Norwegian University of Science and Technology

Master Thesis

Significance of offshore wind farm sound on marine populations

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Preface

The thesis is the result of course "TMR4930 Marine Technology, Master's Thesis" and also for completion of Master of Science in Marine Coastal Development at the department of Marine Technology at the Norwegian University of Science and Technology spring semester 2019. The thesis is also following the work completed in the course "TMR4570 Marine Resources and Aquaculture, Specialization Project" autumn semester 2018.

I would like to thank my supervisor, Professor Gary Harald Isaksen, for helping me with resources and advice. The encouragement and support I got from him is important not just for the thesis work, but also for my future academic career.

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Wenpeng Wang

Summary

Offshore wind energy is one of the most important renewable energy globally. Currently, Europe is leading both in capacity and technology exports. Although Norway has significant wind resources, the development of offshore wind farms (OWF) has been limited to-date, especially when compared with Denmark and the UK. Fifteen zones in Norway are considered suitable for offshore wind farm development, with an estimated overall capacity from 4,600 to 12,600 MW. This work seeks to understand the character of the anthropogenic sound produced during offshore wind farm life-cycle, including the seismic survey phase, the construction phase and the operation phase. During each of these phases sound is introduced into the environment. This work also discusses potential negative effects on marine life.

In the thesis, sound emissions are modeled at five sites. These sites are considered "Category A sites" (most suitable sites) for OWF's development by Norges Vassdrags og Energidirektorat (NVE) The sites are: Sandskallen (Finnmark), Utsira Nord (near Karmøy/Haugesund), Frøyagrunnene (Sogn og Fjordane), and Sørlige Nordsjø I and II (two sites close to each other in North Sea).

Acoustic modelling was based on ray theory in addition to complement at acoustic boundaries. Results are provided for the geophysical survey phase, construction phase and operation phase of the offshore wind farm life-cycle. The decommissioning phase has not been modeled. The acoustic models served as input for assessing if and how sound from offshore windfarms may affect marine mammals and fish species.

Adverse impacts to fish and marine mammals are limited to zones very close to the sound sources in the cases studied. During the survey and construction phases any potential risks (although small) can be further mitigated by marine mammal observers and fishery liaisons. As such, the development of offshore wind farms is not considered a significant threat to Norwegian fisheries or marine mammal populations off Norway's coast.

As an example, using Sandskallen offshore Finnmark in August, and starting with a source pressure level (referenced by convention as 1 meter from the sound source) of 212 dB re 1μPa and sound exposure level (for marine fauna) at 192 dB re 1μPa^{2}s, then SEL 180 dB re 1μPa^{2}s is present less than 5 meters from the sound source (Table 5.3). Likewise, at 100 meters from the sound source the sound exposure level is down to 155 dB re 1μPa^{2}s.

Seasonal variations have also been found from the results. Impact area is most limited in August, which represents ocean environment in summer, while results in March (Spring) and December (Winter) are similar.

Finally, the thesis lists knowledge gaps in the research, e.g., particle motion measurements and its potential impact on marine life and recommendations about possible mitigation measures during operations.

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1 Introduction

1.1 Offshore Wind Farm

The term "offshore wind farm" (OWF) refers to the specific area in the ocean, usually on continental shelf,[1] where groups of wind turbines are located to harvest wind energy. The first offshore wind farm in the world, was installed in Denmark in 1991.[2] Since then, the total energy-generating capacity of offshore wind farms around the world has increased from 5 MW[3] to 23,304 MW at the end of 2018 (Figure 1.1) according to Global Wind Energy Council (GWEC). In Europe, at the end of 2018, there were 4,543 offshore turbines and 18,499 MW cumulative capacity, of which 44% is located in the UK, 34% in Germany, 7% in Denmark, 6.4% in Belgium and 6% in the Netherlands.

Norway has been a potential and emerging market for offshore wind farm development. At the end of 2018, there was only one offshore wind turbine in Norway; the Hywind Demo Project (2.3MW capacity). The Hywind is a floating turbine implemented by Equinor and installed in 2009.[4] In August, 2018, Norway opened two areas for offshore wind projects and several future strategies announced by the government suggests that there will be an increase in wind turbines offshore Norway.[4]

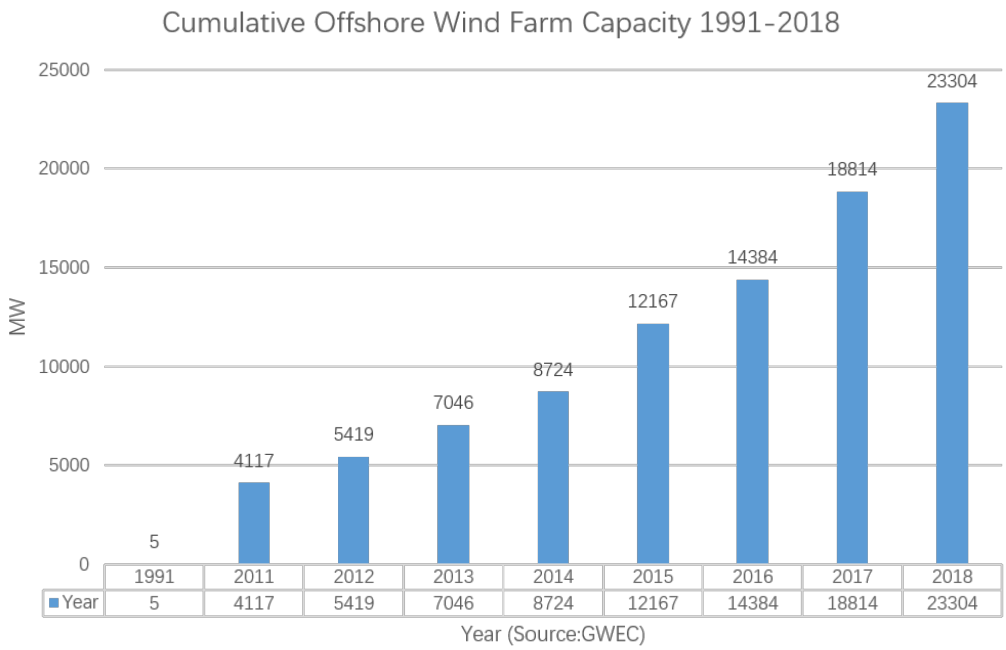


Figure 1.1: Global Cumulative Offshore Wind Capacity from 1991-2018 (Data Source: GWEC)

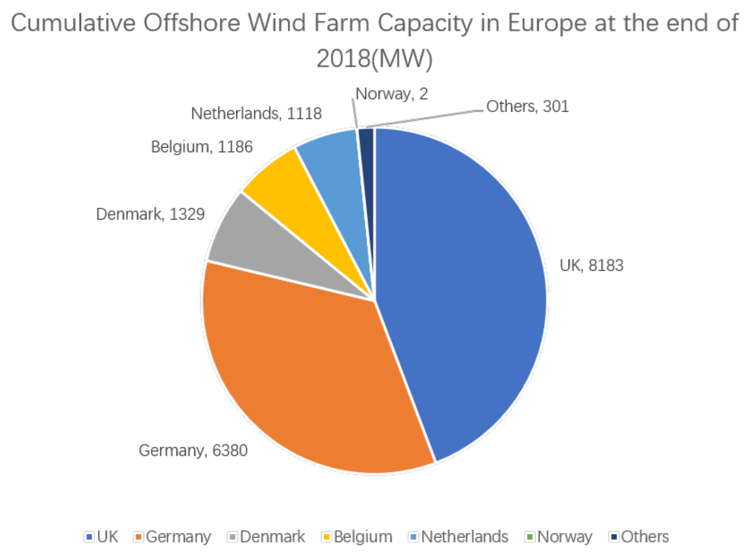


Figure 1.2: Global Cumulative Offshore Wind Capacity in 2018 (Data Source: GWEC)

1.2 Underwater Sound at Offshore Wind Farms

Underwater sounds within and near offshore wind farms can be divided into the following categories:

Background (ambient) sound: potential sources producing background sound can be various, including wave, raindrops, marine organisms, distant boats, and even natural geological seismic events. Ambient sounds varies with season, location, and time of day. Composite of background sound in the ocean was described by Figure 1.3 by Wenz (1962). To describe a sound field, measurements at the site is needed, but in most situations, the sound pressure of background sound is around 90 dB re 1μPa, but typically below 100 dB re 1μPa [5]

Vessel sound: Various vessels would be used during wind farm life-cycle, and different vessels produce different sound. In general, these sound source levels can be 152-192 dB re 1μPa at 1 m. [6] Vessel related sound sources include propellers, hull radiated sound, and navigational sonar and echo-sounders that are typically mounted to vessels, for example, tanker/cargo ships generate continuous sounds of 177dB re 1μPa, [7] at 1 meter from the sound source (typically the propeller).

Geophysical Survey sound: During pre-construction period, a geophysical survey is typically conducted to choose suitable sites or obtain important engineering parameters for the sites chosen for the wind farm installation. The suite of equipment used during a typical shallow hazards survey consists of: single beam and multibeam echosounders which provide water depths and seafloor morphology; a side scan sonar that provides acoustic images of the seafloor; a subbottom profiler (sparker or boomer) which provides 20 to 200 m sub-seafloor penetration with a 6 to 20 cm resolution; and a single channel seismic system with 40 to 600 m sub-seafloor penetration (multichannel used less frequently and only when deeper imaging is needed). The echosounders and subbottom profilers are generally hull-mounted. All other equipment is usually

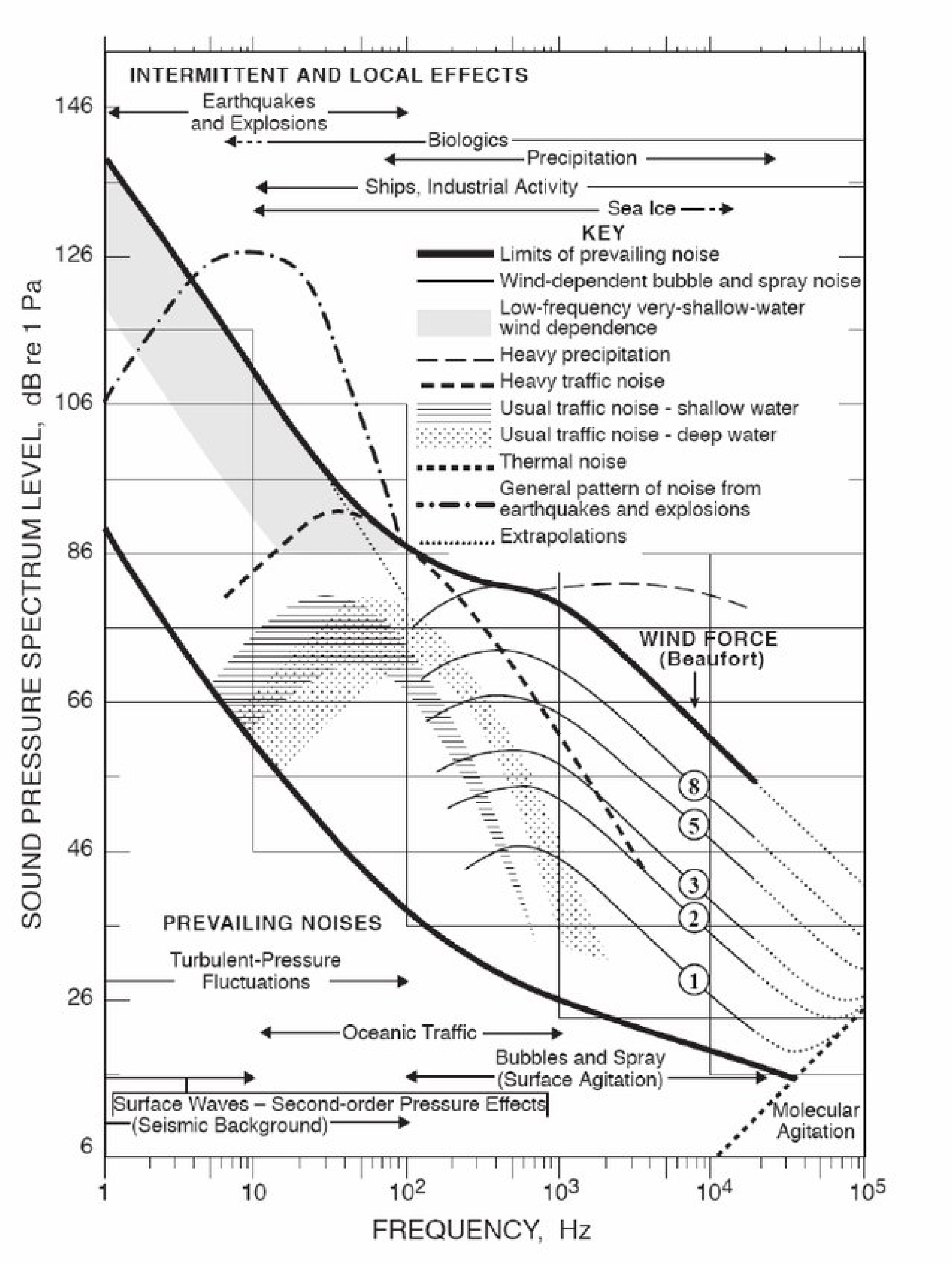


Figure 1.3: Composite of ambient sound spectra by Wenz(1962)

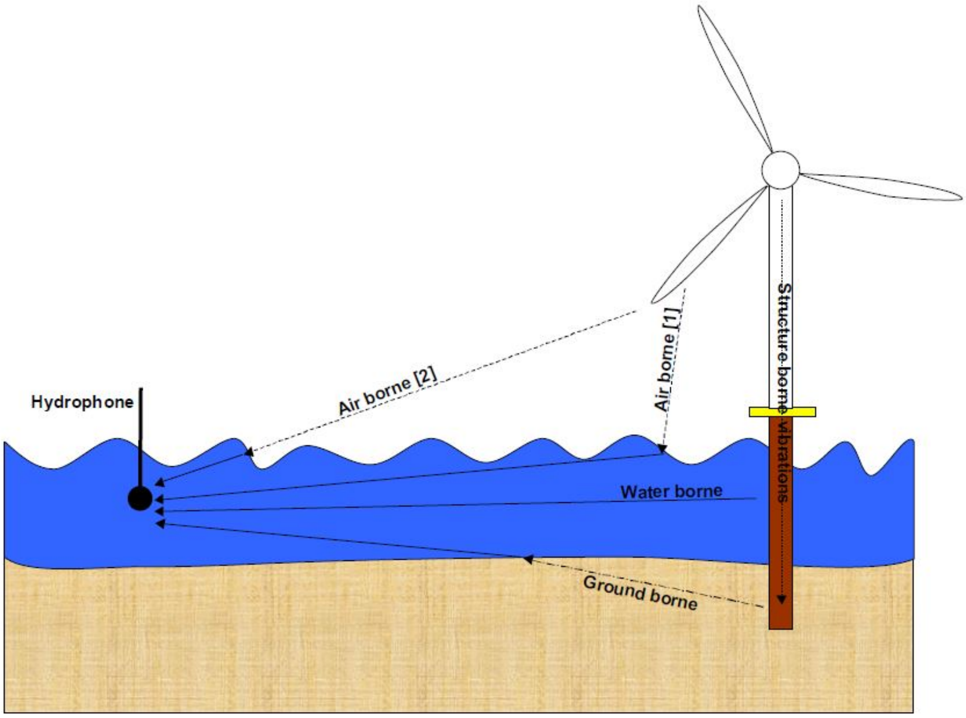


Figure 1.4: Wind turbine producing sound during daily operation.

towed behind the vessel. Boomers and sparkers producing mid-frequency sounds are commonly used for wind farm site surveys. [6]

Construction sound: During construction period, activities including pile driving, drilling, trenching and dredging. It is during this phase that the highest sound levels are generated. Construction sounds have been researched more than the other sound sources. Different pile driving methods produce different sound levels, for example, a 4 m diameter impact-driven monopile hammer strike will produce sound with source level of 200 dB re 1 μPa at 1 m and frequencies peaking between 100 to 1000 Hz. [6] The impact on marine life from particle motion during this phase is poorly understood.

Operation sound: The operation period is the longest period during the wind farm life-cycle. Sounds from this period mainly includes aerodynamic sound from the blades as well as structure vibrations (Figure 1.4). The impact on marine life from particle motion during this phase is also poorly understood. Operation sound is strongly related to wind speeds, the turbine's design, and build quality. Figure 1.5 and 1.6 are respectively records of sound pressure level and frequency range of operation sound in a offshore wind farm.

Decommission sound: Decommission is the process of removing structures in offshore wind farm sites. During the decommission period, different methods (e.g., jet cutting and blasting) will produce different sound levels; however, until now, there are very few offshore wind farms that have been decommissioned and consequently there is no real record or published results

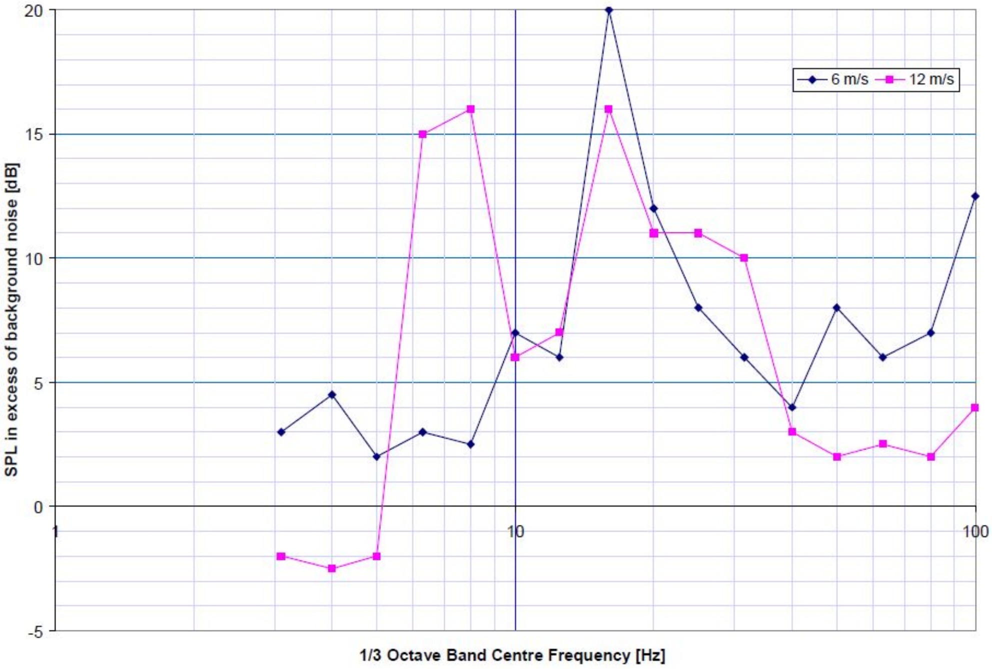


Figure 1.5: A record of sound during operation phase above background at 100m from a 35m, 220kW wind turbine by Windworld AS.

