$	202	0.838	0.172
1.5 m/s fleeing speed		$SEL_{cum,\ mhf}$	155	3.199	-
	TTS	$L_{p,pk}$	196	2.037	0.434
		$SEL_{cum,\ mhf}$	140	28.778	-
	Disturbance	SEL	140	49.1	25.975
Harbour porpoise	PTS	SEL_{cum}	190	14.987	1.256
1.5 m/s fleeing speed	TTS	SEL_{cum}	175	48.868	24.197
Adult Cod	Mortal injury	$L_{p,pk}$	207	0.391	0.079
0.9 m/s fleeing speed		SEL_{cum}	204	1.004	-
	Recoverable injury	$L_{p,pk}$	207	0.391	0.079
		SEL_{cum}	203	1.638	0.002
	TTS	SEL_{cum}	185	28.116	9.571
Juveline Cod	Mortal injury	$L_{p,pk}$	207	0.391	0.079
0.38 m/s fleeing speed		SEL_{cum}	204	3.389	0.004
	Recoverable injury	$L_{p,pk}$	207	0.391	0.079
		SEL_{cum}	203	4.109	0.007
	TTS	SEL_{cum}	185	31.119	12.418
Herring	Mortal injury	$L_{p,pk}$	207	0.391	0.079
1.04 m/s fleeing speed		SEL_{cum}	204	0.473	-
	Recoverable injury	$L_{p,pk}$	207	0.391	0.079
		SEL_{cum}	203	1.069	0.002
	TTS	SEL_{cum}	185	27.338	8.855
Fish eggs and larvae	Mortal injury	$L_{p,pk}$	217	0.083	0.017
0.0 m/s fleeing speed		SEL_{cum}	207	3.749	0.844

10. References

Andersson MH, Andersson S, Ahlsén J, Andersson BL, Hammar J, Persson LKG, Pihl J, Sigray P & Wikström A (2016) Underlag för reglering av undervattensljud vid pålning. Vindval rapport 6723, August 2016.

Danish Energy Agency (2016) Guideline for underwater noise – Installation of impact-driven piles. Energistyrelsen, Center for Energiressourcer, April 2016.

Dähne M, Gilles A, Lucke K *et al.* (2013) Effects of pile-driving on harbour porpoises (*Phocoena phocoena)* at the first offshore wind farm in Germany. Environmental Research Letters, 8: 025002.

National Marine Fisheries Service (2018) Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59, 167 p.

Nehls G & Bellmann M (2016) Weiterentwicklung und erprobung des „Grossen Blasenschleiers" zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten. ITAP.

Popper AN, Hawkins AD, Fay RR, Mann DA, Bartol S, Carlson TJ, Coombs S, Ellison WT, Gentry RL, Halvorsen MB, Løkkeborg S, Rogers PH, Southall BL, Zeddies DG & Tavolga WN (2014) Sound Exposure Guidelines for Fishes and Sea Turtles. ASA S3/SC1.4 TR-2014, SpringerBriefs in Oceanography, Acoustical Society of America 2014.

Russel DJF, Hastie GD, Thompson D, Janik VM, Hammond PS, Scott-Hayward LAS, Matthiopoulos J, Jones EL & McConnell BJ (2016) Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology, 53, 1642-1652.

Southall BL, Finneran JJ, Reichmuth C, Nachtigall PE, Ketten DR, Bowles AE, Ellison WT, Nowacek DP & Tyack PL (2019) Marine mammal noise exposure criteria: updated scientific recommendations for residual hearing effects. Aquatic Mammals, 45(2), 125-232.

Tougaard J & Michaelsen M (2018) Construction and operation of an offshore wind farm at Krieger´s Flak, Sweden. Scientific Report from DCE – Danish Centre for Environment and Energy, 2018.

Bellmann MA., Kühler R., Matuschek R., Müller M., Betke K., Schuckenbrock J., Gündert S. and Remmers P. (2018) Noise Mitigation for large foundations (Monopiles L & XL) – Technical options for complying with noise limits, presentation on the BfN Noise Mitigation Conference, November 22nd/23rd 2018 in Berlin.

Bellmann MA., Schuckenbrock J., Gündert S., Müller M., Holst H. & Remmers P. (2015) Is there a State-of-the-Art to reduce Pile-Driving Noise, proceeding book: Wind Energy and Wildlife Interaction (Presentations from the CWW2015 Conference, Editor Johann Köppel, ISBN978-3-319-51270-9, Springer Verlag, 2015

Bellmann, MA. (2014) Overview of existing Noise Mitigation Systems for reducing Pile-Driving Noise. Proceeding auf der Internoise 2014, Melbourne Australien.

BSH (2011) Messvorschrift für Unterwasserschallmessungen – Aktuelle Vorgehensweise mit Anmerkungen. Bericht im Rahmen des Forschungsvorhabens „Ökologische Begleitforschung am Offshore-Testfeldvorhaben Alpha Ventus zur Evaluierung des Standarduntersuchungskonzeptes des BSH (StUKplus)“, Förderkennzeichen 0327689A

BSH (2013) Offshore-Windparks – Prognosen für Unterwasserschall (Mindestmaß an Dokumentation. Bericht Nr. M100004/29 der Müller-BBM GmbH)

Diederichs A, Pehlke H, Nehls G, Bellmann M, Gerke P, Oldeland J, Grunau C & Witte S (2014) Entwicklung und Erprobung des „Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten (HYDROSCHALL OFF BW II), technischer Abschlussbericht, Förderkennzeichen 0325309 A/B/C.

Gündert S (2014) Empirische Prognosemodelle für Hydroschallimmissionen zum Schutz des Gehörs und der Gesundheit von Meeressäugern. Masterarbeit an der Universität Oldenburg, Institut für Physik, AG Akustik

ISO18406 (2017) Underwater acoustics – Measurement of radiated underwater sound from percussive pile driving

Jensen *et al.* (2010) Jensen FB, Kuperman WA, Porter MB und Schmidt H (2010): Computational Ocean Acoustics. Springer Verlag, AIP Press

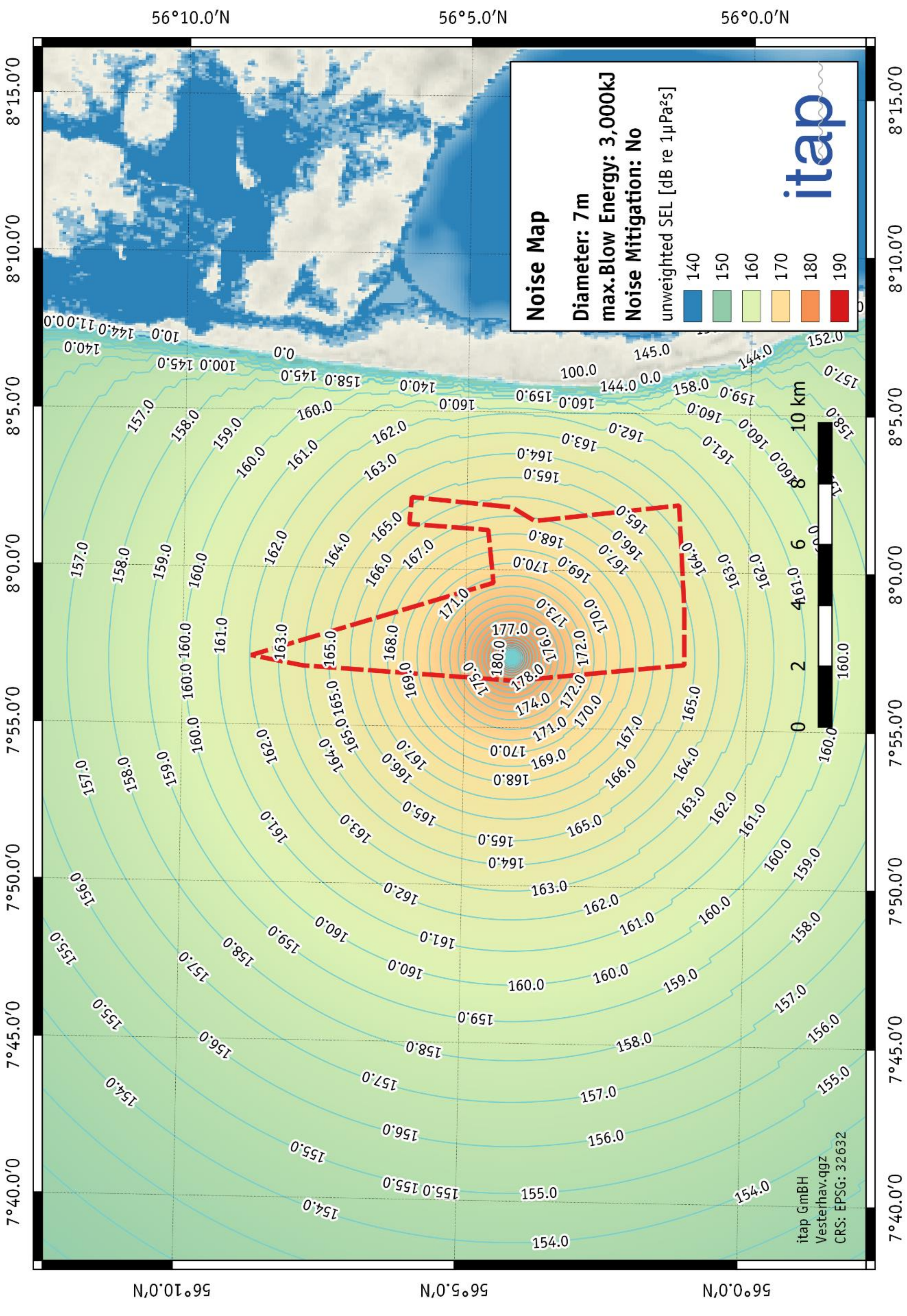
Nehls G & Bellmann MA (2015) Weiterentwicklung und Erprobung des „Großen Blasenschleiers“ zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten. Gefördert durch PTJ und BMWi, FKZ 0325645A/B/C/D (www.hydroschall.de).