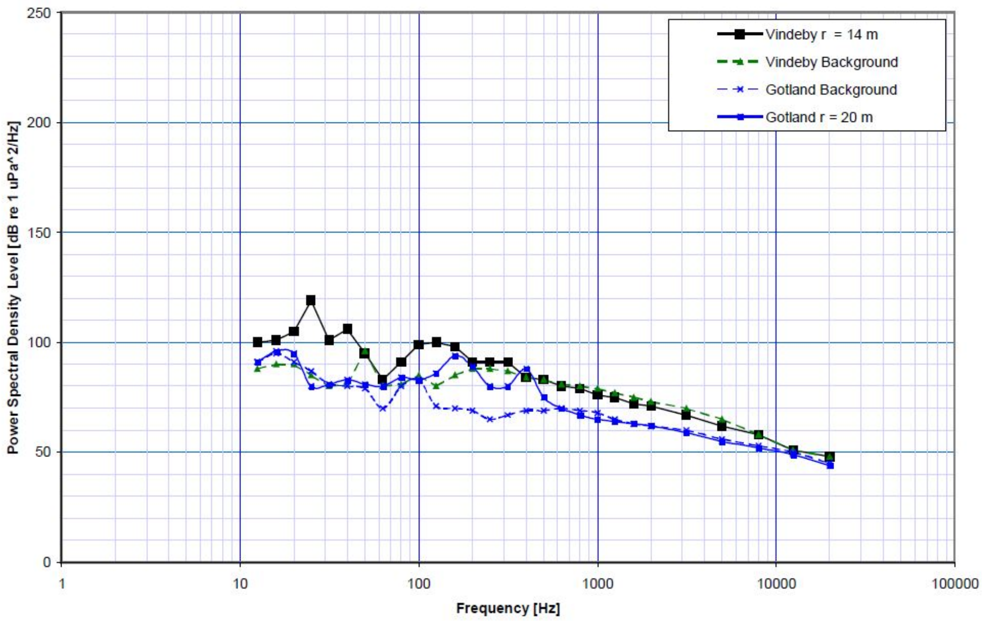


Figure 1.6: A record of sound during operation phase above background at 20m from two wind turbines at 13m/s wind speed.

about decommission sound. That said, the sound generated during the decommissioning phase may be inferred to be similar to the construction phase.

1.3 Fish and underwater sound

Fish can detect sound via auditory system and lateral line system.[8] For species with swim bladder, the connection between the bladder and inner ear is important to detect sound. To be detected, sounds must exceed the hearing threshold of the animal, and they have to approach or exceed the ambient sound levels in the same frequency band. In addition, some fish may be sensitive to particle motion.

Different groups of fish detect, utilize and respond to sounds in different ways. The most relevant biological factors governing how fish detect sounds include:

1. Existence of swim bladder: For fish species with swim bladder, compressing of swim bladder under local pressure caused by sound exposure can transmit sound to inner ear and help them hear.

2. Existence of a swim bladder in proximity to the inner ear: How the swim bladder is connected to inner ear is also important. Such connections have been found via bones called Weberian ossicles, which are located at vertebrae of backbone (mainly otophysan fishes, e.g., catfishes and carps), via an extension of swim bladder, connecting directly with the inner ear (e.g., herring, anchovies and sardines) or via other gas chambers (e.g., some anabantoidei fishes)

3. Lateral linear system: Lateral linear system refers to the sensory system consisting of sensors distributed along the fish body. This factor should be considered when fish are close to the sound source (according to Popper et al. (2014), as close as one or two body lengths).

It is challenging to categorize all the fish species into different groups. The following considerations can be made:

The term"hearing generalists" and "hearing specialist" have been commonly used by scientists, but Popper and Fay (2011)[9] pointed out that these terms are not suitable to categorize fish with hearing ability dependent on frequency, and suggested a continuum to replace the term (see Table 1.1).
For those fishes without swim bladder and other gas-filled structure, e.g, flatfish and tuna, they can only detect particle motion. And for those fishes with swim bladder and simultaneously having a short distance or tight connection between swim bladder and inner ear, they are relatively pressure-sensitive.[9] The other fishes can be categorized into the middle area between these two kinds. In Tabel 1.1, some fish species have been categorized into six different hearing ability level from level 1 to level 6 (such qualitative division is just to clarify the position of each species in the continuum model, see Figure 1.7).

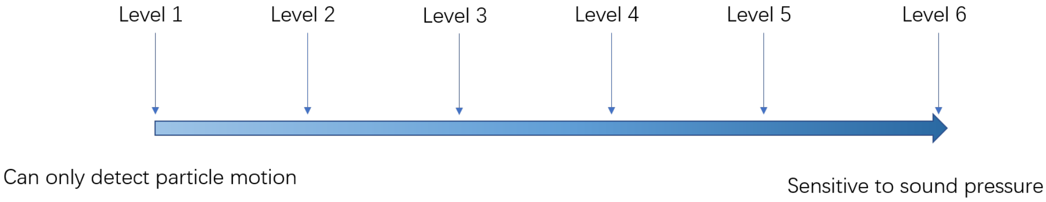


Figure 1.7: Different Hearing Ability Levels

Level 1: Fish species without swim bladder and can only detect particle motion		
Fish species	**Latin name**	**Description**
white spotted bamboo shark	*Chiloscyllium plagiosum*	peak threshold at 50 and 200Hz [10]
brown-banded bamboo shark	*Chiloscyllium punctatum*	peak threshold at 50 and 200Hz [10]
Horn shark	*Heterodontus francisci*	lowest threshold at 80Hz [11]
Common dab	*Limanda limanda*	peak threshold at 40 and 250Hz [12]
European plaice	*Pleuronectes platessa*	peak threshold at 40 and 250Hz [12]
Japanese halibut	*Paralichthys olivaceus*	threshold increased sharply between 200-400Hz [11]
Level 2: Fish with swim bladder, but relatively distance from inner ear		
Atlantic salmon	*Salmo salar*	lowest threshold at 160 Hz (sound pressure) most sensitive to particle motion below 200Hz. [13]
Pacific salmon	*Oncorhynchus*	similar with Atlantic salmon wider hearing frequency range. [14]
Rainbow trout	*Oncorhynchus mykiss*	not affected by sound in RAS system [15]
Yellowfin tuna	*Thunnus albacares*	respond to sound between 200-700Hz
Level 3: Fish with swim bladder, close but without connection to inner ear		
Atlantic cod	*Gadus morhua*	Effects from particle motion change can be observed below 50Hz and sound source 1m near. [16]
Level 4: Fish with swim bladder, and connect with inner ear with other gas chamber		
Croaking gouram	*Trichopsis vittata*	Hearing ranges from 600-2500Hz
pygmy gourami	*Trichopsis pumila*	Hearing ranges from 100-2500Hz. [17]
Level 5: Fish with swim bladder, connecting with inner ear		
Pacific herring	*Clupea pallasii*	Hearing ranges from 100-5000Hz. [18]
American shad	*Alosa sapidissima*	Can detect sound over 20kHz. [19]
Gulf menhaden	*Brevoortia patronus*	Can detect sound over 20kHz. [19]
Level 6: Fish with swim bladder, more specialized connecting with inner ear		
Goldfish	*Carassius auratus*	Be sensitive to particle motion below 500Hz [20]
Mexican tetra	*Astyanax mexicanus*	Can detect sound up to 7kHz [9]

Table 1.1: Continuum classification of fishes with respect to hearing ability.

Impacts of sounds on fish species cover a wide range of possibilities, including rare events that have the potential to injure or have fatal consequences, loss of hearing ability, and hearing threshold shift. For these more severe events to occur, the fish would need to be very close to the sound source. At lower sound levels there can be a temporary change in behavior, e.g., a change in swimming direction. Such changes in behaviour can be short-term (seconds to minutes) or longer-term (hours to a day).

To try to understand the extreme limits where sounds have the potential to cause injury, experiments have been carried out in small cages where the fish are exposed to loud sounds and are unable to move away.

Hasting et al., 1996 found that: [21] *Oscars exposed under continuous tone with sound source level of 180dB re 1μPa and frequency of 300Hz suffered limited damage on inner ear, and the damage is potentially recoverable.*; McCauley et al., 2003 found that: [22] *Pink snapper under airgun pulses with sound source level of 180dB re 1μPa and borad frequency range suffered damage on sensory epithelia in the inner ear, and no recovery after 58 days could been found.*

It is important to note that results from such caged experiments exposing fish to loud sound cannot readily be extrapolated to natural conditions. In the wild, schools of fish will have the ability to move away from loud sound sources. Consequently, adverse impacts from anthropogenic sounds on schools of fish or fisheries is exceedingly rare (Popper et al, 2014).

For behaviour reactions, fish typically display a startle response when very close to the sound source. Bagocius (2015) evaluated the underwater sound from pile-driving sound at an airport construction site and found: [23] *The piling noise has a sound exposure level(SEL) of 218dB re 1$\mu Pa^2 s$ and can potentially block the migration through the area of spawning salmoniod fish.*; To ascertain whether or not migrating or spawining fish are truly affected, sound transmission modeling from the sound source to the biological receiver should be modeled. It is important to keep in mind that the strength of the sound pulse is roughly inversely proportional to the distance the sound travels.

In 1998 the Fisheries Research Services Marine Laboratory in Aberdeen, Scotland, conducted a study using impulsive sounds to evaluate the scare-off effect on a fish bank in the vicinity of a reef in one of the Scottish fjords. A television camera was used to study how the fish reacted to the sound pulses from an air gun. This study showed that there was very little reaction to the sound pulses, despite the fact that the peak value of the pulses was on the order of 229 dB. [24]

1.4 Marine mammals and underwater sound

Research on the potential impact of underwater sound on marine mammals is much further along compared with such research on fish. In order to develop audiograms for different marine mammals, and to understand the conditions that need to exist for injury to occur, experiments have been carried out over a wide range of decibels and frequencies.

Southall et al. (2007) divided marine mammals into five groups according to their hearing functions in different frequency range (Table 1.2).

Concerns about marine mammals under sound exposure also includes whether they will have auditory injury, hearing threshold shift and behaviour change which can be short term and long term.

Hearing group	**Bandwidth**	**Species found in Norway**
Low-frequency cetaceans(M_{lf})	7Hz-22kHz	Blue Whale, Fin whale,Common minke whale, Humpback whale
Mid-frequency cetaceans(M_{mf})	150Hz-160kHz	Killer Whale
High-frequency cetaceans(M_{hf})	200Hz-180kHz	Porpoise
Pinnipeds in water(M_{pw})	75Hz-75kHz	Harp seal, Hooded seal, Grey seal, Harbour seal
Pinnipeds in air(M_{pa})	75Hz-75kHz	Harp seal, Hooded seal, Grey seal, Harbour seal

Table 1.2: Different hearing groups by Southall et.al(2007)

Figure 1.8: Norwegian orca, by Jonathan Ball

1.5 Objectives

Objectives of the thesis are:

1. Model and evaluate the sound profile transmitted from potential offshore wind farm sites during different states of their development.

2. Modelled results was used to investigate potential impact on marine mammals and fish species

3. Give recommendations about possible mitigation measures during operations.

2 Theory

2.1 Physics of Sound

Sound can be defined as the vibration travelling in the form of wave through a medium, which can be gas, solid materials, or in our context, water. Characteristics of sound can be described with parameters including frequency, which is the vibration rate, or intensity, which is the average amount of sound power, and etc.

Underwater sounds can be categorized into two groups according to their characteristics of duration: 1) Transient sound, or pulse, which means it only occurs in a short duration, but usually repeats in a regular or irregular pattern during a period; 2) Continuous sound, which means it occurs continuously during a period. [25]

There are already sounds in the ocean, which can come from wind, waves, ice, earthquakes or aquatic organisms. Sounds from human activities are called anthropogenic sounds. Examples include sounds from fishing sonars, vessel traffic (propellers), navy sonar, construction (pile driving and dredging), use of multibeam echosounders to map the seafloor or the continental margin of a nation, or seismic sources for exploration of oil and gas.

2.2 Metrics to describe sound

There are different metrics for describing sound, and the following paragraphs will present some key metrics used in research about anthropogenic sounds. These theories are mainly from the book *Sound Exposure Guidelines for Fishes and Sea Turtles*, 2014. Some equations are from the review report *Hearing in fish and their reactions to sounds from offshore wind farms* by Wahlberg and Westerberg (2005).

Sound pressure:

Sound pressure refers to the difference between local pressure under sound and the background pressure, and can be derived as:

$$p = P - p_0$$

where P is the instantaneous pressure at any point, and p_0 is the constant equilibrium pressure. And p can be positive or negative, which is the function of x,y,z(position) and t(time):

$$p = p(x, y, z, t)$$

Figure 2.1 illustrates different sound pressure metrics. Root-mean-square sound pressure, or RMS sound pressure is commonly used, which is the root-mean-square value (a time interval is given) of the sound pressure at a point:

$$p_e = \sqrt{\frac{1}{T}\int_0^T P^2 dt}$$

If the vibration is harmonic, RMS can be easily derived via peak sound pressure:

$$p = p_m \cos \omega t$$

$$p_e = \frac{p_m}{\sqrt{2}}$$

where p_m is the peak sound pressure.

And sound pressure level(SPL) can be described:

$$SPL = 20\log_{10}(\frac{p_e}{p_0})$$

where p_0 is 1μPa in water and 20μPa in air. The unit is dB re 1μPa.

RMS sound pressure level is commonly used for continuous sounds, but it is not enough to describe the characteristics of transient sounds. Thus sound exposure level(SEL), which is the time integral of pressure squared, is needed. SEL tells the total energy and commonly used as a complement in description of transient sounds:

$$SEL = 10\log_{10}(\frac{E}{E_0})$$

where E is the total acoustic energy, and E_0 is the reference energy, which is 400 μPa^{2}s in the air and 1 μPa^{2}s in water.

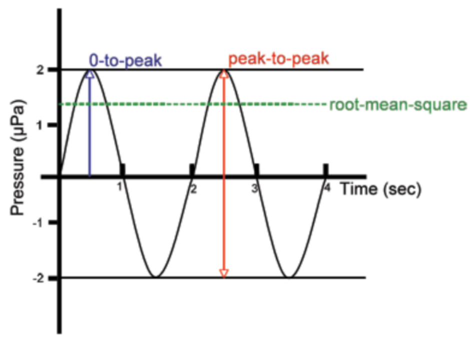


Figure 2.1: Different sound pressure metrics(https://dosits.org)

Frequency and frequency weighting:

Sound is a mechanical wave, and the definiton of frequency is the same as in wave theory, which refers to the number of repeating patter of waves per second. However, since sound is longitudinal wave, the displacement of medium or particles is the same as the direction of the wave.

Since species' hearing abilities are frequency-dependent, sound pressure levels can be "filtered" by frequency-weighting functions. M frequency weighting functions have been used in marine mammals,[26] however, because the relationship between hearing ability and frequency is not known in many fish species, which is essential to derive a frequency weighting functions, there are only few examples with such functions served for fishes, for example, the weighting made by Nedwell et al. (2007). But his model is not considered so scientific and must be used with caution,[27] because he used sound pressure level to describe the audiograms of many species which can only detect particle motions.

Particle motion

Particle motion refers to the motion of an infinitesimal part of the medium, which means it has directions (commonly denoted by a three dimension vector). Particle motion is much more important in research about impacts of anthropogenic sounds on fishes, than the impacts on marine mammals, since there are various of fish species which can only detect particle motion.

However, in near field and far field in a given sound field, particle motion is described in different ways. In far field, particle velocity proportional to sound pressure, can be derived from it. But in near filed, the proportional relationship is not stable, and this is the area where particle motion becomes quite complicated and can only be described by measurement. Particle motion are usually presented in the same unit dB as pressure level, but its reference is based on displacement.

2.3 Sound propagation

The impact of sound emission is not only limited to near-field around the sound source, but can also reach to tens of square kilometers area. In a SOFAR (Sound Fixing And Ranging) channel, the sound wave can concentrate and propagate to thousands of kilometers in a certain range of depths of the ocean. Thus the propagation of sound should be considered when assessing its impact, and sound with different characteristics (e.g., transient sound or continuous sound and high frequency or low frequency) in different ocean environments(e.g., shallow water or deep water and reflection coefficient of seafloor) has different propagation path and arrival intensity. In 2.3, the theory on transmission loss, ray bending, multi-path and propagation modelling will be introduced.

2.3.1 Sound Intensity

Sound intensity (I) is the energy in a unit area along the propagation path per second. It decreases along the propagation path, when it radiates from the source, and if the sound source is omnidirectional, the wave front will be spherical and decreased with r^2:

$$I = P/4\pi r^2$$

where P is the sound power and r is the distance from the sound source. Since acoustic calculation is decibel

$$I = 10\log_{10}(I/I_0)$$

I_0 is the reference sound intensity.

2.3.2 Transmission Loss

Transmission Loss along the sound propagation path can be concluded as:

$$TL = Geometric\ Spreading\ Loss + Attenuation\ Loss$$

Geometric spreading loss is caused by Geometric spreading loss:

$$Geometric\ Spreading\ Loss = N\log_{10}(r)dB$$

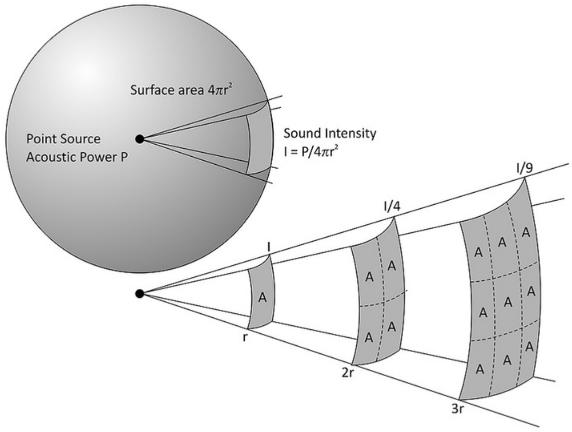


Figure 2.2: Sound power and sound intensity in spherical spreading

where r is the distance from the sound source and N is the factor which is different in shallow water and deep water.

If the propagation is spherical, which is used in nearfield:

$$Geometric\ Spreading\ Loss = 10\log_{10}(I/I_0) = 10\log_{10}(r^2) = 20\log_{10}(r)dB$$

another spreading type is cylindrical spreading which is used to measure long range sound pressure in shallow water. In such case:

$$I = P/2\pi rD$$

where D is the water depth, and r is the distance from the sound source, and the transmission loss can be calculated:

$$Geometric\ Spreading\ Loss = 10\log_{10}(r)$$

A rule which has been used during modelling is that for near-field, r≤D, spherical spreading is used, and for far-field, r≫D, cylindrical spreading is used.

Part of sound energy will be absorbed by different components in seawater, or scattered because of inhomogeneities [28] during propagation. Attenuation caused by absorption and scattering is usually calculated together as the Attenuation Loss, and such attenuation is dependent of frequency, highly significant in high frequency range. Figure 2.3 illustrates different main absorption mechanisms in different frequency ranges. Attenuation Loss can be described as:

$$Attenuation\ Loss = \alpha r$$

where r is the distance from the sound source and α is the factor decided by the sound frequency. α can be calculated by different algorithms according to different frequency range. Absorption mechanisms in frequency region I has not been understood completely, [28] but α in the range is usually low enough to be neglected, for example, transmission loss in 10km range with α 10^{-2} dB/km will be 0.1 dB. The absorption mechanism in region II is the chemical relaxation of $B(OH)_3$ and in region III is the relaxation of $MgSO_4$. Above frquency region III, main absorption is because of shear and bulk viscosity in seawater (BB' curve is the absorption in fresh water).

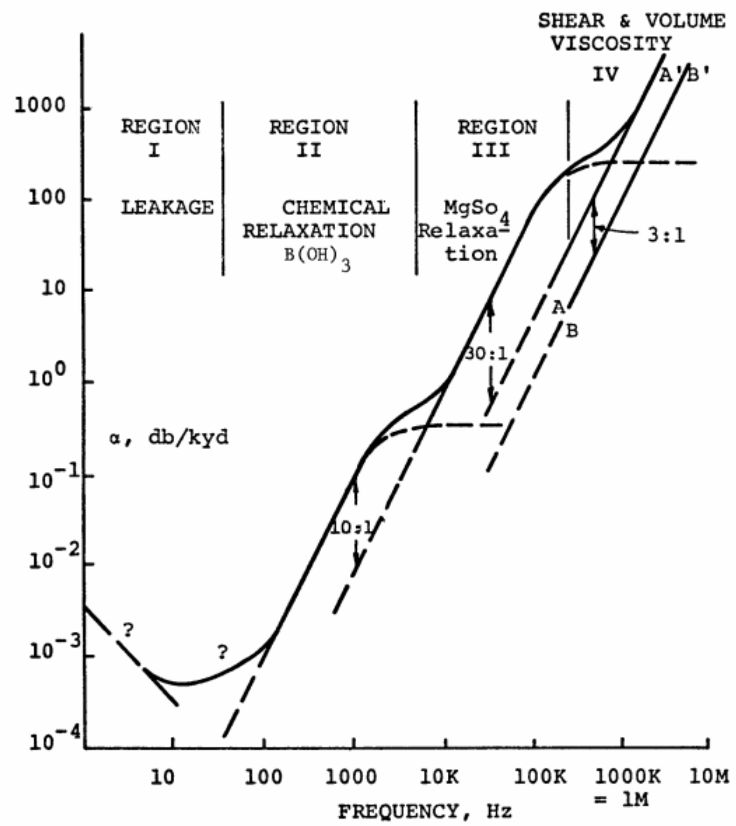


Figure 2.3: Region of different dominant processes of attenuation of sound in seawater.

Apart from geometric spreading loss and attenuation loss, interaction with seafloor and sea surface will also cause loss. For the bottom interaction, the sediment type is the most important factor, especially to decide whether shear waves should be included. If the sediment is clay, silt or sand, the boottom can be modeled to support only compressional waves, else for example, chalk, limestone, basalt or even no sediment over seafloor, shear wave attenuation should be included. Thus a geoacoustic model is applied in the modelling and different parameters have been summarized in Table 2.1 by Hamilton.

Sediment	p(%)	ρ_b/ρ_w	c_p/c_w	$c_p(m/s)$	$c_s(m/s)$	$\alpha_p(dB/\lambda_p)$	$\alpha_s(dB/\lambda_s)$
Clay	70	1.5	1.00	1500	-	0.2	1.0
Silt	55	1.7	1.05	1575	-	1.0	1.5
Sand	45	1.9	1.1	1650	-	0.8	2.5
Gravel	35	2.0	1.2	1800	-	0.6	1.5
Moraine	25	2.1	1.3	1950	600	0.4	1.0
Chalk	-	2.2	1.6	2400	1000	0.2	0.5
Limestone	-	2.4	2.0	3000	1500	0.1	0.2
Basalt	-	2.7	3.5	5250	2500	0.1	0.2

Table 2.1: Parameters used in the geoacoustic modelling.

2.3.3 Ray bending

Ray, as shown in the Figure 2.4, is normal to the wave front and can be used to trace the sound wave propagation. An omnidirectional sound source emits rays in every directions around it and sound source with a certain beam pattern can emits rays in particular directions, e.g., sidescan sonar. Underwater acoustic sound rays are curves because of the inhomogeneities of environment and the most important factor is the sound speed.

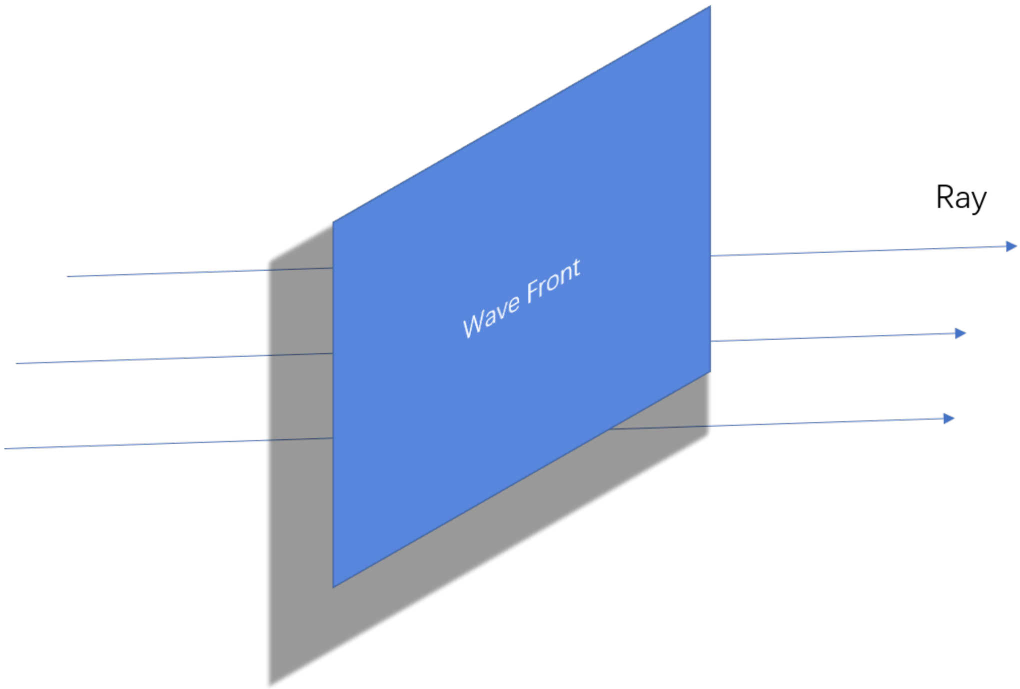
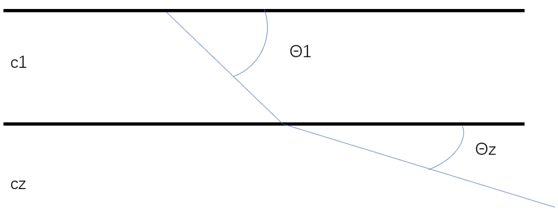
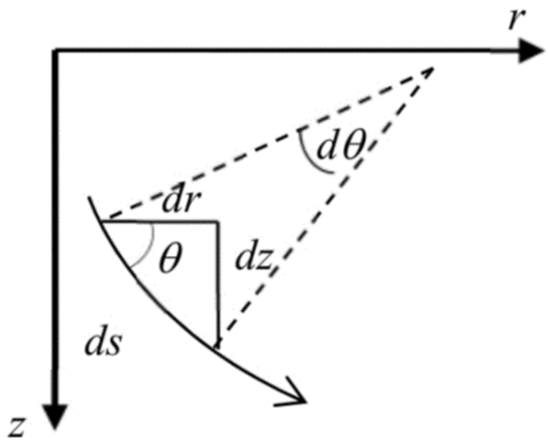


Figure 2.4: wave front and ray



(a) Snell's Law



(b) Curve ray

Figure 2.5: Illustration of sound rays

According to Snell's Law shown in figure 2.5

$$\frac{cos\theta_z}{c_z} = \frac{cos\theta_1}{c_1} = \zeta$$

R is defined as the radius of curvature:

$$R = \frac{ds}{d\theta} = \frac{dz}{sin(\theta)d\theta}$$

considering Snell's Law

$$\frac{dcos(\theta)}{d\theta} = \frac{\zeta dc}{d\theta} = sin(\theta)$$

Then

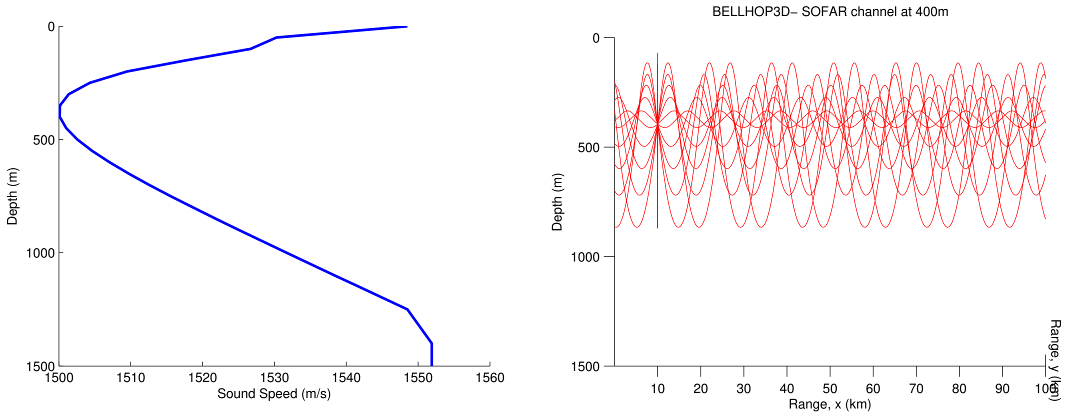
$$R = \frac{dz}{dc\zeta} = \frac{1}{\zeta g(z)}$$

and g(z) is the gradient of sound speed at depth z

$$g(z) = \frac{dc(z)}{dz}$$

If g(z)>0, R>0, then the ray will curve upward, else the ray will curve downward. Therefor the sound wave will always curve toward the depth where the sound speed is the lowest along the z axis and such sound channel in the ocean is called SOFAR (Sound Fixing and Ranging) channel. Sound with low frequency, which means it suffers less absorption loss can propagate thousands of kilometers.

For example, Figure 2.6 is a case of SOFAR channel at 400m depth, where the sound speed is at lowest. The sound rays travel horizontally far from the source at depth around 400m, and curve upward and downward the 400m axis.



(a) Sound speed profile of SOFAR channel

(b) Ray trace of SOFAR channel

Figure 2.6: Illustration of a SOFAR channel

2.3.4 Multi-path

The sound energy can reach the location of interest via many paths, and in underwater acoustics, there are two main factors causing multi-path:

1. Reflection because of interaction with sea surface and seafloor. Such reflection has much more significance in shallow water, shown in Figure 2.7.
2. Ray bending described in **2.3.3** and this is the main reason of multi-path effect in deep water, shown in Figure 2.7.

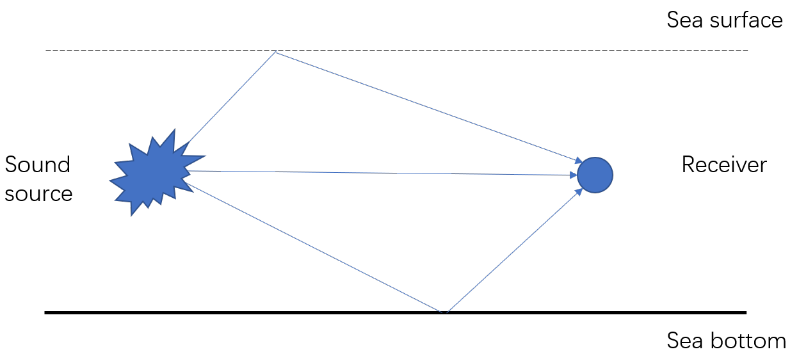


Figure 2.7: Multi-path effect in shallow water

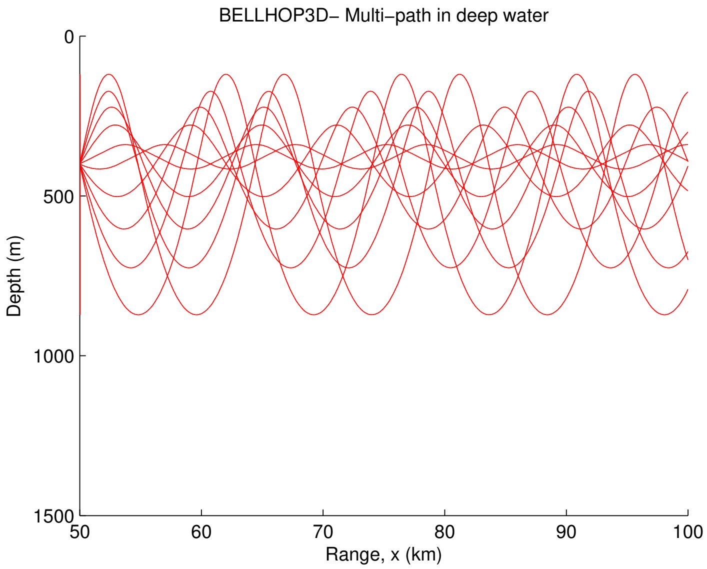


Figure 2.8: Multi-path effect in deep water

2.3.5 Propagation Modelling

To trace the sound wave, ray theory has been used as the basic theory of the modelling. Solution of ray coordinates can be derived from ray equation(2.1)

$$\begin{aligned}\frac{\mathrm{d}x}{\mathrm{d}s} &= c\xi\left(s\right), \frac{\mathrm{d}\xi}{\mathrm{d}s} = -\frac{\mathrm{d}c}{\mathrm{d}x}c^{-2}\\ \frac{\mathrm{d}y}{\mathrm{d}s} &= c\eta\left(s\right), \frac{\mathrm{d}\eta}{\mathrm{d}s} = -\frac{\mathrm{d}c}{\mathrm{d}y}c^{-2}\\ \frac{\mathrm{d}z}{\mathrm{d}s} &= c\zeta\left(s\right), \frac{\mathrm{d}\zeta}{\mathrm{d}s} = -\frac{\mathrm{d}c}{\mathrm{d}z}c^{-2}\end{aligned} \tag{2.1}$$

where c is the sound speed matrix(c_x,c_y,c_z), and the initial conditions(input) including source position(x_0,y_0,z_0) and take-off angles(ξ,η,ζ) are from information obtained in specific sites.

However, ray theory will not be precise if diffraction, absorption and scattering effects are strong, or when the bottom is elastic in shallow sea. To avoid these problems, several models have been added:

1. Absorption loss calculation has been included, and theory can be found in **2.3.2**.
2. Bounce model, which is to include reflection coefficient for elastic bottom in the model, has been used. Relevant theory can be found in **2.3.2**.
3. Removal of infinity data. Some result points in ray theory will go up to infinity because of caustic, and these data have been removed.

3 Modelling set

3.1 Baseline

Bathymetry data used in modelling come from North Sea Bathymetry database provided by The European Marine Observation and Data Network (EMODnet). Data was collected from bathymetric survey in the European seas.

Sound speed profile data come from World Ocean Atlas 2009 database provided by U.S. National Oceanic and Atmospheric Administration (NOAA). Main parameters related to sound speed including temperature, salinity and depth can be obtained in the database.

Seabed composition data come from dbSEABED provided by Institude of Arctic and Alpine Research. Data was collected through bathymetric survey around the world and data in the center of specific offshore wind farm sites will be used.