Thiele & Schellstede (1980) Standardwerte zur Ausbreitungsdämpfung in der Nordsee. FWG-Bericht 1980-7, Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik

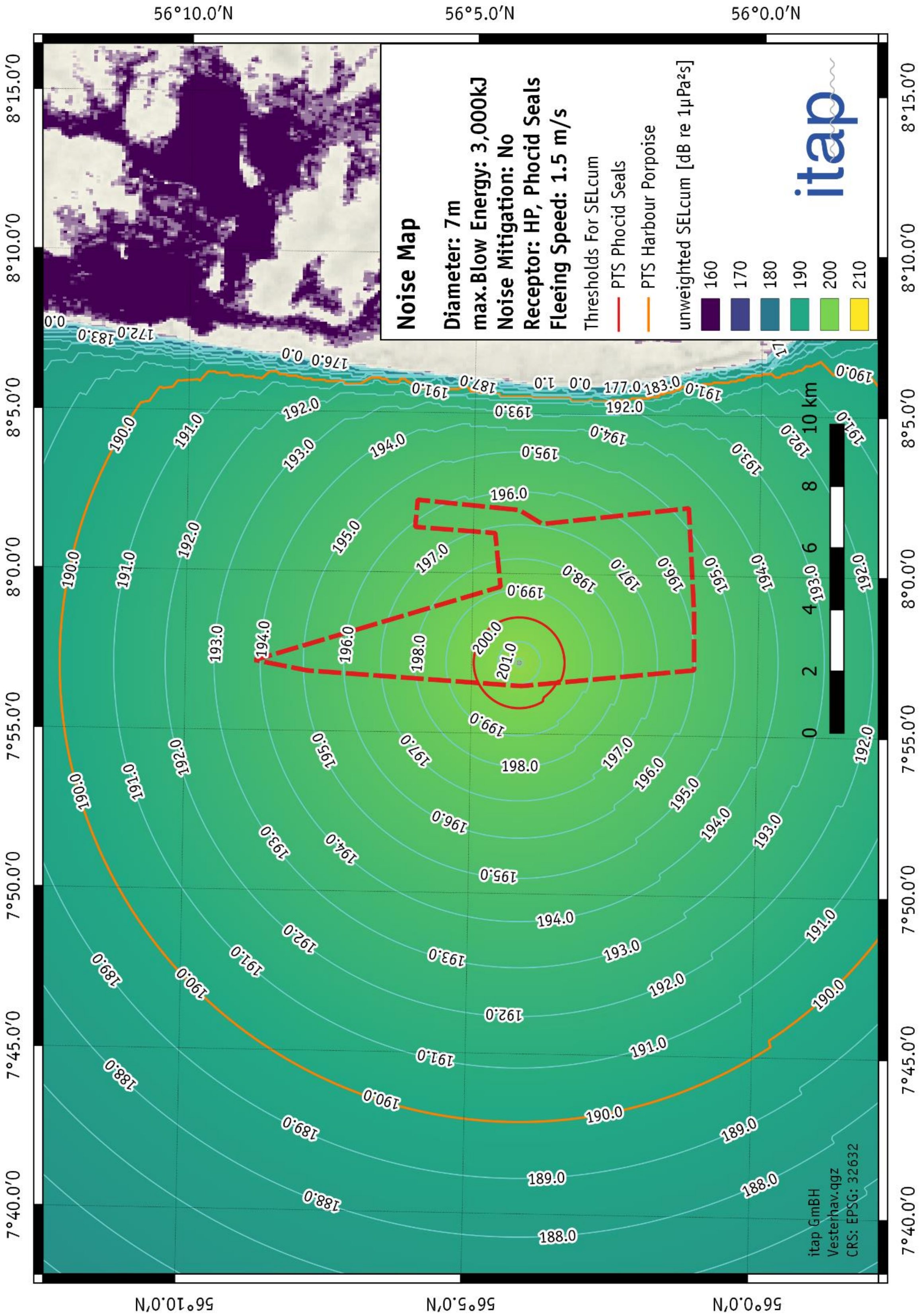
Urick (1983) Principles of underwater sound, 3rd ed. Pensinsula Publishing, Los Altos