3.2 Processing platform

MATLAB 2014a was used for modelling and the processing part is called BELLHOP 3D based on ray theory. Input of the data flow include:

1. Environment file(.env): Define the boundary, ray number, beam pattern, frequency range, take-off angles and other basic parameters.
2. Bathymetry file(.bty): Define the water depth in the modelling field.
3. Bottom reflection file(.brc): Define bottom reflection coefficient in different seabed conditions.
4. Sound speed profile file(.ssp): Define sound speed profile in the field.
5. Source beam pattern file(.sbp): Define the beam pattern of the sound source.

Through BELLHOP 3D processing, there will be outputs in several forms for evaluation:

1. Ray trace figure: Illustrates the ray trace in the field.
2. Vertical sound pressure: Results illustrating the vertical sound pressure distribution in a chosen transect.
3. Horizontal sound pressure: Results illustrating the horizontal sound pressure distribution which can be set as the max value along depth.
4. Sound pressure at a certain coordinate.

4 Literature Review

4.1 Offshore Wind farm development in Norway

Offshore wind energy is one of the most important renewable energy sources globally, and Europe is leading both in capacity and technology export. At the end of 2018, the cumulative wind farm capacity of Europe accounted for about 80% of the world's usage. [29] According to EWEA (European Wind Energy Association), the overall wind farm capacity in Europe will be 150,000 MW in 2030, growing from 23,304 MW in 2018 and supplying 14% electricity need in Europe. [29]

Offshore wind farms are usually built in shallow water with depth less than 50m. But as the scale is growing fast, also in order to harvest better wind resources and mitigate conflicts with other stakeholders, offshore wind farms in deep water are becoming more feasible. Today, the market for deep water wind farm is expanding in Europe (North Sea, Atlantic and Mediterranean), Asia (Japan, Korea and China) and the U.S. [29]

According to NVE (Norwegian Water Resources and Energy Directorate), there are 15 zones in Norway considered suitable for offshore wind farm with estimated overall capacity from 4,600 to 12,600 MW. [30] Although Norway has been regarded as a country with very good wind resources, development of wind farms has been relatively limited, compared with other European countries. As of 2019, there is only one floating wind turbine installed by Equinor (former Statoil) off Karmøy, on the west coast of Norway. It has 2.3 MW capacity. In August 2018, the government announced plans for new wind farms in two areas and several proposals are still being discussed in the Parliament.

Overall, the 15 zones shown in Table 4.1 given by NVE are located along the Norwegian coast from south to north, covering 9000 km^2, with different sizes and potential wind turbine types. The area for floating turbines ranges from 500-1500 km^2 and the area for bottom-fixed turbines ranges from 50-300 km^2. [30] In Table 4.1, all 15 zones are categorized into three types according to corresponding assessment of technical and economic feasibility and potential conflicts with other sectors.

1. **A**: Feasible in technology and economy, and will cause little impacts. Before 2025, the grid connection will be completed.
2. **B**: There are some technical or economic challenges, or the wind farm will cause conflicts. But these challenges can be resolved in foreseeable time.
3. **C**: Relevant challenges or conflicts are great that it is hard to solve in a foreseeable time. Although wind energy in these locations can be harvested, but it is not recommended to open them now.

4.2 Potential sound

As stated in section 1.3, potential sound caused by wind farms in these 15 areas can be divided into different groups mainly according to the sound source. Information about these sounds include:

1. Frequency: the range of frequency and the peaking frequency where the sound energy is the greatest. Frequency is related to absorption, reflection and propagation especially for high

Figure 4.1: 15 potential zones for wind farms by NVE

Name	**Location**	**Sea**	**Area(km^2)**	**Water Depth(m)**	**Floating**	**bottom-fixed**	**Feasibility**
Sandskallen	Finnmark	Barents Sea	260	40-80	◯	◯	**A**
Vannøya Nordøst	Troms	Barents Sea	154	20-80	◯	◯	**B**
Auvær	Troms	Barents Sea	105	20-40	×	◯	**B**
Nordmela	Nordand	Barents Sea	332	20-80	◯	◯	**C**
Gimsøy Nord	Nordland	Barents Sea	245	20-40	×	◯	**C**
Trænafjorden-Selvær	Nordland	Norwegian Sea	197	0-60	◯	◯	**B**
Træna Vest	Nordland	Norwegian Sea	773	181-352	◯	×	**B**
Nordøyan-Ytre Vikna	Vikna	Norwegian Sea	140	0-60	×	◯	**B**
Frøyabanken	Frøya	Norwegian Sea	819	160-310	◯	×	**B**
Stadthavet	Nordfjord	North Sea	520	170-210	◯	×	**B**
Olderveggen	Måløy	North Sea	76	5-60	×	◯	**B**
Frøyagrunnene	Bremangerlandet	North Sea	58	5-60	×	◯	**A**
Utsira Nord	Haugesund	North Sea	1010	185-280	◯	×	**A**
Sørlige Nordsjø I	150km offshore	North Sea	1375	40-70	◯	◯	**A**
Sørlige Nordsjø II	150km offshore	North Sea	2591	40-70	◯	◯	**A**

◯ means certain technology can be applied and × means certain technology can not be applied

Table 4.1: 15 potential zones for wind farms by NVE

frequency sound. Frequency also affects the impact on marine populations and weighting functions.

2. Sound Pressure Level(zero to peak): SPL_{z-p} is the maximum sound pressure level over a given time. It is important for transient sound with high energy, e.g., explosion.

$$SPL_{z-p} = 20\log_{10}(\frac{P_{max}}{P_{ref}})$$

3. RMS Sound Pressure Level: SPL_{rms} is the mean square sound pressure level over a given time. It is important for continuous sound, e.g., operational sound and shipping sound.

$$SPL_{rms} = 20\log_{10}(\frac{P_{rms}}{P_{ref}})$$

4. Sound Exposure Level: SEL is the time integral of square sound pressure over the pulse. It is important for all transient sound.

$$SEL = 10\log_{10}\left(\int_0^T \frac{(p\,(t))^2}{{P_{ref}}^2}\,\mathrm{d}t\right)$$

   SEL can usually easily be calculated from SPL:

$$SEL = SPL + 10\log_{10} T$$

   T is the sound time period.

5. Culmulative SEL: $SEL_{cumulative}$ is the sum of SEL during a event time, e.g., pile driving during construction.

$$SEL_{cum} = SEL + 10\log_{10} N$$

   N is the number of impulses.

6. Beam pattern: If the sound source is not omnidirectional, beam pattern is needed for modelling sound energy emitted in different angles.

7. In situ information: depth of sound source, time of the event, etc.

This thesis will not model every type sound during wind farm life cycle due to limited time and resources, but cover most concerned and potentially negative sound. Information about these sound source are mainly collected via technical assessment report and help from DHI A/S.

4.2.1 Geophysical Survey

Geophysical surveys are conducted at the early stage during wind farm life cycle. The results are used to choose suitable sites, and/or obtain parameters for engineering after a site has been chosen. Geophysical surveys can also take place for biological and archaeological investigation and conservation. However, in the thesis, only engineering surveys will be discussed because the main potential impact to marine life is from equipment used in high-resolution geophysical engineering survey.

Considering the fact that wind turbines are located in relatively shallow water, mid-frequency intermediate penetrating systems are typically used. The suite of equipment used during a typical shallow survey consists of: single beam and multibeam echosounders which provide water depths and seafloor morphology; a side scan sonar that provides acoustic images of the seafloor; a subbottom profiler (sparker or boomer) which provides 20 to 200 m sub-seafloor penetration with a 6 to 20 cm resolution; and a single channel seismic system with 40 to 600 m sub-seafloor penetration (multichannel used less frequently and only when deeper imaging is needed). The echosounders and subbottom profilers are generally hull-mounted. All other equipment is usually towed behind the vessel. Boomers [31] and Sparkers [32] are showin in Figure 4.2 and Figure 4.3, respectively.

Boomers generate sound signal by relative electromagnetic movement between the flat coil and the plate below it. The movement will cause seawater cavitation which acts as an underwater sound source. Boomer has widely used in water depth less than 80 meters, and also occasionally acts as supplement in deeper water. [33] The frequency ranges from 300 Hz to 6 kHz with peak frequency at around 2.5 kHz. The sound source level is typically 212-215 dB re 1μPa at 1m, with 200-300J energy.

Sparkers generate pressure impulse sound signal by vaporizing water using spark. Sparker has been widely used in deep water, e.g., floating wind farm survey. The frequency ranges from 40 Hz to 1.5 kHz with peak frequency at around 1.25 kHz. The sound source level is typically 226 dB re 1μPa at 1m.

4.2.2 Construction

Most offshore wind farms in Europe nowadays are located in the North Sea and Baltic Sea areas, mostly because of suitable water depth ($< 50m$) there. Thus most installations are limited to monopile, jacket and gravity foundations. [34] However, following the development of floating wind turbine technology and interest in deep-water offshore wind energy, there will likely be more floating installations in the future. According to EWEA, there are already 9 floating units installed in Europe (Figure 4.5).

Different types of construction will produce different level of underwater sound. Here we focus on the sound produced during Monopile and Jacket foundations since these two types are mostly possible to be used and will produce most sound.

For Monopile foundation, sound will be produced mainly from pile-driving, during which a steel pile will be forced by hammering into the seafloor to provide foundation for a wind turbine above. When the pile is being hammered, sound from the striking, pile vibration will be produced. Although there will also be sound produced above sea surface, its contribution can be neglected, especially in far field. [6] The most important parameters related to sound level during pile driving is the diameter of monopile. A 3 MW size wind turbine usually needs 5 m diameter monopile, [35] with SPL_{z-p} 270 dB re 1μPa. Although there are some conceptual design for monopile wind turbines in deeper water, jacket foundation is still the most suitable for water depth between 30-60m.

Jacket foundation typically has four piles in each corner of the frame at seafloor. Before the jacket structure is installed, pre-piling is needed to hammer these four piles into the seabed and sound is mainly produced during this period. Each pile usually has 30-50m length and 1.8m diameter. The SPL_{z-p} is around 260 dB re 1μPa and SEL source level is around 210 dB re 1μPa^{2}s. [36]

Figure 4.2: AA251 Boomer Plate

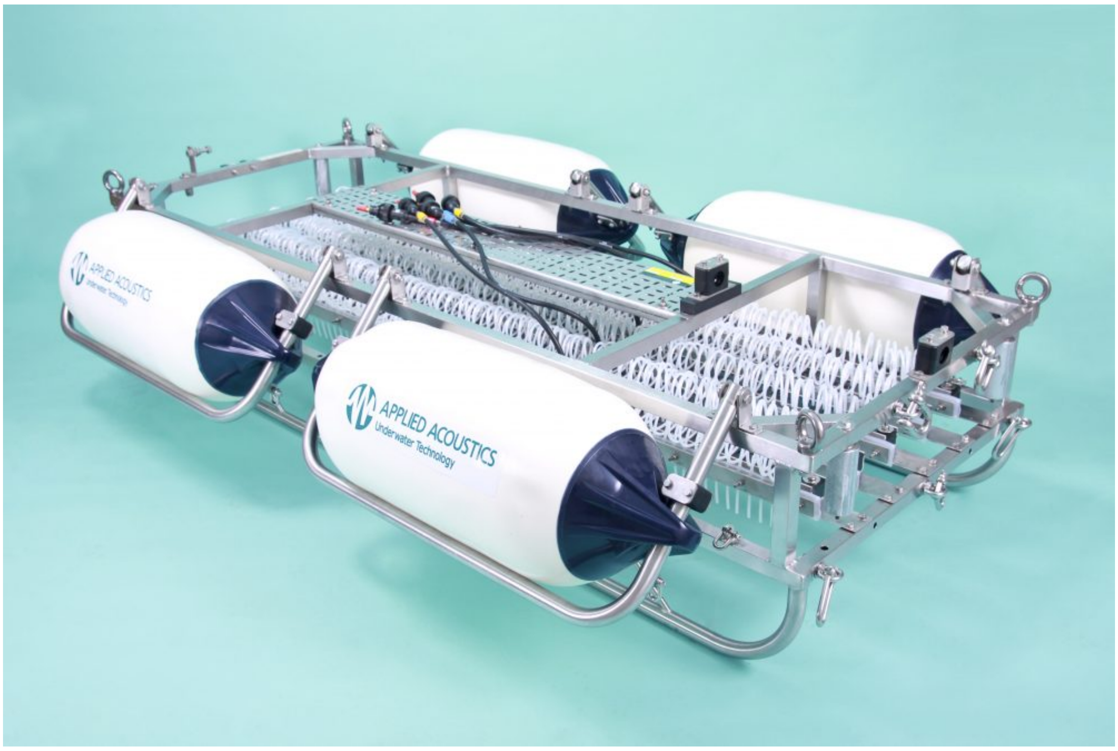


Figure 4.3: Dura-Spark-UHD

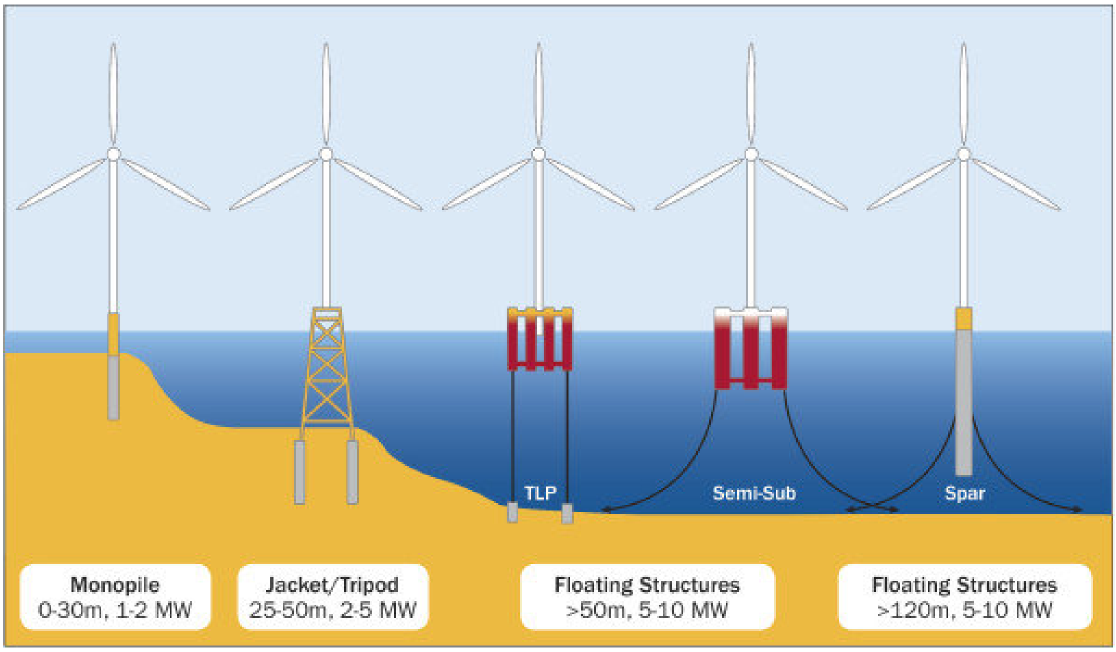


Figure 4.4: Different types of wind turbines

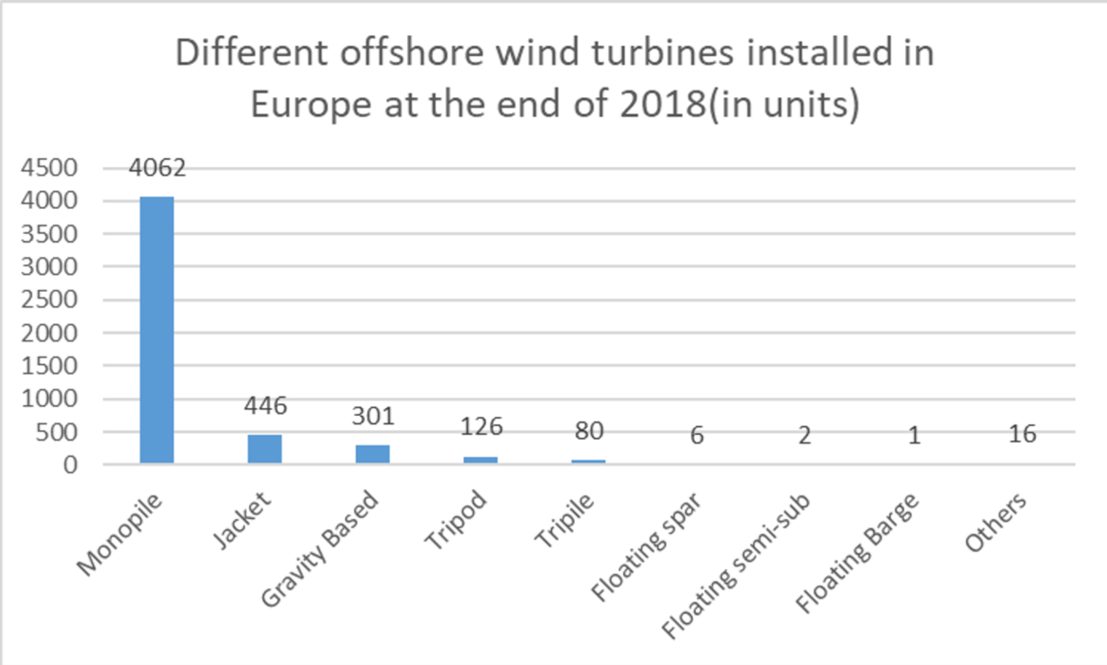


Figure 4.5: Different offshore wind turbines installed in Europe at the end of 2018(in units) by EWEA

4.2.3 Operation

The sound produced during operation phase has the lowest sound level, but has the longest period. A wind turbine is typically designed to maintain 20-25 years,[37] and that means the impact from operational sound can affect more than one generation of marine populations. Thus assessment and modelling of operation sound is not just necessary but also should be included in related standard.

Information and measurement about operational sound is limited since most assessment focus on construction sound. But according to literature collected, there are two main sound sources during operation:

1. Aerodynamic sound from the blades which penetrates into the water. This type of sound will be mostly reflected back to the air when it goes through the sea surface interface.

2. Waterborne sound caused by mechanical vibration. This type of sound will be the main contributor and can propagate to the most distant biological receivers.

4.3 Criteria of evaluation

In the thesis, the focus is on the potential impact of sound on fish and marine mammals which inhabit near the wind farm. Thus relevant criteria for different consequences under sound exposure is needed. Criteria about fish species are mainly from *Sound Exposure Guidelines for Fishes and Sea Turtles* by Popper et.al, 2014, and criteria about marine mammals are mainly from *Aquatic Mammals Noise Exposure Criteria* [26] Southal et.al, 2007.

In summary, impacts from sound can be categorized into the following groups:

1. Injury or fatal consequence: Marine species may suffer from auditory tissue damage, Barotrauma or even death under certain types of sound exposure. These occurrences are rare when the operation is properly mitigated.
2. Temporary or permanent loss of hearing ability: Marine species may be affected by from TTS (Temporary hearing Threshold Shift) or PTS (Permanent hearing Threshold Shift). Offshore operations have mitigation measures in place to greatly reduce the risk of PTS.
3. Behaviour change: Marine species may exhibit a temporary from behaviour change such as a startle reaction, or a change in swimming pattern and feeding behaviour. These are typically of very short duration (a startle response is measured in 1 0r 2 seconds). If the swimming pattern is affected such that the school of fish leaves an area then the catch rates for fisheries may be affected.

4.3.1 Marine mammals

To ensure that the evaluation is scientific and aligned to existed acknowledged criteria, two criteria will be included: 1) U.S. Marine Mammal Protection Act [38] and 2)Aquatic Mammals Noise Exposure Criteria provided by Southall et al, 2007. Summary of these criteria are listed in Table 4.2, and metrics including $SPL_{zero-peark}$, RMS SPL and SEL have been used.

4.3.2 Fish species

As stated in section **1.4**, research about fish under sound exposure is limited compared with marine mammals, especially considering that it is not realistic to develop weighting functions for each species. The author did not find many reliable criteria for certain fish species, but there is one developed by Popper et.al (2014) within which criteria are given in different production events (Table 4.3).

Effect	**Species**	**Limit above these dB's**
Auditory Injury	Pinnipeds	(RMS)190 dB re $1\mu Pa$
Auditory Injury	Cetaceans	(RMS)180 dB re $1\mu Pa$
Behaviour disturbance	Both	(RMS)160 dB re $1\mu Pa$
TTS injury	Both	(SEL)195 dB re $1\mu Pa^2s$
PTS injury	Both	(SEL)215 dB re $1\mu Pa^2s$
TTS onset	Pinnipeds	(M SEL)171 dB re $1\mu Pa^2s$
TTS onset	Cetaceans	(M SEL)183 dB re $1\mu Pa^2s$
PTS onset	Pinnipeds	(M SEL)186 dB re $1\mu Pa^2s$
PTS onset	Cetaceans	(M SEL)198 dB re $1\mu Pa^2s$
TTS onset	Pinnipeds	(Peak)212 dB re $1\mu Pa$
TTS onset	Cetaceans	(Peak)224 dB re $1\mu Pa$
PTS injury onset	Pinnipeds	(Peak)218 dB re $1\mu Pa$
PTS injury onset	Cetaceans	(Peak)230 dB re $1\mu Pa$

Table 4.2: Evaluation criteria for marine mammals

Pile driving			
Fish type	Unrecoverable Injury	Recoverable Injury	TTS
No swim bladder	(SEL)219 dB re 1$\mu Pa^2 s$ (Peak)213 dB re 1μPa	(SEL)216 dB re 1$\mu Pa^2 s$ (Peak)213 dB re 1μPa	(SEL)186 dB re 1$\mu Pa^2 s$ (SEL)186 dB re 1$\mu Pa^2 s$
Swim bladder not involved in hearing	(SEL)210 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)203 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)186 dB re 1$\mu Pa^2 s$ (SEL)186 dB re 1$\mu Pa^2 s$
Swim bladder involved in hearing	(SEL)207 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)203 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)186 dB re 1$\mu Pa^2 s$ (SEL)186 dB re 1$\mu Pa^2 s$
Larvae	(SEL)210 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	- -	- -
Seismic survey			
No swim bladder	(SEL)219 dB re 1$\mu Pa^2 s$ (Peak)213 dB re 1μPa	(SEL)216 dB re 1$\mu Pa^2 s$ (Peak)213 dB re 1μPa	(SEL)186 dB re 1$\mu Pa^2 s$ (SEL)186 dB re 1$\mu Pa^2 s$
Swim bladder not involved in hearing	(SEL)210 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)203 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)186 dB re 1$\mu Pa^2 s$ (SEL)186 dB re 1$\mu Pa^2 s$
Swim bladder involved in hearing	(SEL)207 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)203 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	(SEL)186 dB re 1$\mu Pa^2 s$ (SEL)186 dB re 1$\mu Pa^2 s$
Larvae	(SEL)210 dB re 1$\mu Pa^2 s$ (Peak)207 dB re 1μPa	- -	- -
Operation			
No swim bladder	- -	- -	- -
No swim bladder	- -	- -	- -
Swim bladder involved in hearing	- -	(RMS)170 dB re1μPa for 48h	(RMS)158 dB re 1μPa for 12h
Larvae	- -	- -	- -

Table 4.3: Evaluation criteria for fish species,"-" means no quantitative standard existed

5 Results

Modelling has been done at five sites which considered as Category A site in NVE(Norwegian Water Resources and Energy Directorate) report: Sandskallen(Finnmark), Frøyagrunnene(Sogn and Fjordane), Utsira Nord(Haugesund), Sørlige Nordsjø I and II(two sites close to each other in North Sea),

Results of modelling include:

1. Sound pressure (maximum-over-depth) horizontal propagation, and different metrics will be used in different scenarios
2. Sound pressure (maximum-over-depth) after M-frequency weighting propagation
3. Sound pressure vertical propagation, and several slices in one site will be researched
4. Impact level area ranges for different marine populations
5. Variation of results in different seasons

Summary of different metrics which will be used have been listed in Table 5.1 (◯means metric will be included and ×means metric will not be included.). Shipping sound will not be included because specific shipping activities data is lacking for these areas. Results for sound pressure impact area will be presented in this part, and results for sound pressure horizontal and vertical distribution will be presented in the Appendix.

Phase	SPL(RMS)	SPL(zero-peak)	SEL	Seasonal variations
Geophysical Survey Phase	◯	×	◯	Yes
Construction Phase	×	◯	◯	Yes
Operation Phase	◯	×	×	Yes

Table 5.1: summary of metrics included in modelling.

5.1 Sandskallen

5.1.1 Basic Information

Sandskallen OWF(Offshore Wind Farm) has an area of 260 km^2 in plan and will likely be constructed 14 km off Sørøya Island in Finnmark (Figure 5.1). Water depths here varies from 40 m to 80 m, so it is most suitable for Jacket wind turbines and also applicable for floating turbines. Advantages in this site is that average wind speed can be up to 9.4 m/s and shipping activity nearby is moderate. Also there is a developing electricity demand in the area where mining and petroleum activities are increasing.

However, according to NVE, Norwegian Directorate of Fisheries does not recommend the construction because of frequent fishing activities in the area, and there are also several cod spawning areas nearby (Figure 5.2, Red fish labels represents fish farms, Pink line area represents active fishing spots, Black line area represents passive fishing spots and green line area represents spawning area). Prudent environmental impact analysis necessitates acoustic modeling before construction.

Figure 5.1: Location and area of sandskallen site

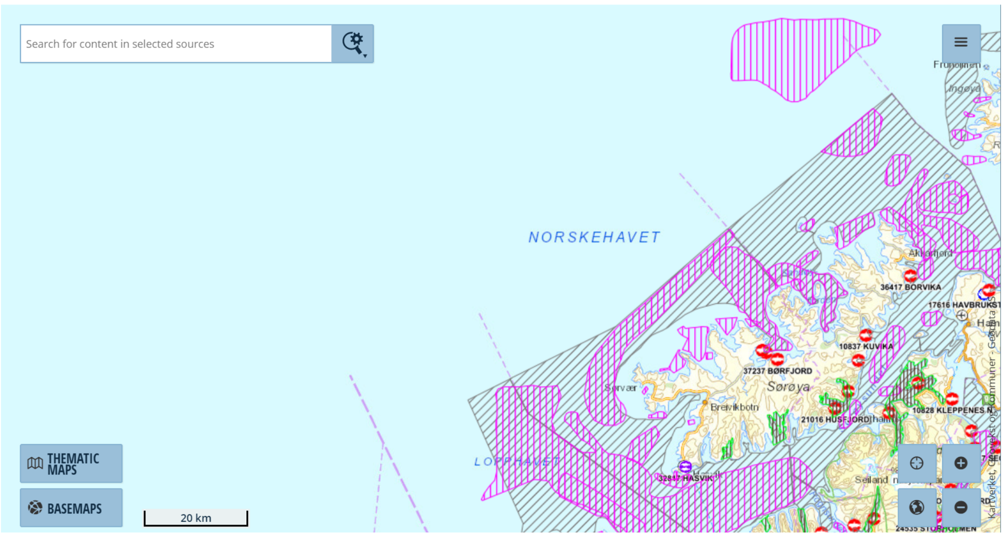


Figure 5.2: Activities around Sandskallen OWF

5.1.2 Bathymetry

Due to constriction of time and resources, it was not realistic to conduct a seabed sampling on site. Consequently available bathymetry database will be used, e.g., dbSEABED database which integrates thousands of other individual datasets.

Since water depth in the area is relatively shallow, seabed layer composition and thickness of each layer should be considered as important factors in modelling. According to the dbSEABED database provided by Institute for Arctic and Alpine Research, seabed sediment layer in this area mainly consists of rock, gravel and sand (Figure 5.3), for example, at center of Sandskallen site, the seabed layer consists of 17% gravel and 83% sand.

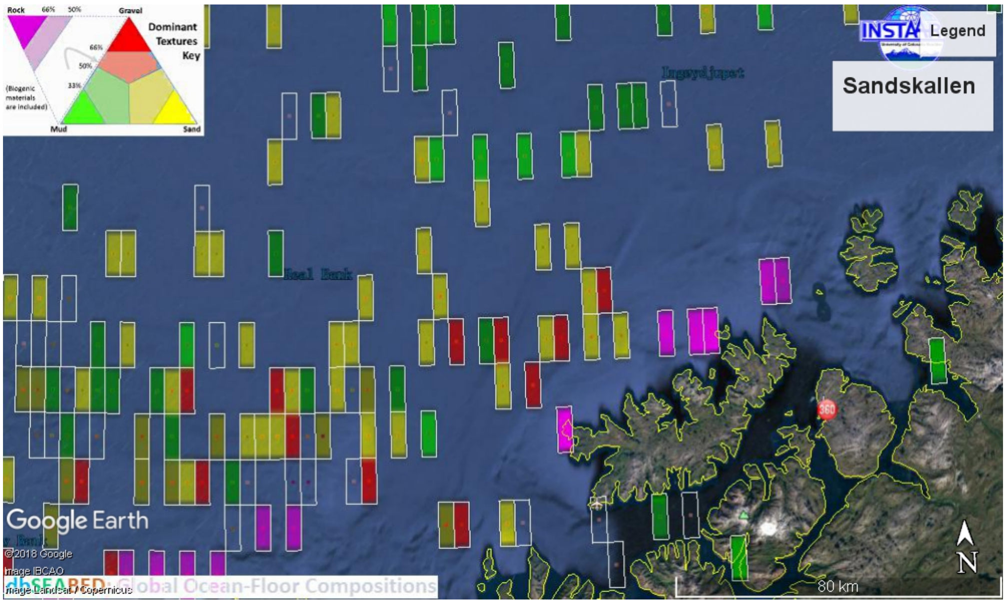


Figure 5.3: Seabed composition in Sandskallen site

5.1.3 Sound speed Profile in different seasons

Sandskallen site is located in Barents Sea. According to WOA09 database provided by NOAA (National Oceanic And Atmospheric Administration), sound speed in shallow water (less than 100m) increases from January to August, and decreases back until December (Figure 5.4 and 5.5). Such variation means modelling in different months is necessary due to ray bending phenomenon discussed in **2.3.3**.

To describe different impacts in different seasons in a year, and also to give recommendation about time to conduct related survey and construction, sound speed profiles in March, August and December are included (Figure 5.5).

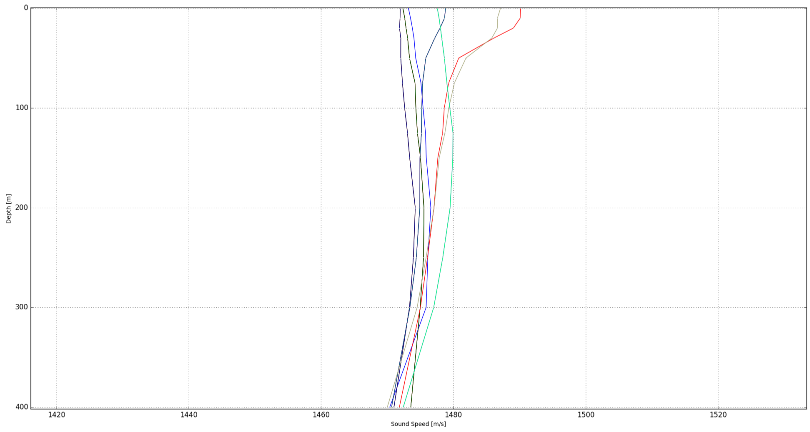


Figure 5.4: SSP(sound speed profile) variation in one year in Sandskallen site

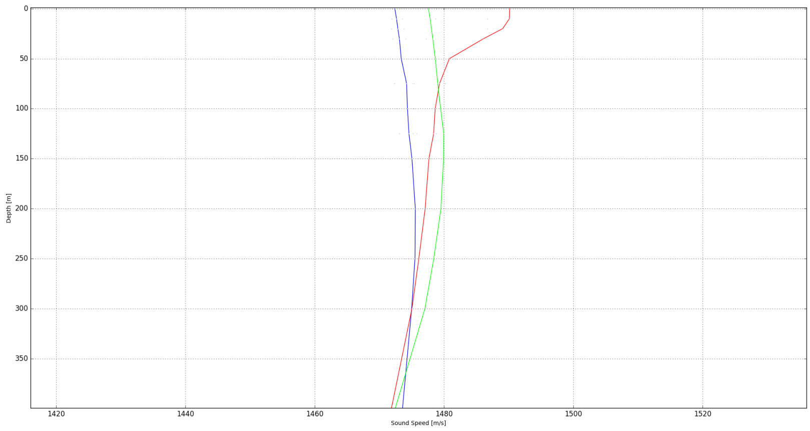


Figure 5.5: SSP in March(blue), August(red) and December(green)

5.1.4 Results-Geophysical Survey Phase

Although water depth surrounding Sandskallen site can reach up to 400m, construction will only happen in area with water depth ranging from 40m-80m. Thus the most suitable equipment for geophysical survey phase is the Boomer. As stated in **3.2.1**, a typical Boomer with 212 dB re 1μPa SPL and 192 dB re 1μPa^{2}s SEL will be used in modelling (Table 5.2, $R_{3,max}$means the max range of certain sound pressure in January, $R_{8,max}$means the max range of certain sound pressure in August and $R_{12,max}$means the max range of certain sound pressure in December.)

Sound source	AA251 Boomer Plate
Energy/shot	50-300J
Average energy/s	600J
Bandwidth	300Hz-6kHz
Source Level(SPL at 1m)	212 dB re 1μPa
Source Level(SEL at 1m)	192 dB re 1μPa$^2 s$
Pulse length	120-180μs

Table 5.2: Sound source information

SEL(dB re 1μPa$^2 s$)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
180	$< 5m$	$< 5m$	$< 5m$	200	$< 5m$	$< 5m$	$< 5m$
170	$< 20m$	$< 20m$	$< 20m$	190	$< 10m$	$< 10m$	15m
165	30m	28m	34m	185	28m	28m	30m
160	54m	56m	60m	180	52m	52m	54m
155	96m	100m	98m	175	98m	96m	96m
150	166m	294m	278m	170	284m	290m	298m
145	626m	1.6km	650m	165	636m	708m	676m
140	1km	1.7km	1.1km	160	958m	2km	1.9km
135	16km	10.6km	2.3km	155	15.4km	3.2km	3.2km
130	39km	11.7km	5.2km	150	40.4km	6.2km	8.4km
125	43.1km	14.7km	16.6km	145	42.4km	12.1km	16.6km
120	45.1km	15.8km	42.9km	140	46km	13.4km	43km
115	47km	16.6km	50km	135	47.6km	17.6km	50km
110	$> 50km$	$> 30km$	$> 50km$	130	50km	43.1km	$> 50km$

Table 5.3: Result for Geophysical survey phase at Sandskallen

From results in Table 5.3, propagation range of sound pressure is more limited in August (R8, max), and it can be explained by differences of sound speed profile: Both in March and December, there is a surface sound channel which facilitates the sound wave such that it suffers less transmission loss and propagates further.

Using August as an example, and starting with a source pressure level (referenced by convention as 1 meter from the sound source) of 212 dB re 1 μPa and sound exposure level (for marine fauna) at 192 dB re 1 μPa^{2}s, then SEL 180 dB re 1 μPa^{2}s is present less than 5 meters from the sound source (table 5.3). Likewise, at 100 meters from the sound source the sound exposure level is down to 155 dB re 1 μPa^{2}s. For sound pressure levels the distance to (RMS)180 dB re 1μPa is 52-54 meter.

5.1.5 Evaluation-Geophysical Survey Phase

Table 5.4 illustrates the evaluation results of geophysical survey phase according to criteria given in **3.3.1** and **3.3.2**. It can be observed that potential adverse effects will be limited to less than 10 meters.