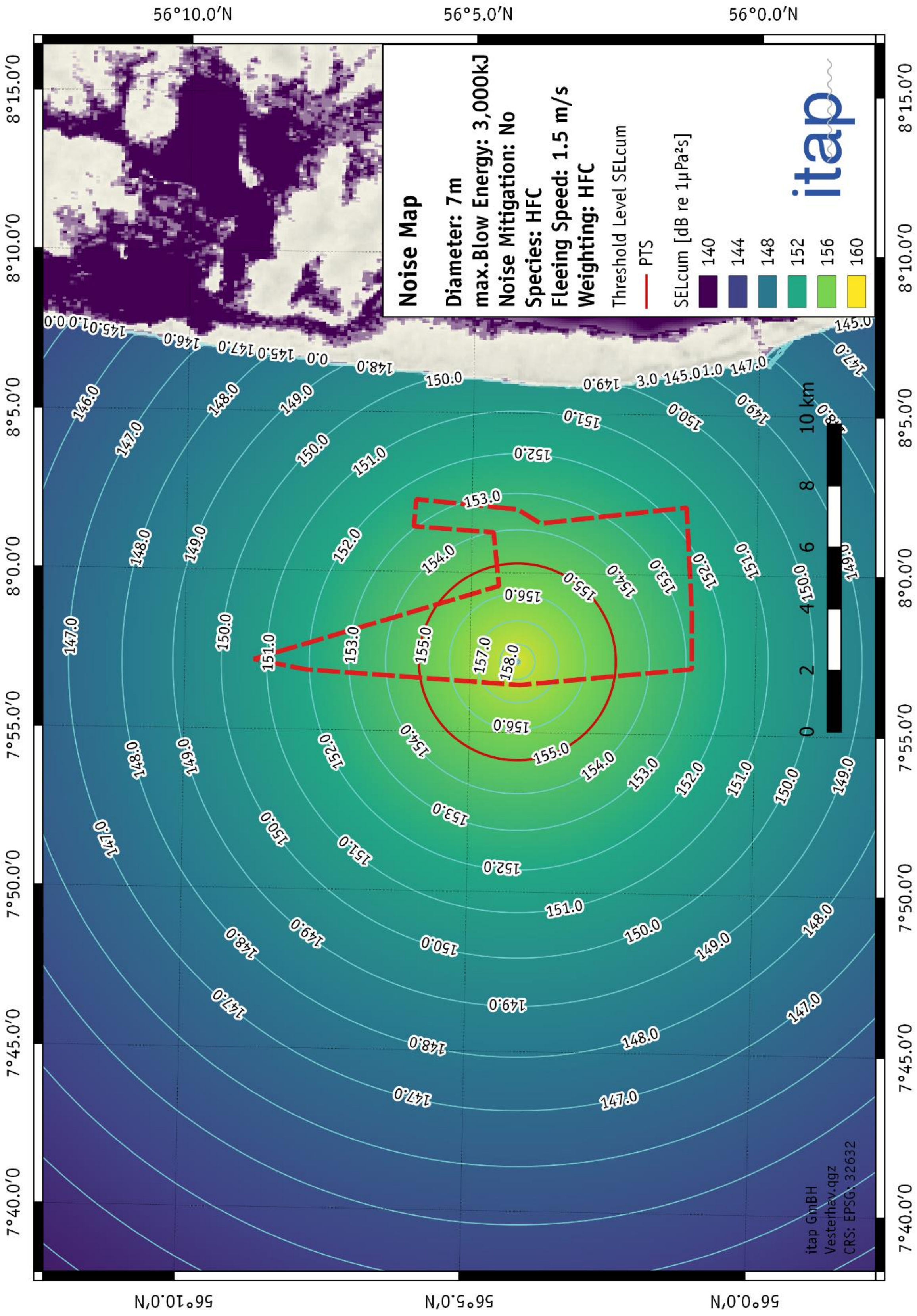
Annex

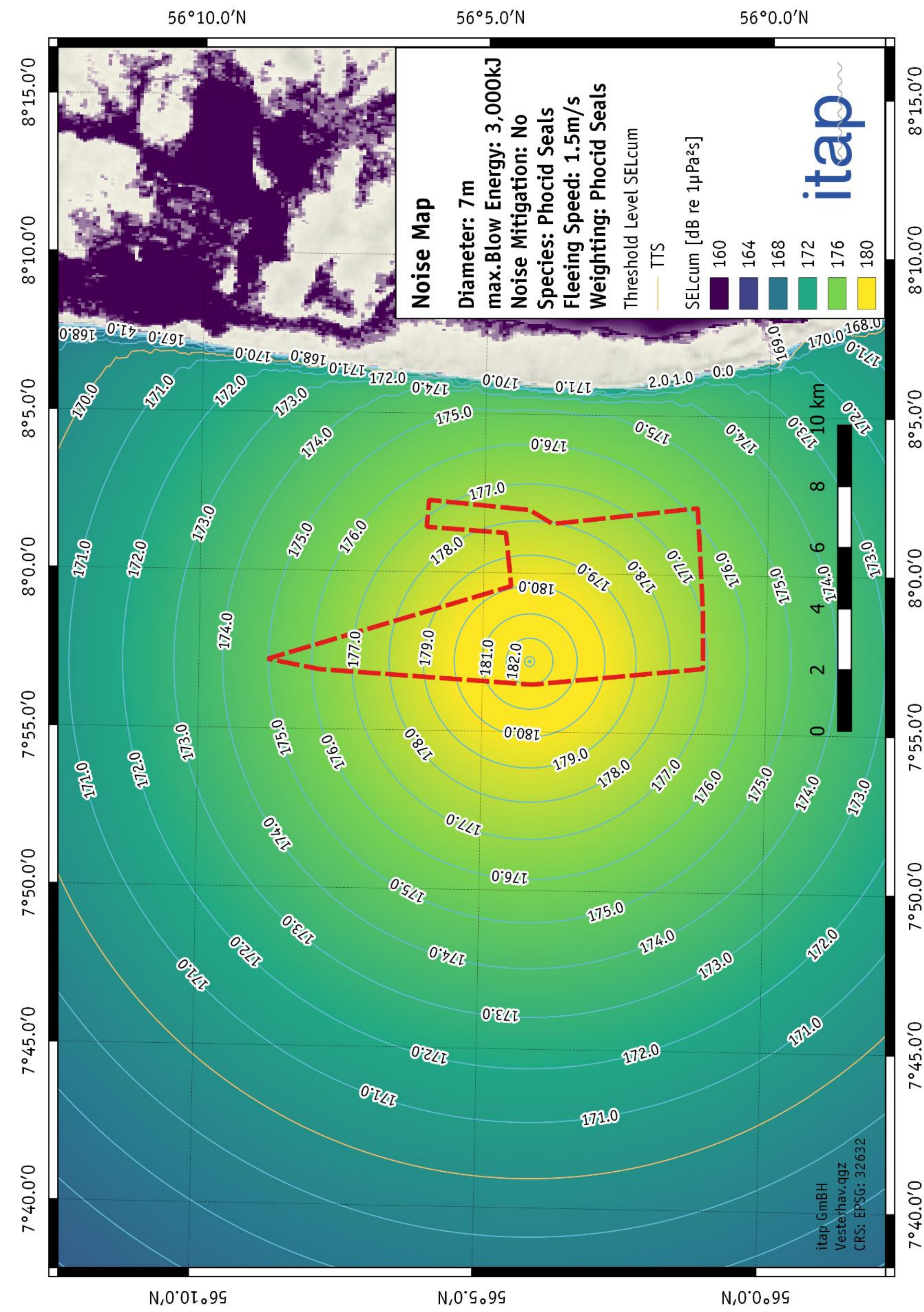
Noise Maps VHS12

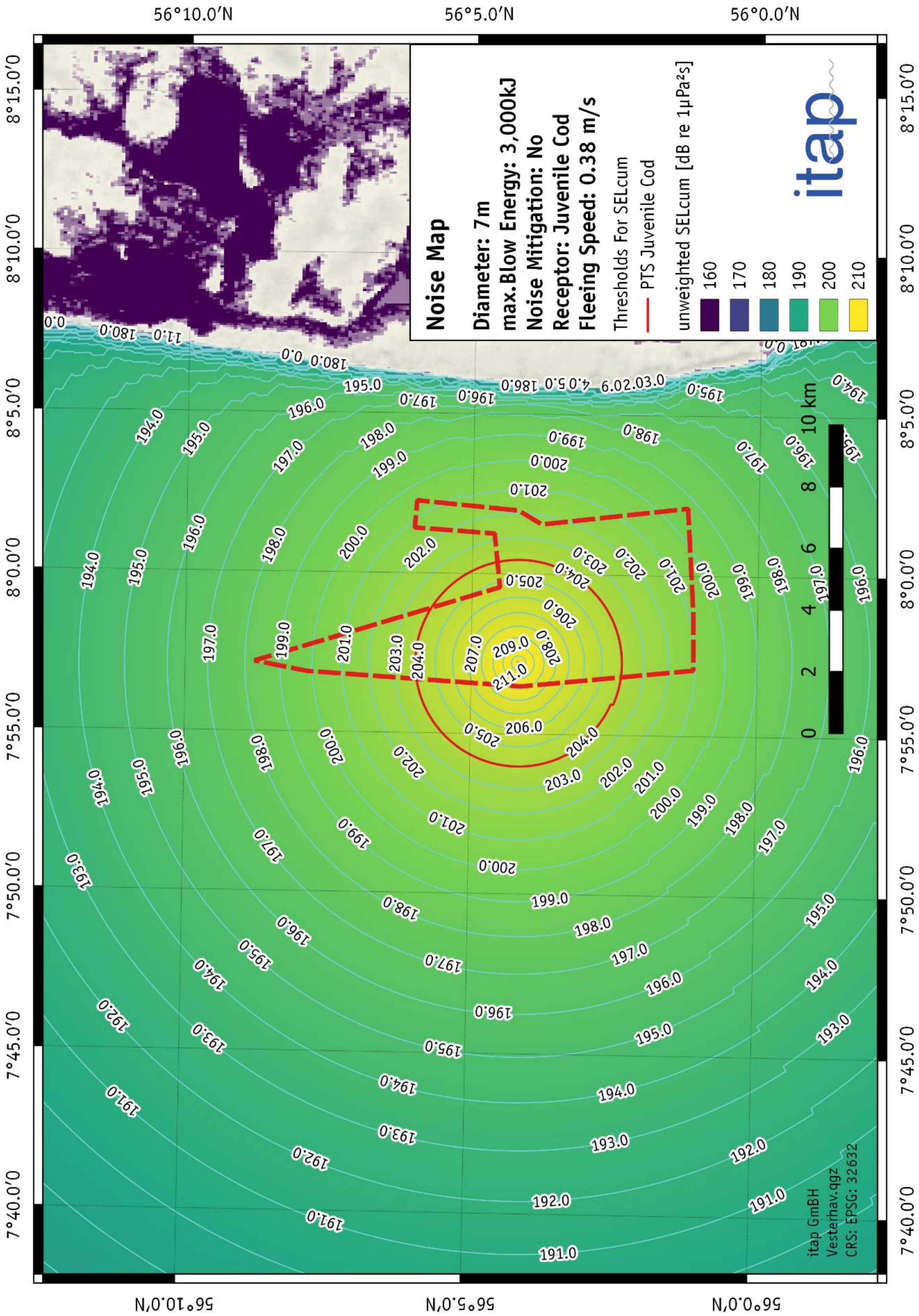


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
unweighted SEL [dB re 1µPa²s]
140
150
160
170
180
190
0 2 4 6 8 10 km
56°10.0'N
56°5.0'N
56°0.0'N
8°15.0'0
8°10.0'0
8°5.0'0
8°0.0'0
7°55.0'0
7°50.0'0
7°45.0'0
7°40.0'0
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632