Popper et al, 2014 showed the so-called temporary threshold shift (TTS) levels, i.e. temporary diminished hearing sensation followed by full recovery for different types of fish. Given that this scenario is only viable for sound levels between 203 dB SEL and 186 dB SEL for some fish species, the modeling for Sandskallen shows that this can only occur in a zone less than 5 meters from the sound sources. Furthermore, this would only apply to fish that would remain within this sound field for a period of time, i.e. the target fish would need to swim within the 5 m zone during sound emission but this is a highly unlikely natural event.

Using Table 4.2, we see that PTS onset for cetaceans is at sound exposure levels greater than 183 dB re 1 μPa^{2}s. This situation would only occur closer than 5 meters from the sound source, i.e. a highly unlikely situation in the real world. A behavioural disturbance (i.e. a marine mammal sensing and reacting to sound) could occur when sound exposure levels are greater than (RMS) 160 dB re 1µPa. This could occur if the marine mammal was closer than 958 meters to the sound source in March to closer than 2 km to the sound source in August.

From evaluation above, it is recommended to confirm existence and distance from the sound source of marine mammals nearby. This can be done by trained Marine Mammal Observers.

Limit	R_{max} in March	R_{max} in August	R_{max} in December
Auditory Injury for Pinnipeds			
(RMS)190 dB re 1μPa	$< 10m$	$< 10m$	15m
Auditory Injury for Cetaceans			
(RMS)180 dB re 1μPa	52m	52m	54m
Behaviour disturbance for marine mammals			
(RMS)160 dB re 1μPa	958m	2km	1.95km
TTS onset for Pinnipeds			
(M SEL)171 dB re 1$\mu Pa^2 s$	$< 20m$	$< 20m$	$< 20m$
TTS onset for Cetaceans			
(M SEL)183 dB re 1$\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
PTS onset for Pinnipeds			
(M SEL)186 dB re 1$\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
TTS injury for fish speices			
(SEL)186 dB re 1$\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$

Table 5.4: Evaluation of results in Geophysical Survey phase

5.1.6 Results-Construction Phase

Water depth in construction area ranges from 40m-80m. Thus the most suitable foundation is the Jacket foundation. As stated in **3.2.2**, a typical pile driving in one corner of the frame (30m length, 1.8m diameter) will produce source SPL_{z-p} 240 dB re 1μPa and source SEL 210 dB re 1μPa^{2}s.

Sound source	Jacket foundation pile driving
Pile length	30m
Energy per stroke	412KJ
Duration	319min
Source Level(SPL_{z-p} at 1m)	240 dB re 1μPa
Source Level(SEL at 1m)	210 dB re 1μPa$^2 s$

Table 5.5: Sound source information

SEL(dB re 1μPa$^2 s$)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
200	$< 5m$	$< 5m$	$< 5m$	230	$< 5m$	$< 5m$	$< 5m$
190	$< 10m$	$< 10m$	$< 10m$	220	$< 10m$	$< 10m$	$< 10m$
185	20m	16m	20m	215	20m	17m	19m
180	32m	24m	32m	210	32m	28m	32m
175	56m	40m	56m	205	58m	48m	57m
170	140m	124m	132m	200	147m	128m	136m
165	408m	460m	472m	195	400m	404m	408m
160	3.36km	1.8km	1.1km	190	952m	1.7km	952m
155	6.72km	2.3km	3.4km	185	16.7km	2.7km	3.4km
150	26.74km	7.2km	12.9km	180	33.4km	7.2km	12.9km
145	46.76km	9.7km	19.7km	175	46.8km	10.2km	19.7km
140	50km	14.5km	46.8km	170	50km	14.5km	46.8km
135	$> 50km$	21.2km	$> 50km$	165	$> 50km$	21.2km	$> 50km$

Table 5.6: Result for Construction phase at Sandskallen

From results in Table 5.6, propagation range of sound pressure has similar features in Geophysical survey phase: propagation in August is most limited.

5.1.7 Evaluation-Construction Survey Phase

Table 5.7 illustrates the evaluation results of construction phase according to criteria given in **3.3.1** and **3.3.2**. It can be observed that most effects nincluding TTS, PTS will be limited to under 200m range, and even near field($< 10m$), there will not be significant impact. From evaluation above, it is recommended to confirm existence and distance from the sound source of marine mammals nearby.

5.1.8 Results-Operation Phase

According to the assessment by Marine Scotland, [39] operation sound of Jacket foundation is at the lowest level compared with Monopile and Gravity foundation. The sound pressure emitted from Jacket foundation wind turbines is below the background sound, and modelling results will not be presented here since no effects can be observed.

Limit	R_{max} in March	R_{max} in August	R_{max} in December
TTS onset for Pinnipeds			
(Peak)212 dB re 1μPa	20-32m	17-28m	19-32m
TTS onset for Cetaceans			
(Peak)224 dB re 1μPa	$< 10m$	$< 10m$	$< 10m$
PTS injusry onset for Pinnipeds			
(Peak)218 dB re 1μPa	10-20m	10-17m	10-19m
PTS injury onset for Cetaceans			
(Peak)230 dB re 1μPa	$< 5m$	$< 5m$	$< 5m$
TTS onset for Pinnipeds			
(M SEL)171 dB re 1μPa^2s	140m	124m	132m
TTS onset for Cetaceans			
(M SEL)183 dB re 1μPa^2s	20-32m	16-24m	20-32m
PTS onset for Pinnipeds			
(M SEL)186 dB re 1μPa^2s	20m	16m	20m
PTS onset for Cetaceans			
(M SEL)198 dB re 1μPa^2s	5-10m	5-10m	5-10m
TTS injury for fish speices			
(SEL)186 dB re 1μPa^2s	10-20m	10-16m	10-20m
Unrecoverable Injury for fish species			
(Peak)207 dB re 1μPa^2s	32-58m	28-48m	32-57m

Table 5.7: Evaluation of results in Construction phase

5.2 Utsira Nord

5.2.1 Basic Information

Utsira Nord OWF is located 22km off the coast of Haugesund, and has an area of 1010 km^2 (Figure 5.6), Water depth here varies from 185m to 280m, so it is most suitable for floating wind turbine construction. Advantages in this site is that average wind speed can be up to 10.2 m/s, which is one best wind condition of 15 potential zones.

However, according to NVE, traffic activities is extensive here. There are also areas of active, passive fishing and spawning nearby (Figure 5.7). To evaluate potential impact on these areas in the future, modelling is necessary.

5.2.2 Bathymetry

According to the dbSEABED database, seabed sediment layer in this area mainly consists of mud and sand(see Figure 5.8), for example, at center of Sandskallen site, the seabed layer consists of nearly 100% mud.

5.2.3 Sound speed Profile in different seasons

Utsira Nord site is located in North sea. According to WOA09 database, sound speed in shallow water (less than 100m)increases from January to August, and decreases back until December (Figure 5.9). And such variation means modelling in different months is necessary for the same

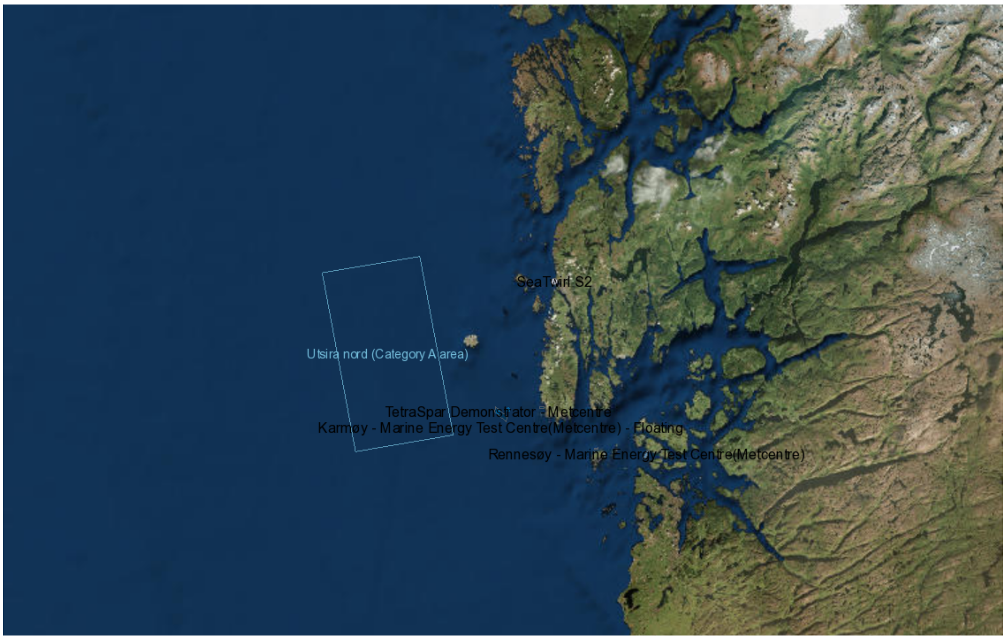


Figure 5.6: Location and area of Utsira Nord site

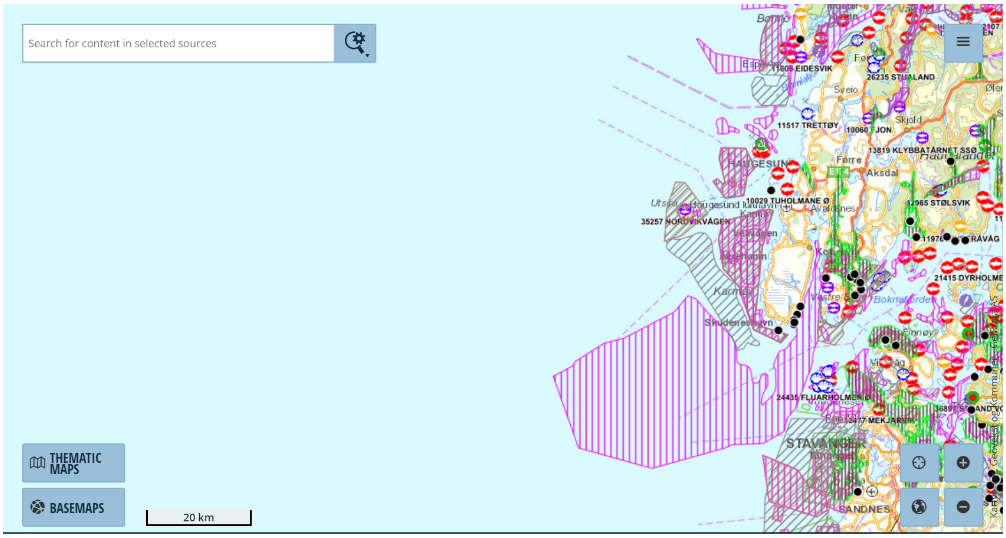


Figure 5.7: Activities around Utsira Nord OWF

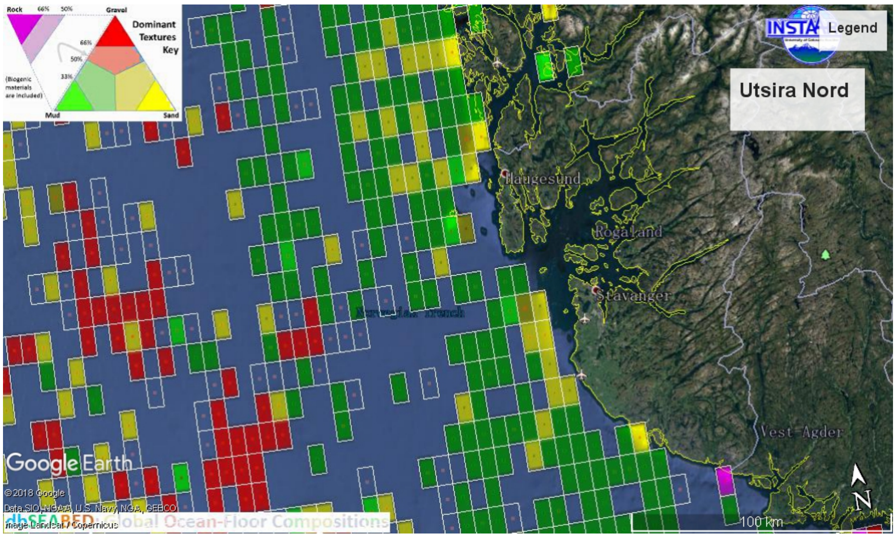


Figure 5.8: Seabed composition in Utsira Nord site

reason in Sandskallen site.

To describe different impacts in different seasons in a year, and also to give recommendation about time to conduct related survey and construction, sound speed profile in March, August and December will be included.

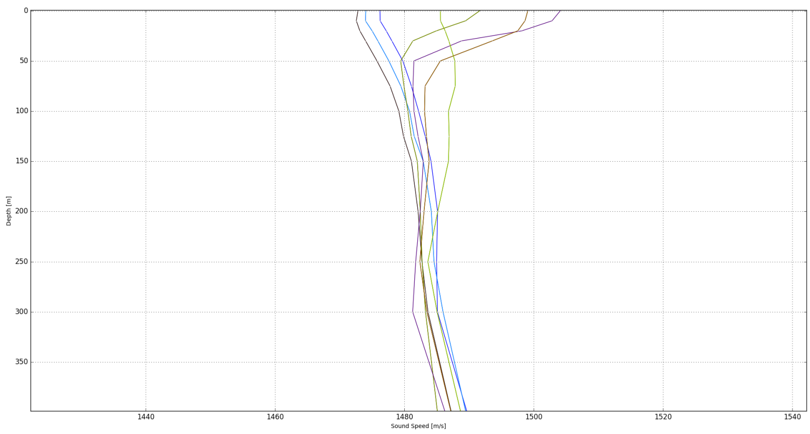


Figure 5.9: SSP(sound speed profile) variation in one year in Utsira Nord site

5.2.4 Results-Geophysical Survey Phase

Water depth surrounding Utsira Nord is relatively deep, Thus the most suitable equipment for geophysical survey phase is the Spark. As stated in **3.2.1**, a typical Spark with 226 dB re 1μPa

SPL and 197 dB re 1 μPa2s SEL will be used in modelling (Table 5.8)

Sound source	Dura-Spark UHD
Bandwidth	300Hz-1.2kHz
Set	3 or 5 arrays of 80 tips
Source Level(SPL at 1m)	226 dB re 1μPa
Source Level(SEL at 1m)	197 dB re 1μPa^2s
Pulse length	0.5-1.5ms

Table 5.8: Sound source information

SEL(dB re 1μPa^2s)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
180	$< 10m$	$< 10m$	$< 10m$	210	$< 10m$	$< 10m$	$< 10m$
170	30m	29m	29m	200	27m	28m	26m
165	56m	54m	55m	195	49m	47m	49m
160	98m	97m	105m	190	89m	81m	87m
155	170m	173m	181m	185	157m	153m	143m
150	314m	280m	308km	180	268m	253m	273m
145	2.9km	452m	1.1km	175	1.3km	409m	1.4km
140	4.2km	4.5km	3.2km	170	4km	4.8km	3.2km
135	11.0km	19.8km	7.2km	165	11km	20km	7.4km
130	38.3km	21.6km	28.6km	160	39km	22km	29km
125	$> 40km$	23km	37.7km	155	$> 40km$	24.4km	37.9km

Table 5.9: Results for Geophysical survey phase at Utsira Nord

Results in Table 5.8 has similar features with results in Sandskallen site, and this is because the similar variation of sound speed profile through one year.

5.2.5 Evaluation-Geophysical Survey Phase

Table 5.10 illustrates the evaluation results of construction phase according to criteria given in **3.3.1** and **3.3.2**. It can be observed that impact area in Utsira Nord site will be larger than Sandskallen site, especially the range of auditory injury impact (up to 273m from the sound source for SPL's an up to only 10 meters from the sound source for SEL) and behaviour disturbance (up to 39km from the sound source for SPL (RMS)160 dB re 1μPa).

This implies that biological assessment should be done before and after the geophysical survey. Since the results are from modelling and many environment parameters are not obtained by in-site sampling, more detailed modelling should also be done before the survey.

Limit	R_{max} in March	R_{max} in August	R_{max} in December
Auditory Injury for Pinnipeds			
(RMS)190 dB re $1\mu Pa$	89m	81m	87m
Auditory Injury for Cetaceans			
(RMS)180 dB re $1\mu Pa$	268m	253m	273m
Behaviour disturbance for marine mammals			
(RMS)160 dB re $1\mu Pa$	39km	22km	29km
TTS onset for Pinnipeds			
(M SEL)171 dB re $1\mu Pa^2 s$	30m	29m	29m
TTS onset for Cetaceans			
(M SEL)183 dB re $1\mu Pa^2 s$	$< 10m$	$< 10m$	$< 10m$
PTS onset for Pinnipeds			
(M SEL)186 dB re $1\mu Pa^2 s$	$< 10m$	$< 10m$	$< 10m$
TTS injury for fish speices			
(SEL)186 dB re $1\mu Pa^2 s$	$< 10m$	$< 10m$	$< 10m$

Table 5.10: Evaluation of results in Geophysical Survey phase

5.2.6 Results-Construction phase

During construction phase of a floating wind turbine, suction anchors will be put into the seabed, connecting to the turbine with mooring chains. [6] Measurement of sound during suction is limited and only one event with peak SPL of 177 dB re 1μ Pa has been documented. Such level of sound will not meet any limit in the criteria, thus modelling will not be done to assess its impact.

5.2.7 Results-Operation phase

As stated in **1.3**, sound during operation mainly come from the structure vibration which strongly relates to wind speed. Fortunately, there is already a floating wind turbine Hywind near Utsira Nord site, and measurement of operation sound has been done there. According to Equinor measurement report, [40] source RMS SPL is around 166 dB re 1μPa at 1 m from the sound source under local wind condition.

SPL(dB re 1μ Pa)	$R_{March,max}$	$R_{August,max}$	$R_{December,max}$
150	$< 10m$	$< 10m$	$< 10m$
140	29m	25m	25m
130	86m	88m	88m
125	162m	128m	162m
120	280m	289m	1.29km
115	1.62km	504m	1.7km
110	4.12km	1.78km	4.24km

Table 5.11: Result for Operation phase at Utsira Nord

Table 5.11 illustrates that no criteria listed above can be met, thus operation sound here is not sigificant as it is close to the background (ambient) sound levels.