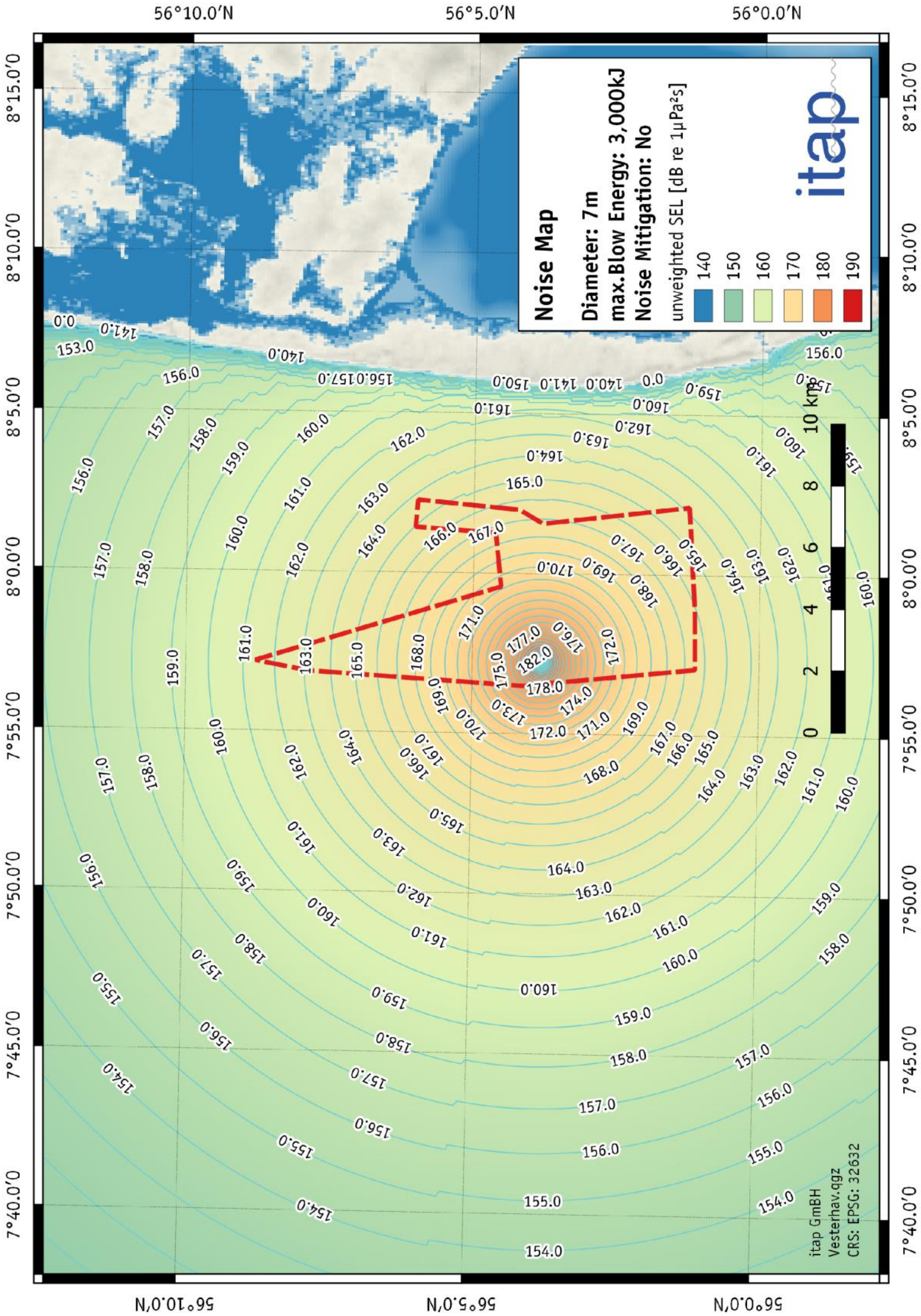

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Receptor: HP, Phocid Seals
Fleeing Speed: 1.5 m/s
Thresholds For SELcum
PTS Phocid Seals
PTS Harbour Porpoise
unweighted SELcum [dB re 1µPa²s]
160
170
180
190
200
210
itap
10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′O
8°10.0′O
8°5.0′O
8°0.0′O
7°55.0′O
7°50.0′O
7°45.0′O
7°40.0′O

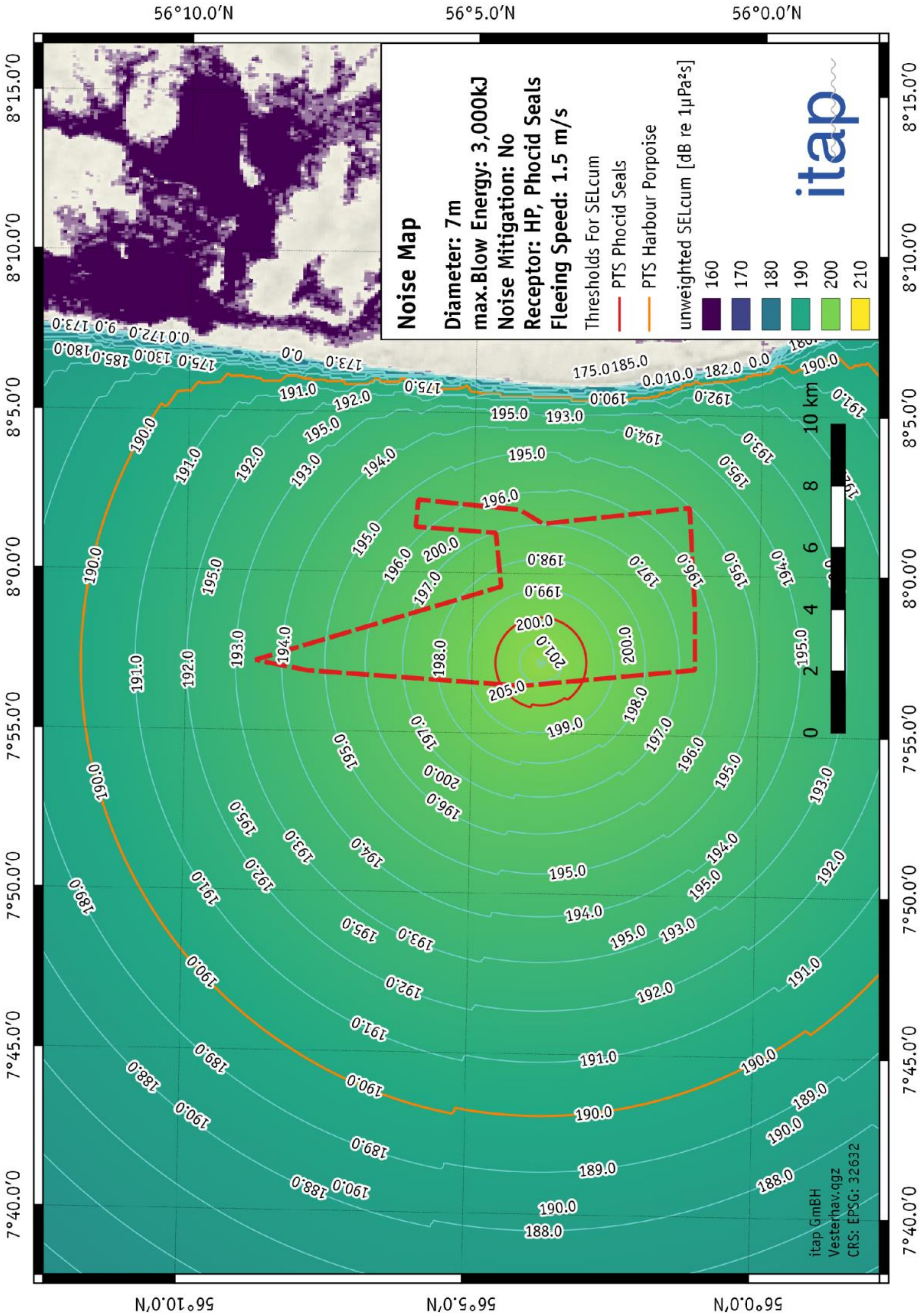

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Species: HFC
Fleeing Speed: 1.5 m/s
Weighting: HFC
Threshold Level SELcum
PTS
SELcum [dB re 1µPa²s]
140
144
148
152
156
160
itap
0 2 4 6 8 10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0

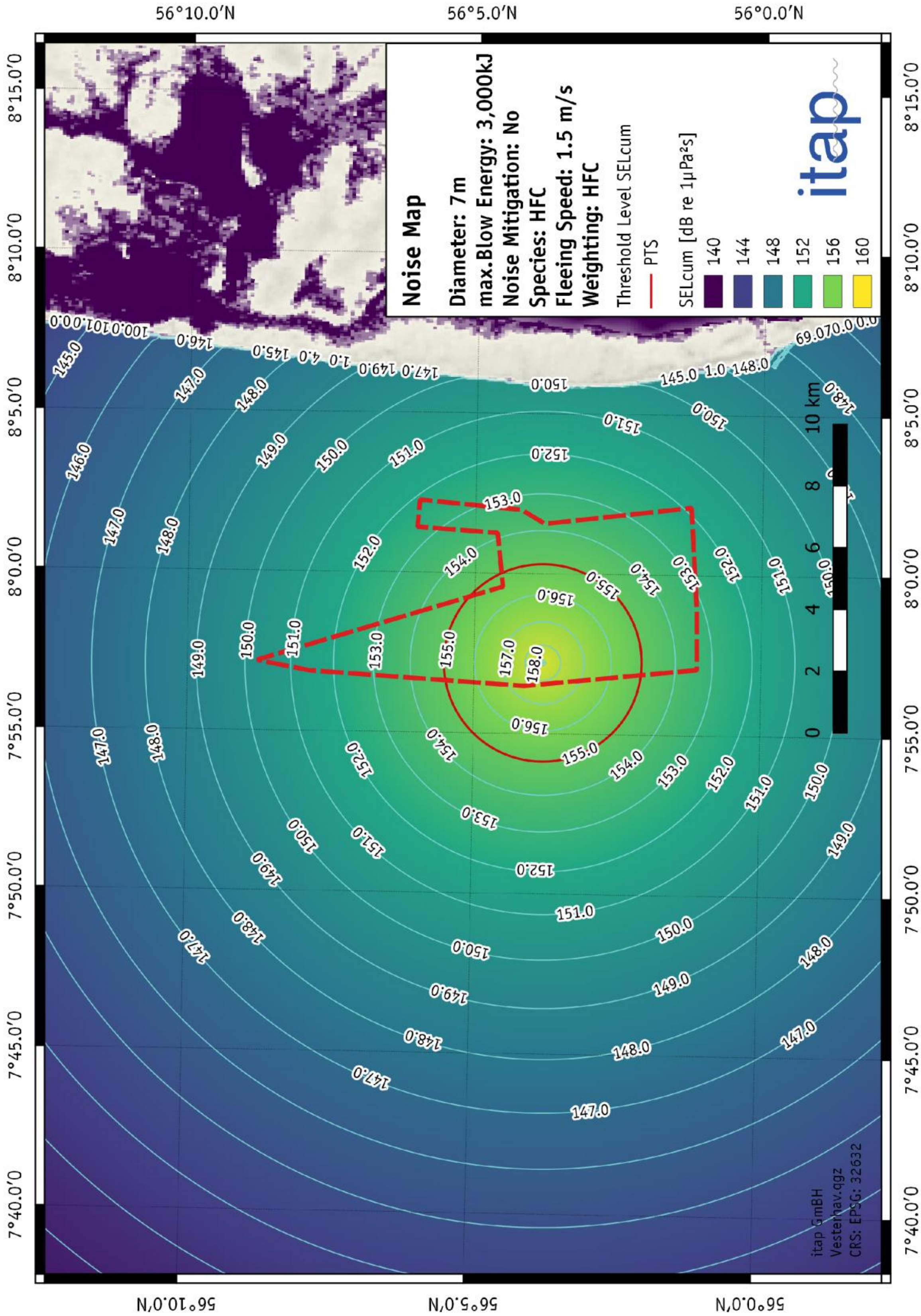

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Species: Phocid Seals
Fleeing Speed: 1.5m/s
Weighting: Phocid Seals
Threshold Level SELcum
TTS
SELcum [dB re 1µPa²s]
160
164
168
172
176
180
itap
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0
10 km

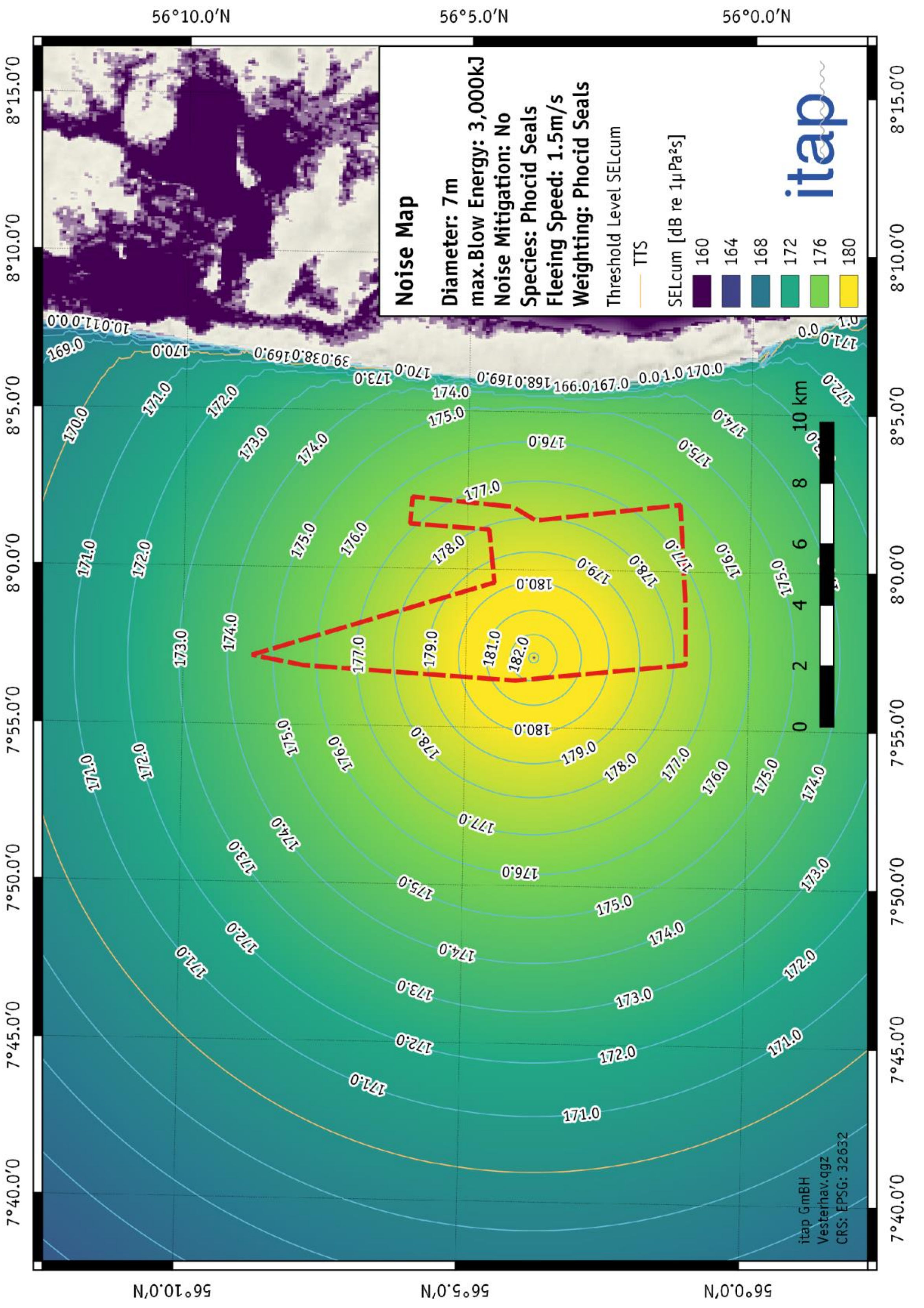

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Receptor: Juvenile Cod
Fleeing Speed: 0.38 m/s
Thresholds For SELcum
PTS Juvenile Cod
unweighted SELcum [dB re 1µPa²s]
160
170
180
190
200
210
itap
10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0