5.3 Frøyagrunnene

5.3.1 Basic Information

Frøyagrunnene OWF is located 10km southwest of Bremangerlandet(Sogn and Fjordane), and has an area of 59 km^2 (Figure 5.10). Water depth here is around 5-60m, so bottom fixed wind turbine is most suitable. According to NVE, there are already existed infrastructure in the site and wind condition is "excellent". [30]

However, Directorate for Fisheries has pointed out that fishing activities around the site is extensive and it is not recommended to open it.

Figure 5.10: Location and area of Frøyagrunnene site

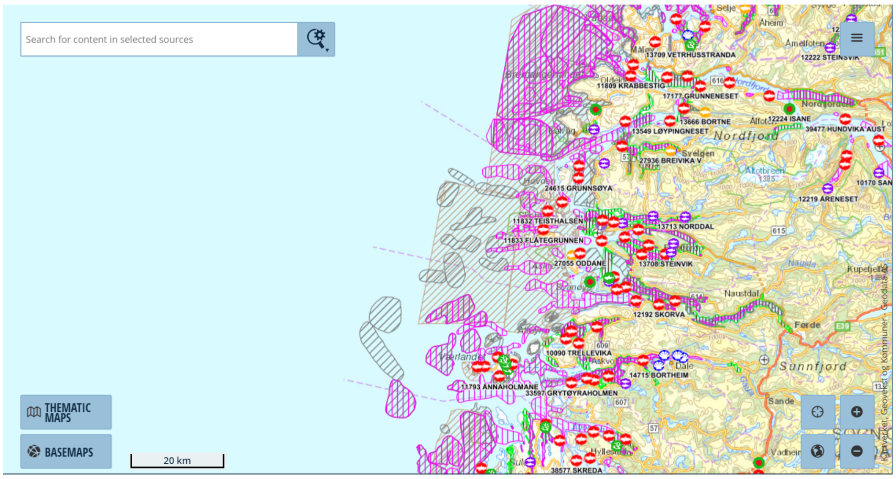


Figure 5.11: Activities around Frøyagrunnene OWF

5.3.2 Bathymetry

According to the dbSEABED database, seabed sediment layer in this area mainly consists of mud and rock (Figure 5.12). At center of Frøyagrunnene site, the seabed layer consists of nearly

100% mud.

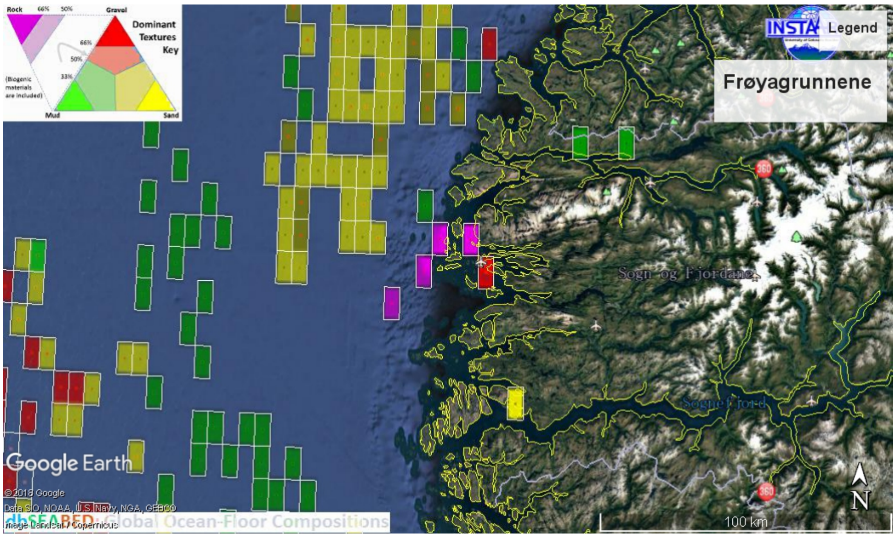


Figure 5.12: Seabed composition in Frøyagrunnene site

5.3.3 Sound speed profile in different seasons

Frøyagrunnene site is located in North sea. Three typical sound speed profiles (March,August and December) was picked for use of modelling (Figure 5.13)

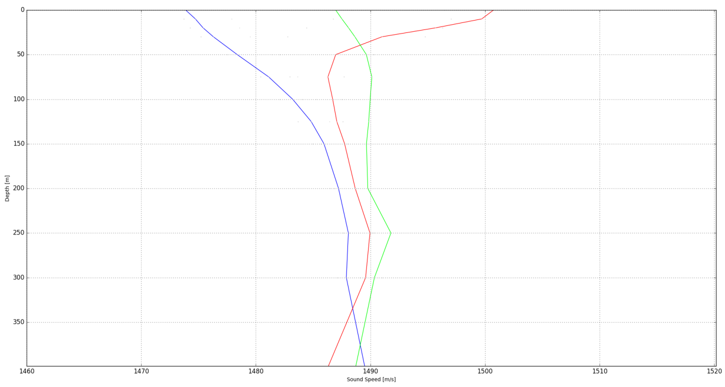


Figure 5.13: SSP in March(blue), August(red) and December(green)

5.3.4 Results-Geophysical Survey Phase

Water depth in Frøyagrunnene site is shallow and inputs of Boomer sound source will be used (Table 5.5). The source SPL will be 212 dB re 1μ Pa and SEL will be 192 dB re 1μ Pa^2s.

SEL(dB re 1μPa$^2 s$)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
180	$< 5m$	$< 5m$	$< 5m$	200	$< 5m$	$< 5m$	$< 5m$
170	$< 20m$	$< 20m$	$< 20m$	190	$< 20m$	$< 20m$	$< 20m$
165	30m	30m	29m	185	30m	28m	30m
160	74m	73m	69m	180	87m	85m	87m
155	199m	205m	201m	175	201m	199m	225m
150	443m	436m	416m	170	409m	435m	420m
145	1.3km	1.3km	642m	165	657m	1.3km	688m
140	1.5km	1.5km	1.2km	160	1.2km	1.4km	1.6km
135	3.6km	1.6km	4.4km	155	3.7km	2.1km	3.4km
130	13.5km	3.1km	15km	150	13.5km	3.1km	15km
125	24.2km	4.1km	22.2km	145	4.2km	12.1km	22.1km
120	$> 35km$	15.3km	$> 35km$	140	$> 35km$	15.2km	$> 35km$

Table 5.12: Result for Geophysical survey phase at Frøyagrunnene

5.3.5 Evaluation-Geophysical Survey Phase

Limit	R_{max} in March	R_{max} in August	R_{max} in December
Auditory Injury for Pinnipeds			
(RMS)190 dB re 1μPa	$< 20m$	$< 20m$	$< 20m$
Auditory Injury for Cetaceans			
(RMS)180 dB re 1μPa	87m	85m	87m
Behaviour disturbance for marine mammals			
(RMS)160 dB re 1μPa	1.259km	1.368km	1.594km
TTS onset for Pinnipeds			
(M SEL)171 dB re 1$\mu Pa^2 s$	$< 20m$	$< 20m$	$< 20m$
TTS onset for Cetaceans			
(M SEL)183 dB re 1$\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
PTS onset for Pinnipeds			
(M SEL)186 dB re 1$\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
TTS injury for fish speices			
(SEL)186 dB re 1$\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$

Table 5.13: Evaluation of results in Geophysical Survey phase

Table 5.13 illustrates the evaluation results of geophysical survey phase according to criteria given in **3.3.1** and **3.3.2**. It can be observed that the risk for auditory injury is limited to distances closer than 85–87 meters for cetaceans based on the SPL data. For SEL, the cetacean would need to be within 5 meters of the sound source before risk of auditory injury could occur.

From evaluation above, it is recommended to confirm existence and distance from the sound source of marine mammals nearby.

5.3.6 Construction Phase

Water depth in Frøyagrunnene site zone is mostly below 30m although some area can reach above 30m. So Monopile foundation will be used for modelling (Figure 3.4). After discussion, the worst scenario will be used (Table 5.14), and the scenario is for a 10m-diameter 10MW monopile foundation wind turbine.[41]

Sound source	Monopile foundation pile driving
Duration	6h
Number of strikes	7000
Source Level(SPL_{z-p} at 1m)	244.7 dB re 1μPa
Source Level(SEL at 1m)	221.6 dB re 1μPa$^2 s$

Table 5.14: Sound source information

SEL(dB re 1μPa$^2 s$)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
210	$< 5m$	$< 5m$	$< 5m$	230	$< 5m$	$< 5m$	$< 5m$
200	$< 10m$	$< 10m$	$< 10m$	220	22m	20m	22m
195	21m	21m	20m	215	41m	40m	44m
190	38m	39m	41m	210	136m	126m	135m
185	106m	100m	105m	205	332m	325m	330m
180	410m	407m	417m	200	518m	885m	525m
175	659m	1.4km	649m	195	873m	1.4km	1.1km
170	1.3km	1.6km	1.2km	190	3.3km	1.6km	1.7km
165	3.5km	3.1km	2.4km	185	8.9km	3.1km	3.3km
160	17.9km	11km	21.3km	180	26.9km	21.1km	21.3km
155	$> 37km$	29.4km	$> 37km$	175	$> 37km$	29.8km	$> 37km$

Table 5.15: Result for Construction phase at Frøyagrunnene

Table 5.15 illustrates the evaluation results of construction phase in Frøyagrunnene . It can be observed that the impact area is larger than Sandskallen site and most effects will be limited in range of 500m. However, limit for TTS onset for Pinnipeds will be met out to 1.3km to 1.6km.Fish species closer than 330m from the sound source could suffer physical injury.

Popper et al, 2014 also show the so-called temporary threshold shift (TTS) levels, i.e. temporary diminished hearing sensation followed by full recovery for different types of fish.

Limit	R_{max} in March	R_{max} in August	R_{max} in December
TTS onset for Pinnipeds			
(Peak)212 dB re $1\mu Pa$	41-136m	40-126m	44-135m
TTS onset for Cetaceans			
(Peak)224 dB re $1\mu Pa$	5-22m	2-20m	2-22m
PTS injusry onset for Pinnipeds			
(Peak)218 dB re $1\mu Pa$	22-41m	20-40m	22-44m
PTS injury onset for Cetaceans			
(Peak)230 dB re $1\mu Pa$	$< 5m$	$< 5m$	$< 5m$
TTS onset for Pinnipeds			
(M SEL)171 dB re $1\mu Pa^2 s$	1.295km	1.623km	1.25km
TTS onset for Cetaceans			
(M SEL)183 dB re $1\mu Pa^2 s$	106-410m	100-407m	105-417m
PTS onset for Pinnipeds			
(M SEL)186 dB re $1\mu Pa^2 s$	38-106m	39-100m	41-105m
PTS onset for Cetaceans			
(M SEL)198 dB re $1\mu Pa^2 s$	10-21m	10-21m	10-20m
TTS injury for fish speices			
(SEL)186 dB re $1\mu Pa^2 s$	38-106m	39-100m	41-105m
Unrecoverable Injury for fish species			
(Peak)207 dB re $1\mu Pa^2 s$	136-332m	126-325m	135-330m

Table 5.16: Evaluation of results in Construction phase

5.3.7 Operation phase

According to the assessment by Marine Scotland, [39] operation sound of Monopile foundation is the greatest among all different foundations, and some marine mammals, e.g., Minke whales and fish species, e.g., Atlantic salmon and European eels can detect the sound. However the pressure level is not enough to cause any negative effects except at very close proximities to the sound source. Thus modelling was not done here, also because of lacking of measurement.

5.4 Sørlige Nordsjø I & II

5.4.1 Basic Information

Sørlige Nordsjø I and II sites were evaluated together by NVE because they are close to each other and have similar environment features. Both sites are located in the North sea, 140-150 km off Norwegian coast (Figure 5.14 and 5.15). Sørlige Nordsjø I site has an area of 1375 km^2 and Sørlige Nordsjø II site has an area of 2591 km^2, which is also the largest among all 15 sites.

Wind condition here is also "excellent" with average wind speed of 10.5m/s. However, there are some sandeel spawning grounds nearby, thus it is necessary to model potential impact before constructions.

5.4.2 Bathymetry

Seabed sediment layer in this area mainly consists of sand and rock (Figure 5.16). At center area of Sørlige Nordsjø site, the seabed layer consists of 100% sand.

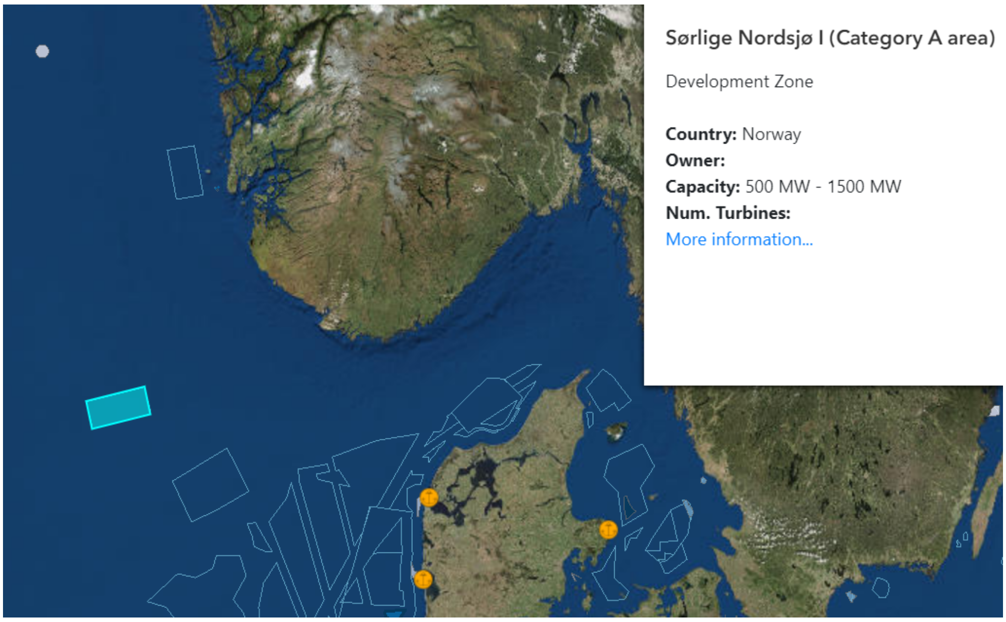


Figure 5.14: Location and area of Sørlige Nordsjø I

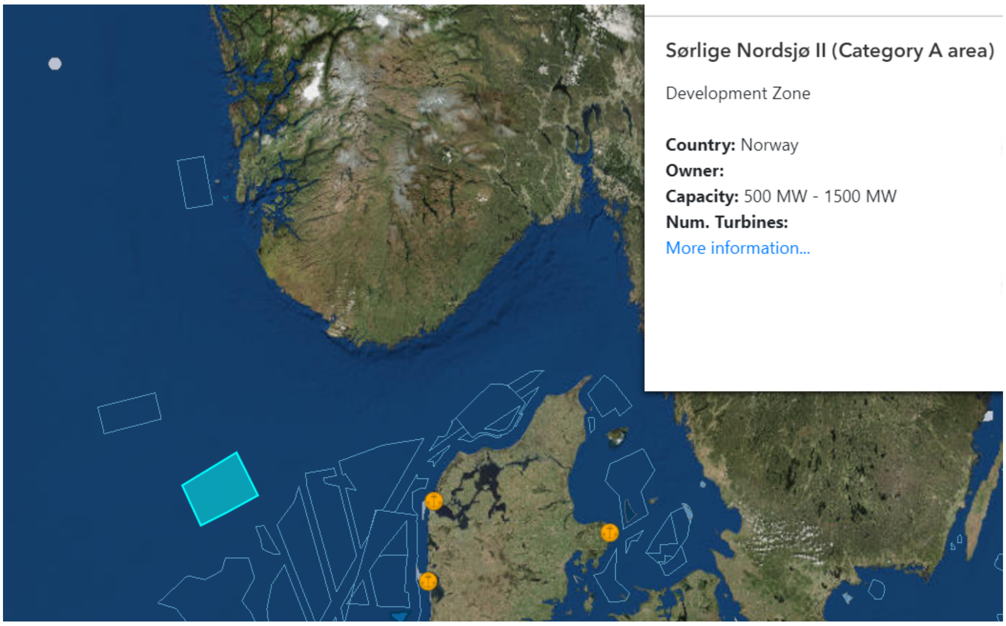


Figure 5.15: Sørlige Nordsjø II

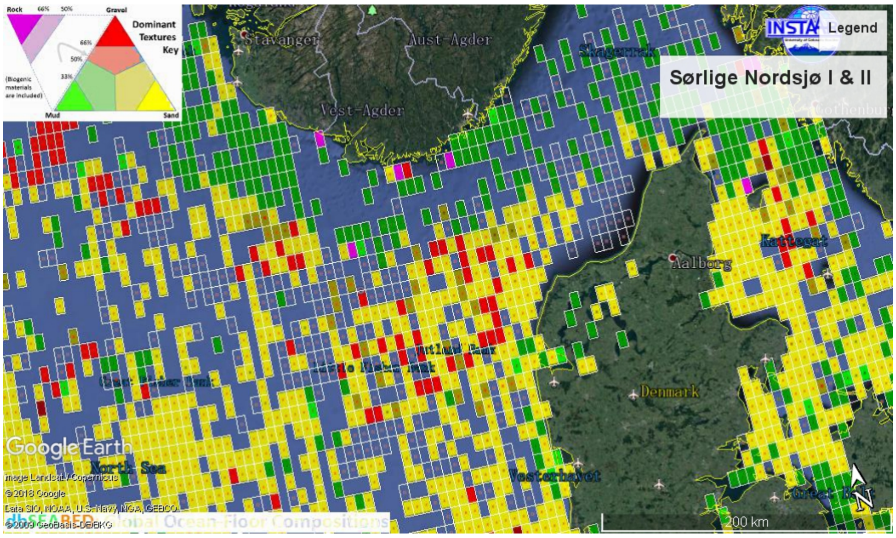


Figure 5.16: Seabed composition in Sørlige Nordsjø site

5.4.3 Sound speed profile in different seasons

Sound speed profile has similar variation as other Category A sites: sound speed close to surface increases from January to August and decreases back until December (Figure 5.17).