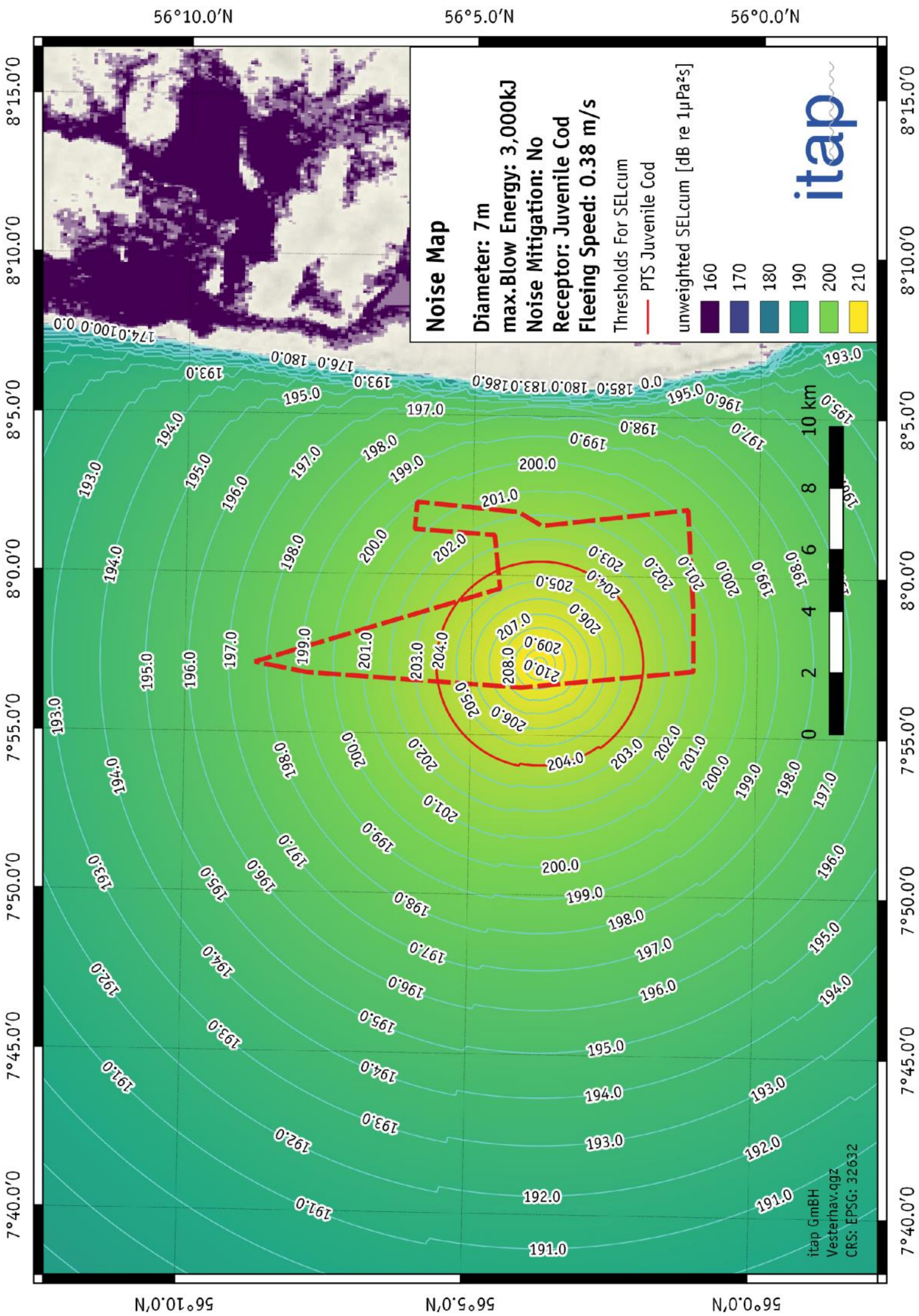
Noise Maps VHS13


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
unweighted SEL [dB re 1µPa²s]
140
150
160
170
180
190
itap
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0
0 2 4 6 8 10 km

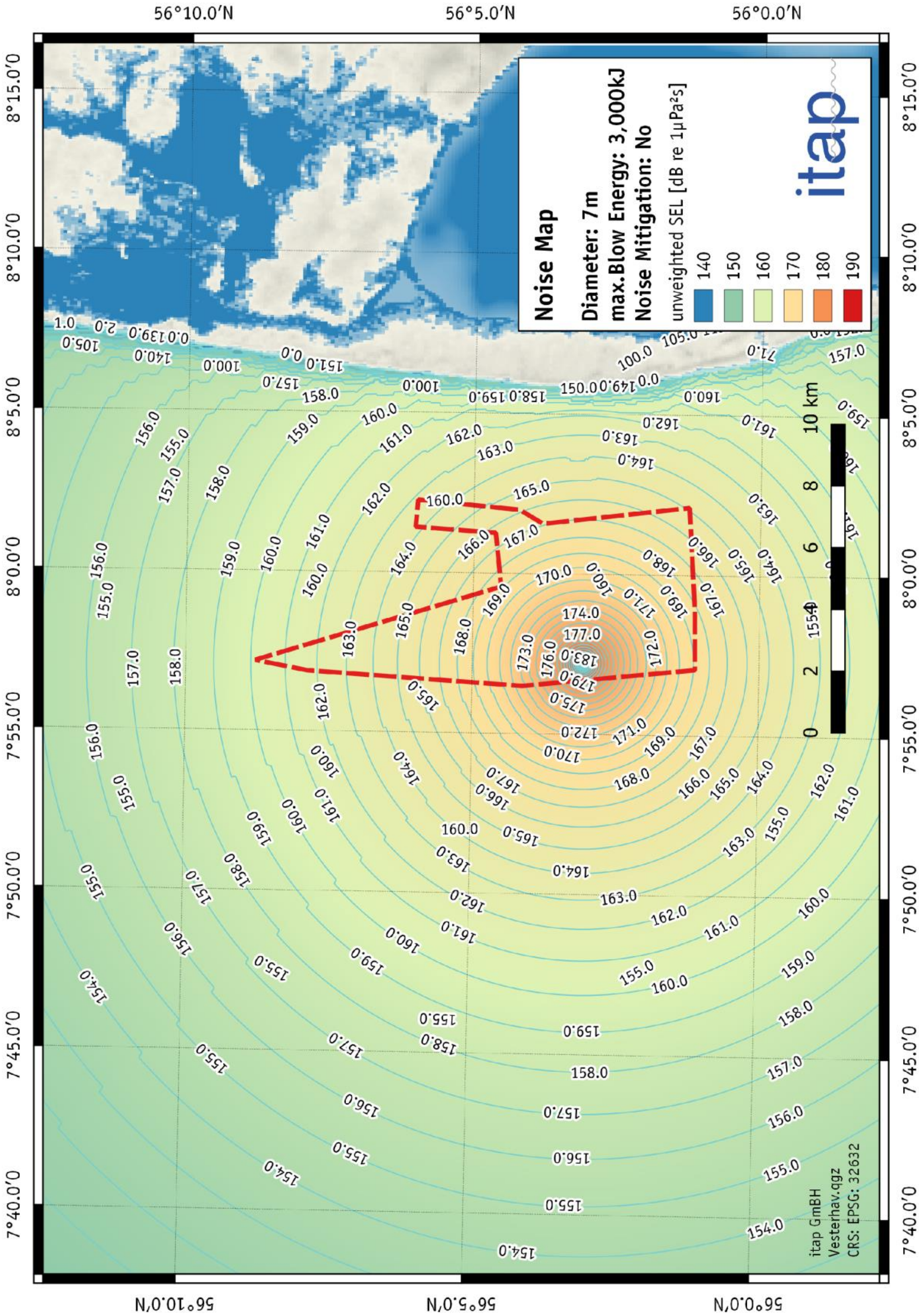

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Receptor: HP, Phocid Seals
Fleeing Speed: 1.5 m/s
Thresholds For SELcum
PTS Phocid Seals
PTS Harbour Porpoise
unweighted SELcum [dB re 1µPa²s]
160
170
180
190
200
210
itap
10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0

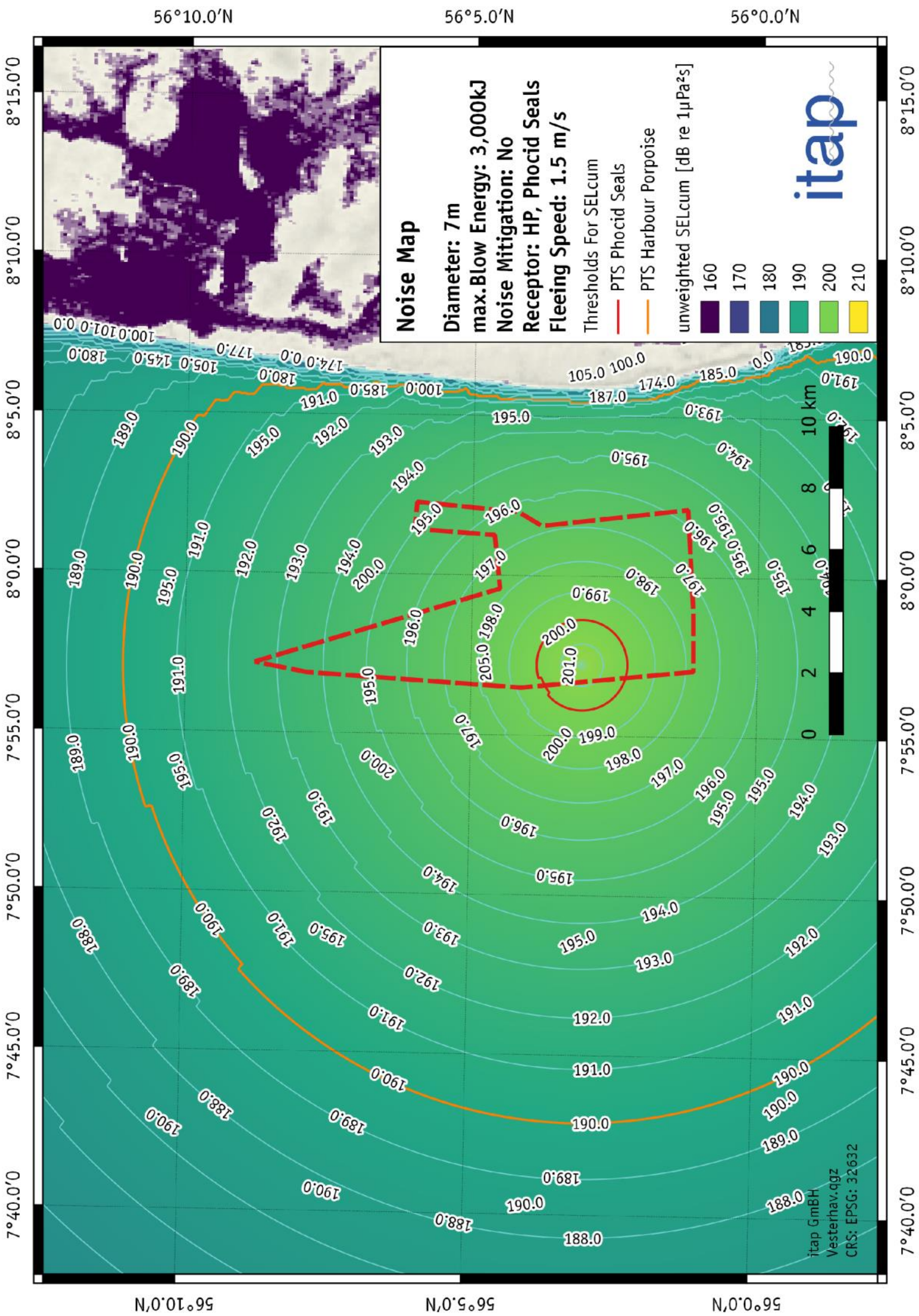

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Species: HFC
Fleeing Speed: 1.5 m/s
Weighting: HFC
Threshold Level SELcum
PTS
SELcum [dB re 1µPa²s]
140
144
148
152
156
160
itap
0 2 4 6 8 10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0

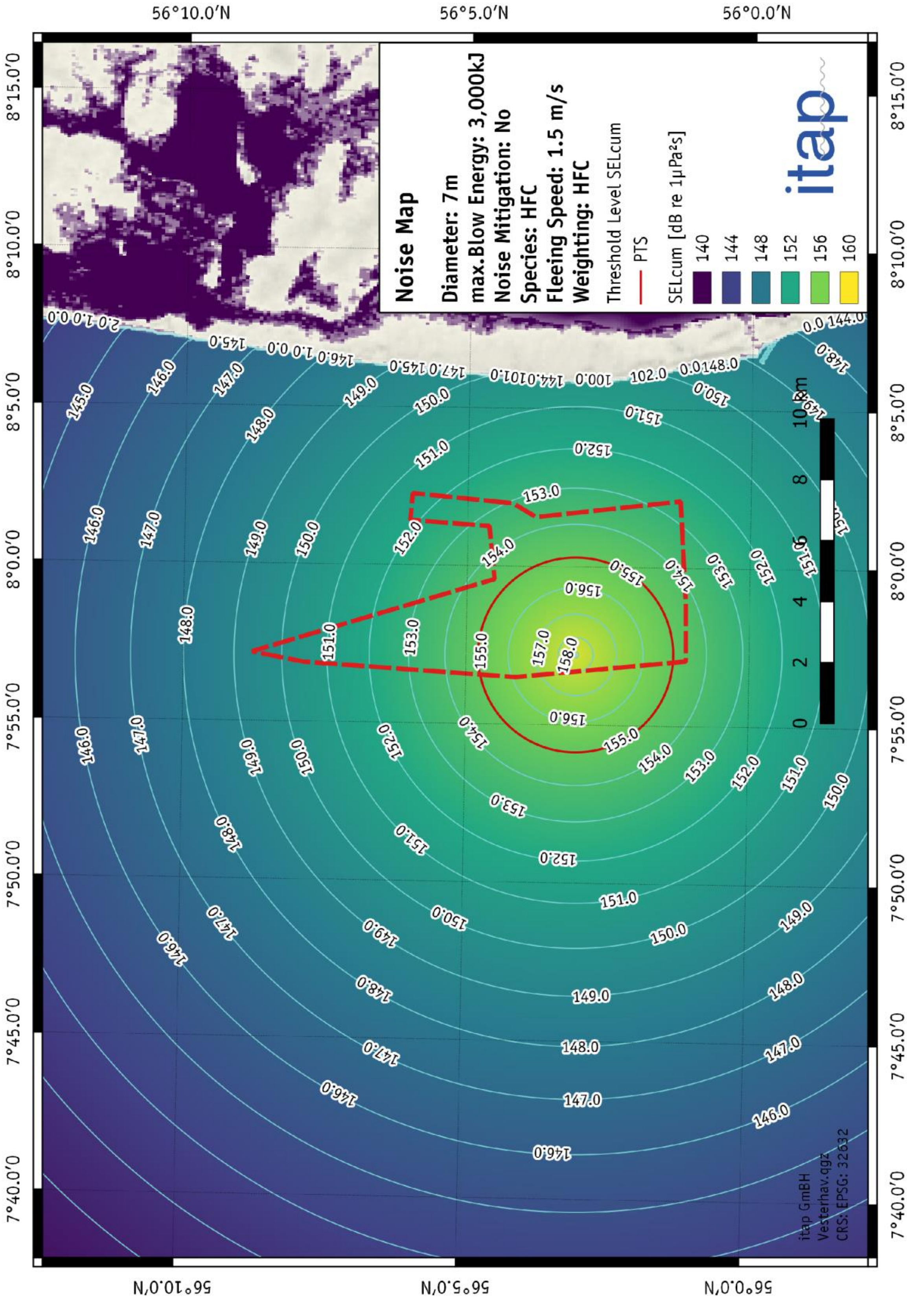

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Species: Phocid Seals
Fleeing Speed: 1.5m/s
Weighting: Phocid Seals
Threshold Level SELcum
TTS
SELcum [dB re 1µPa²s]
160
164
168
172
176
180
itap GmBH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′0
8°10.0′0
8°5.0′0
8°0.0′0
7°55.0′0
7°50.0′0
7°45.0′0
7°40.0′0
0 2 4 6 8 10 km

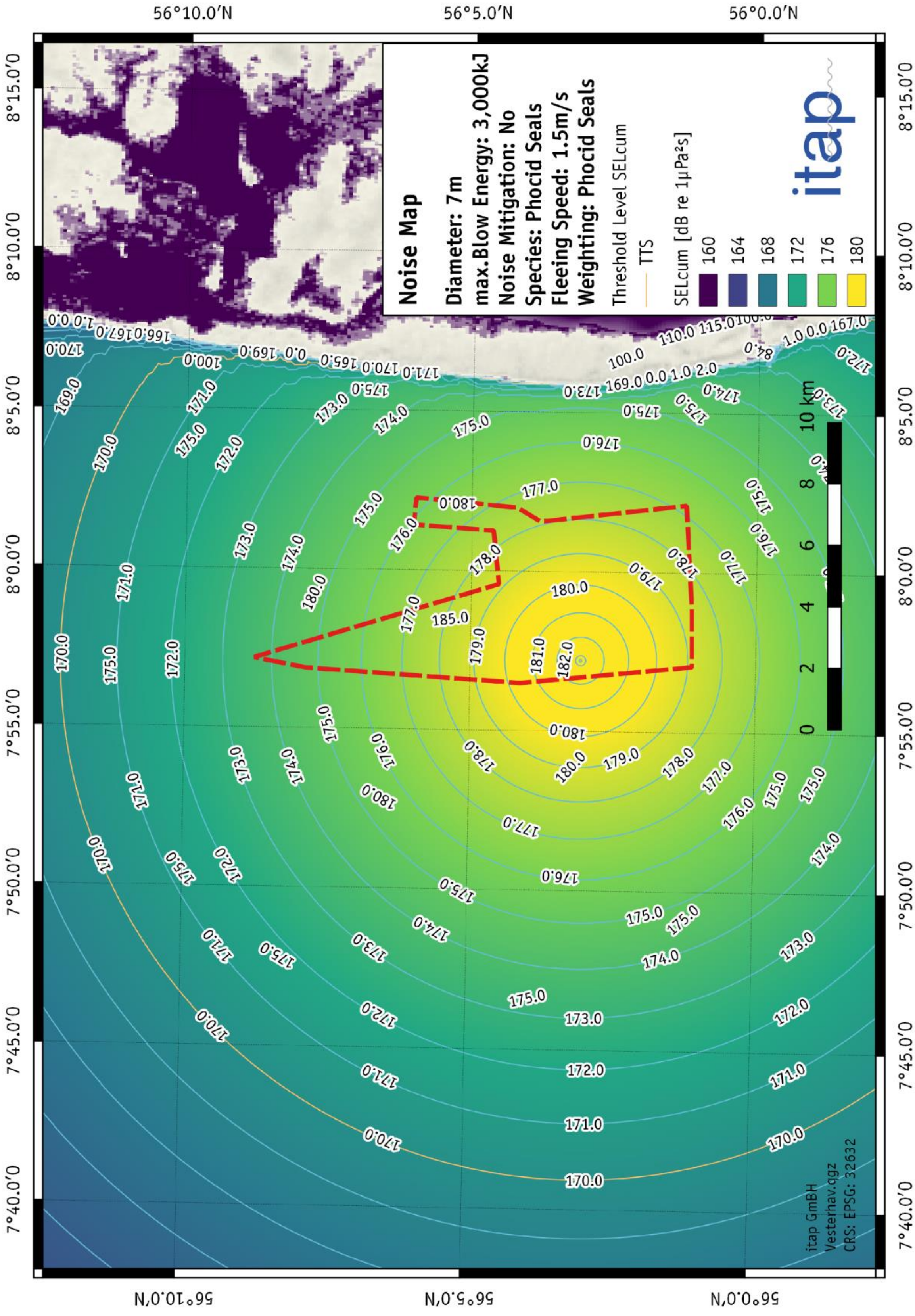

Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Receptor: Juvenile Cod
Fleeing Speed: 0.38 m/s
Thresholds For SELcum
PTS Juvenile Cod
unweighted SELcum [dB re 1µPa²s]
160
170
180
190
200
210
10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0′N
56°5.0′N
56°0.0′N
8°15.0′O
8°10.0′O
8°5.0′O
8°0.0′O
7°55.0′O
7°50.0′O
7°45.0′O
7°40.0′O

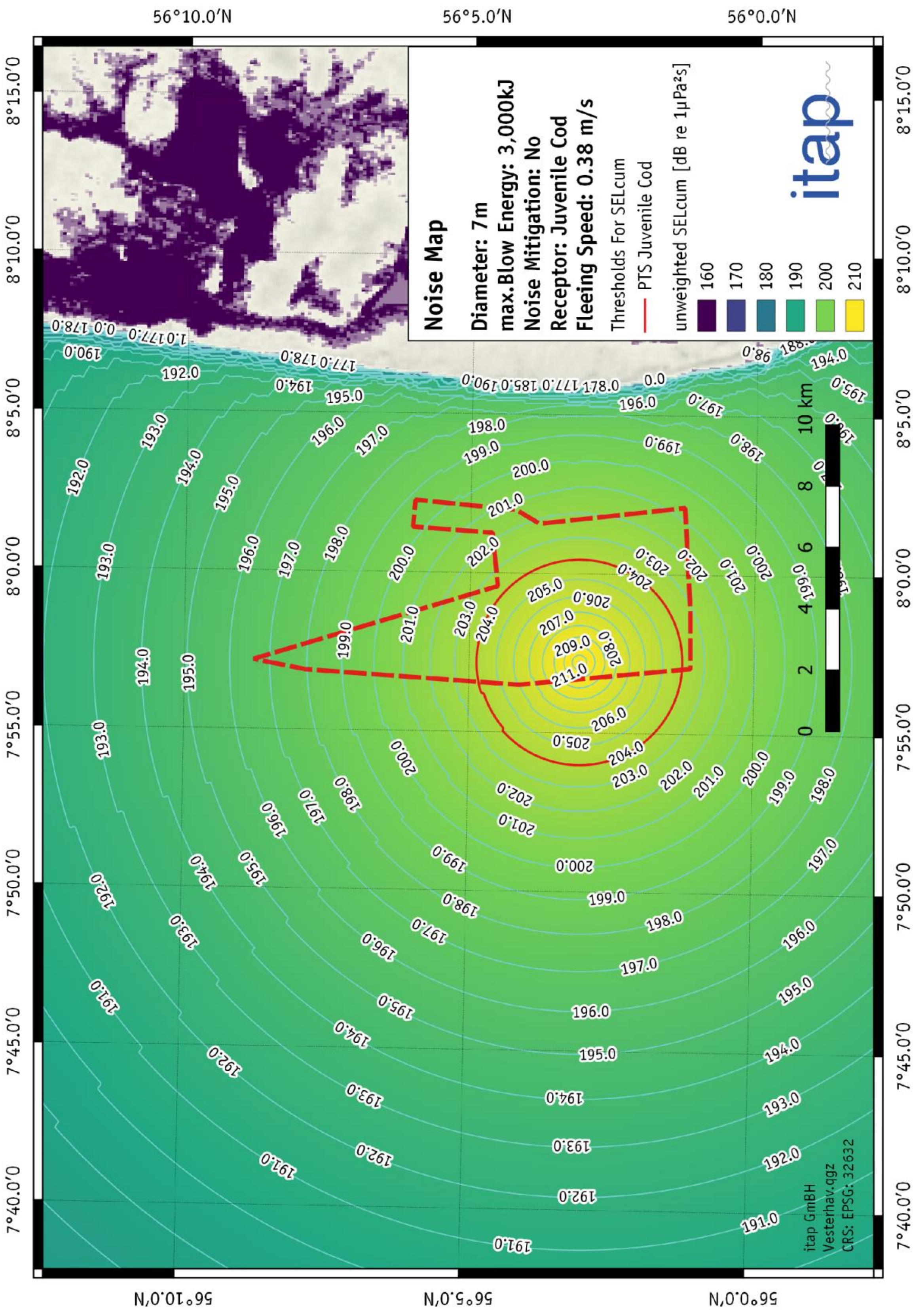
Noise Maps VHS15


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
unweighted SEL [dB re 1µPa²s]
140
150
160
170
180
190
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Receptor: HP, Phocid Seals
Fleeing Speed: 1.5 m/s
Thresholds For SELcum
PTS Phocid Seals
PTS Harbour Porpoise
unweighted SELcum [dB re 1µPa²s]
160
170
180
190
200
210
itap
10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0'N
56°5.0'N
56°0.0'N
8°15.0'O
8°10.0'O
8°5.0'O
8°0.0'O
7°55.0'O
7°50.0'O
7°45.0'O
7°40.0'O


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Species: HFC
Fleeing Speed: 1.5 m/s
Weighting: HFC
Threshold Level SELcum
PTS
SELcum [dB re 1µPa²s]
140
144
148
152
156
160
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Species: Phocid Seals
Fleeing Speed: 1.5m/s
Weighting: Phocid Seals
Threshold Level SELcum
TTS
SELcum [dB re 1µPa²s]
160
164
168
172
176
180
itap
0 2 4 6 8 10 km
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0'N
56°5.0'N
56°0.0'N
8°15.0'O
8°10.0'O
8°5.0'O
8°0.0'O
7°55.0'O
7°50.0'O
7°45.0'O
7°40.0'O


Noise Map
Diameter: 7m
max.Blow Energy: 3,000kJ
Noise Mitigation: No
Receptor: Juvenile Cod
Fleeing Speed: 0.38 m/s
Thresholds For SELcum
PTS Juvenile Cod
unweighted SELcum [dB re 1µPa²s]
160
170
180
190
200
210
itap GmbH
Vesterhav.qgz
CRS: EPSG: 32632
56°10.0'N
56°5.0'N
56°0.0'N
8°15.0'O
8°10.0'O
8°5.0'O
8°0.0'O
7°55.0'O
7°50.0'O
7°45.0'O
7°40.0'O
0 2 4 6 8 10 km