5.4.4 Results-Geophysical Survey phase

Water depth in Sørlige Nordsjø site is around 40-70m, so Boomer will be used for geophysical survey. Sound source information can be obtained in Table 5.2 (Source RMS SPL 212 dB re 1μPa, Source SEL 192 dB re 1μPa^{2}s)

SEL(dB re 1μPa$^2 s$)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
180	$< 5m$	$< 5m$	$< 5m$	200	$< 5m$	$< 5m$	$< 5m$
170	$< 20m$	$< 20m$	$< 20m$	190	$< 20m$	$< 20m$	$< 20m$
165	28m	29m	28m	185	32m	28m	29m
160	60m	56m	52m	180	56m	57m	56m
155	100m	100m	96m	175	100m	100m	100m
150	236m	176m	248m	170	200m	236m	276m
145	672m	680m	660m	165	624m	676m	612m
140	1.4km	1.8km	1.4km	160	1.7km	1.5km	1.4km
135	4.8km	3km	3km	155	3km	3.1km	3km
130	7.2km	5.2km	7.1	150	8.2km	5.3km	7.1km
125	18.2km	10.1km	20.6km	145	18.2km	11.6km	20.6km
120	42.1km	17.7km	40km	140	37.6km	17.7km	40km
110	$> 45km$	32km	$> 45km$	130	$> 45km$	37.4km	$> 45km$

Table 5.17: Result for Geophysical survey phase at Sørlige Nordsjø I

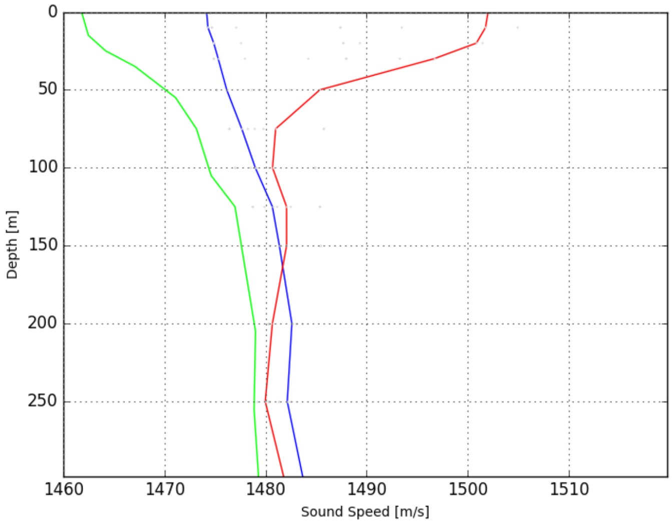


Figure 5.17: SSP in March(blue), August(red) and December(green)

SEL(dB re 1μPa$^2 s$)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$	SPL(dB re 1μ Pa)	$R_{3,max}$	$R_{8,max}$	$R_{12,max}$
180	$< 5m$	$< 5m$	$< 5m$	200	$< 5m$	$< 5m$	$< 5m$
170	$< 20m$	$< 20m$	$< 20m$	190	$< 20m$	$< 20m$	$< 20m$
165	28m	29m	24m	185	28m	24m	28m
160	52m	60m	52m	180	56m	52m	52m
155	100m	100m	100m	175	100m	96m	100m
150	224m	180m	228m	170	228m	220m	230m
145	608m	644m	624m	165	604m	664m	596m
140	1.7km	1.5km	1.4km	160	1.7km	1.3km	1.4km
135	3km	2.3km	3km	155	4.6km	2.5km	3.1km
130	7.2km	4.9km	7.1km	150	7.2km	5.2km	7.1km
125	18.2km	9.1km	20.6km	145	18.2km	10.1km	22.1km
120	44km	21.1km	48.6km	140	37.6km	21.1km	49.2km
110	$> 50km$	42.2km	$> 50km$	130	$> 50km$	43.4km	$> 50km$

Table 5.18: Result for Geophysical survey phase at Sørlige Nordsjø II

From Table 5.17 and 5.18, sound pressure propagation is also the most limited in august, which is the same situation in other sites. And propagation range in Sørlige Nordsjø II is further and Sørlige Nordsjø I site.

5.4.5 Evalutaion-Geophysical Survey Phase

Limit	R_{max} in March	R_{max} in August	R_{max} in December
Auditory Injury for Pinnipeds			
I (RMS)190 dB re $1\mu Pa$	$< 20m$	$< 20m$	$< 20m$
II (RMS)190 dB re $1\mu Pa$	$< 20m$	$< 20m$	$< 20m$
Auditory Injury for Cetaceans			
I (RMS)180 dB re $1\mu Pa$	56m	57m	56m
II (RMS)180 dB re $1\mu Pa$	56m	52m	52m
Behaviour disturbance for marine mammals			
I (RMS)160 dB re $1\mu Pa$	1.68km	1.47km	1.39km
II (RMS)160 dB re $1\mu Pa$	1.7km	1.3km	1.4km
TTS onset for Pinnipeds			
I (M SEL)171 dB re $1\mu Pa^2 s$	$< 20m$	$< 20m$	$< 20m$
II (M SEL)171 dB re $1\mu Pa^2 s$	$< 20m$	$< 20m$	$< 20m$
TTS onset for Cetaceans			
I (M SEL)183 dB re $1\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
II (M SEL)183 dB re $1\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
PTS onset for Pinnipeds			
I (M SEL)186 dB re $1\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
II (M SEL)186 dB re $1\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
TTS injury for fish speices			
I (SEL)186 dB re $1\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$
II (SEL)186 dB re $1\mu Pa^2 s$	$< 5m$	$< 5m$	$< 5m$

Table 5.19: Evaluation of results in Geophysical Survey phase

Table 5.19 illustrates the evaluation results of geophysical survey phase according to chosen criteria. Potential auditory injury at sound exposure levels greater than 180 SEL(dB re 1μPa^{2}s) is limited to closer than 5 meters from the sound source for cetaceans, pinnipeds and fish. When using the SPL metric, injusry onset could take place when marine mammals are closer than 56 meters from the sound source.

From evaluation above, it is recommended to confirm existence and distance from the sound source of marine mammals nearby, and if the survey could be conducted in summer, the impact will be the least.

5.4.6 Results-Construction Phase

As stated in 5.2.6, construction sound during floating wind turbine construction is below the criteria and thus will not be modelled here.

5.4.7 Results-Operation phase

SPL(dB re 1μ Pa)	$R_{March,max}$	$R_{August,max}$	$R_{December,max}$
150	$< 10m$	$< 10m$	$< 10m$
140	28m	24m	28m
130	88m	92m	88m
125	160m	156m	160m
120	556mm	560m	536m
115	1.7km	1.3m	1.2km
110	3km	1.8km	3km

Table 5.20: Result for Operation phase in Sørlige Nordsjø I

SPL(dB re 1μ Pa)	$R_{March,max}$	$R_{August,max}$	$R_{December,max}$
150	$< 10m$	$< 10m$	$< 10m$
140	28m	24m	27m
130	88m	84m	92m
125	156m	156m	160m
120	536m	540m	532m
115	1.3km	1.4m	1.1km
110	3.1km	2.8km	3km

Table 5.21: Result for Operation phase at Sørlige Nordsjø II

From Table 5.20 and 5.21, it can be found that in Sørlige Nordsjø I and II sites, if a floating wind turbine was installed, only fish species with swim bladder extremely close (within meters) to the turbine will suffer temporary hearing threshold shift. Considering escaping from the sound source, the pressure is not high level. Cetaceans and pinnipeds are not adversely affected.

6 Conclusion and Recommendation

The thesis presents modelling of acoustic impact range and propagation from five potential offshore wind farm sites, which have been targeted as Category A sites by NVE (Norwegian Water Resources and Energy Directorate). Results of modelling are also evaluated following the criteria given by existed regulations and acknowledged research. Marine populations included into evaluation includes main marine mammals and fish species which can be found in Norwegian waters.

Results are presented and divided into events happening in different offshore wind farm life-cycle: Geophysical Survey phase, Construction Phase and Operation Phase. Shipping sound are not included mainly because relevant data is lacked and difficulty to exclude shipping activities not serving for the wind farm, especially in areas being heavily trafficked. Decommissioning phase is not included mainly because that there is few cases and research providing sound source information and several already existed research has shown that it can be beneficial to keep the structure for multi-use.

In the geophysical survey phase, Boomers were used for modelling in sites with relative shallow water ($< 100m$), e.g., Sandskallen site, and Sparkers were used for modelling in sites with deeper water, e.g., Utsira Nord site. Being different from results in Utsira Nord site, which is located in area with water depth from 185 m to 280 m, impact area in other sites in shallower water was more limited: PTS effects both for marine mammals and fish species are inside a 20m radius from the sound source, Auditory injury effect for cetaceans, e.g., killer whale, humpback whale, porpoise and etc, can extend to around 50 m in Sadskallen site, 85m in Frøyagrunnene site and 55 m in Sørlige Nordsjø I and II sites. However, behaviour disturbance effects for marine mammals can extend to 1 km to 2 km from the sound source, especially in summer season (August).

Impact area produced during geophysical survey phase in Utsira Nord site is the largest among five sites, although adverse effects were still limited inside 30 m radius range. The potential for auditory injury range for Pinnipeds, e.g., harp seal, grey seal and harbour seal can reach up to 89 meters radius from the sound source. Auditory injury range for Cetaceans can reach up to 273 m. Behaviour disturbance ($> 160dB$) area for marine mammals can reach up to 105 meters when measured in SEL, and 39 km when measured in SPL.

In Construction phase, different foundations were used according to different water depth in sites. Jacket foundation was used in Sandskallen site, floating foundation was used in Utsira Nord site, Sørlige Nordsjø I and II sites. Monopile foundation was used in Frøyagrunnene site.

In Sandskallen site where jacket foundation sound source was used, adverse effects both for marine mammals and fish species are limited inside 32 meters, except for the TTS onset for Pinnipeds extending out to 140 meters. Unrecoverable injury for fish species can be observed out to 58 meters from the sound source.

Impact area in Frøyagrunnene where monopile foundation sound source was used is even larger: adverse effects both for marine mammals and fish species can reach up to 1.6 km from the sound source. Unrecoverable injury for fish species may occur out to 332 meters radius distance from the sound source.

Floating foundation is a new technology and there are only few cases (9 turbines installed in

Europe at the end of 2018). It has the advantage during construction phase due to its "mild" method: Turbine is connected by mooring chains connected to suction anchors. Modelling was not conducted in the thesis because that relevant measurement is lacking and already existed cases has shown that the sound level is much lower than any criteria.

Sound produced during operation phase has been considered not important for many years for traditional foundations, because relevant measurements have shown that sound level is lower than existed regulations or criteria. It has been found in the thesis that sound from operation phase of floating wind turbine has an adverse impact area that is very limited. In Utsira Nord site, if a floating wind turbine was installed, fish species with swim bladder close to the turbine ($< 10m$) could suffer temporary hearing threshold shift. There effects for marine mammals are negligible.

Seasonal variation is the same for all events and sound: Sound pressure can propagate further in March and December due to the existence of a sound channel in shallow phase. Impact range in August is the most limited, especially in far field.

Based on results above, following recommendations are listed:

1. Data on the fish and marine mammal species that will likely be in a given region at different times during the year should be gathered before geophysical survey and construction in these sites.
2. In the thesis, sound source information in geophysical survey phase was based on previous measurements, however, different tools could be used. Thus data in the sound-generating characteristics of specific geotechnical engineering tools should be gathered before the survey.
3. Although operation sound impact is quite limited according to the resutls, a risk assessment to determine if the operation has the potential to cause adverse affects to marine mammal populations and fish stocks is still recommended.
4. Mitigation measures should be used to lower the potential risks down to acceptable levels. Such mitigation measures could include:

   - Use of Marine Mammal Observers or Fisheries Liaisons on the vessels generating sounds.

   - Maintenance of an "exclusion zone" into which no marine mammals should enter. The size of the exclusion zone is typically based on the radius from the sound source out to which there could be injury - i.e. out to SEL 180 dB re 1μPa^{2}s

   - Use of a soft start for sound generating tools, i.e., the power will be increased gradually to the full operation level in order to cause a movement away from the vicinity of the operations during the operational time period.

   - Potential use of Passive Acoustic Monitoring (PAM) to detect vocalizing species in the region and to triangulate their movements.

7 Discussion and Future Work

7.1 Particle motion

For fish species which can only detect particle motion, e.g., common dab and halibut, evaluation of particle motion is necessary. However, regulations and criteria are either lacking or calculated from sound pressure which can be quite imprecise near seabed and surface. Unfortunately, impact from particle motion is usually the largest for fish near boundaries. Modelling of particle motion has been tried by calculating numerical gradient of sound pressure, but the results is disappointing in near field and boundaries.

The necessity of developing particle motion measurement standards and instrument has been acknowledged by academic world. But until now, relevant research and measurement are still lacking and many caged experiment design are not reliable enough. Thus research about particle motion propagation and effects should be one of the most important work in future.

7.2 Sound attenuating measures

Sound attenuating measure can be considered when impact area of sound is relatively large. Common measures used nowadays, for example, bubble curtain (Figure 7.1), in low current sceanrios (ocean currents can distort the bubble curtain), can lower sound source level by 2-12 dB.

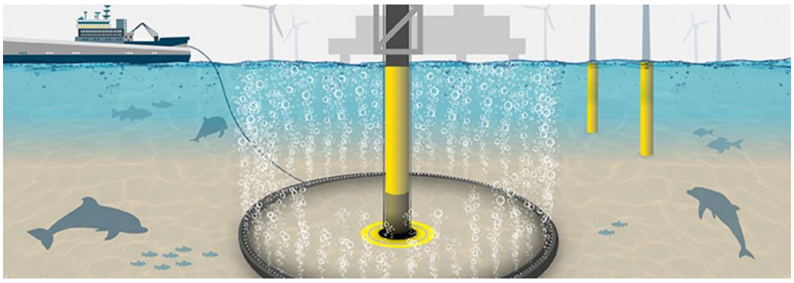


Figure 7.1: Bubble curtain used to attenuate sound

7.3 Possibility to share the ocean together

Along with development of offshore wind farm, proposal to combine offshore wind farm and other industries, especially fishery and aquaculture has been discussed more and more. Reasons behind the concept mainly include:

1. In order to establish optimal marine spatial planning considering minimizing environment and economic pressure, the offshore platform should combine various functions.
2. Quest of spatial scarcity in the ocean.
3. Cost of expensive infrastructure facilities which offshore aquaculture and wind farm can share.
4. Fish farm in the wind farm can be regarded as an alternative livelihood for fishermen community whose fishing sites are constricted because of wind farm.

Existing projects are mostly combination of wind farm and aquaculture of extractive species(seaweed, mussels,etc), but there are some conceptual designs combining offshore wind farm and fish farm. For example, offshore wind farm may be combined with aquaculture (Figure 7.2), or used as artificial reef (Figure 7.3).

However, there are relevant legislative uncertainties in these conceptual design and may cause concerns among different stakeholders once such projects are established. So in order to share the ocean together, potential effects, no matter positive or negative, should be explored and stated before, and effects from sound can not be ignored.

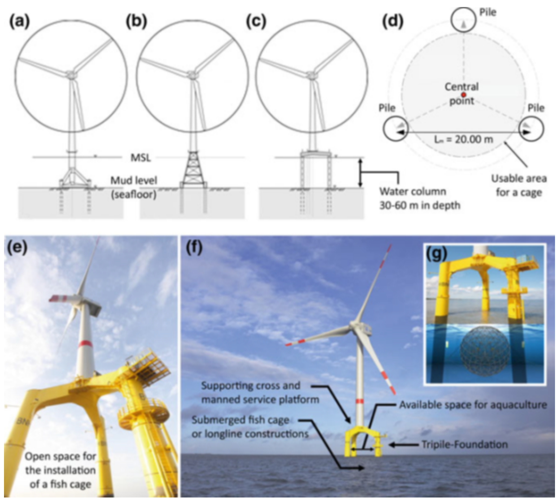


Figure 7.2: Multi-use concept combining "Aquapod" sea cage and "BARD-Wind-Turbine" by OFT.

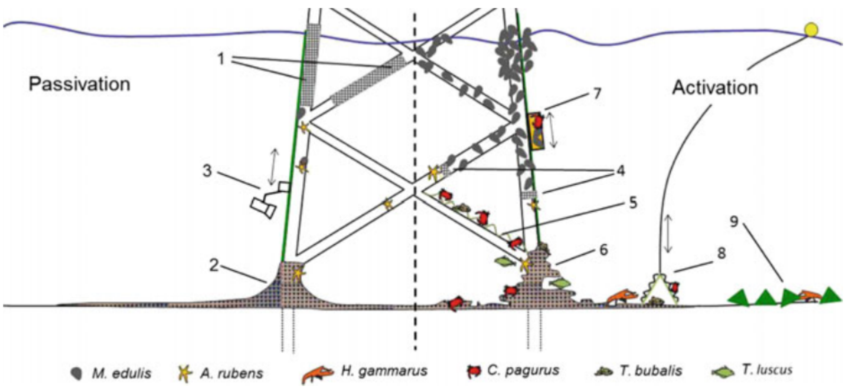


Figure 7.3: Multi-use concept using wind power foundations as artificial reef.

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]APPENDIX-Modelling results

APPENDIX 1 Sound Pressure Level and Sound Exposure Level max-over depth horizontal distribution

1. $SPL_{zero-peak}$
2. RMS SPL
3. SEL

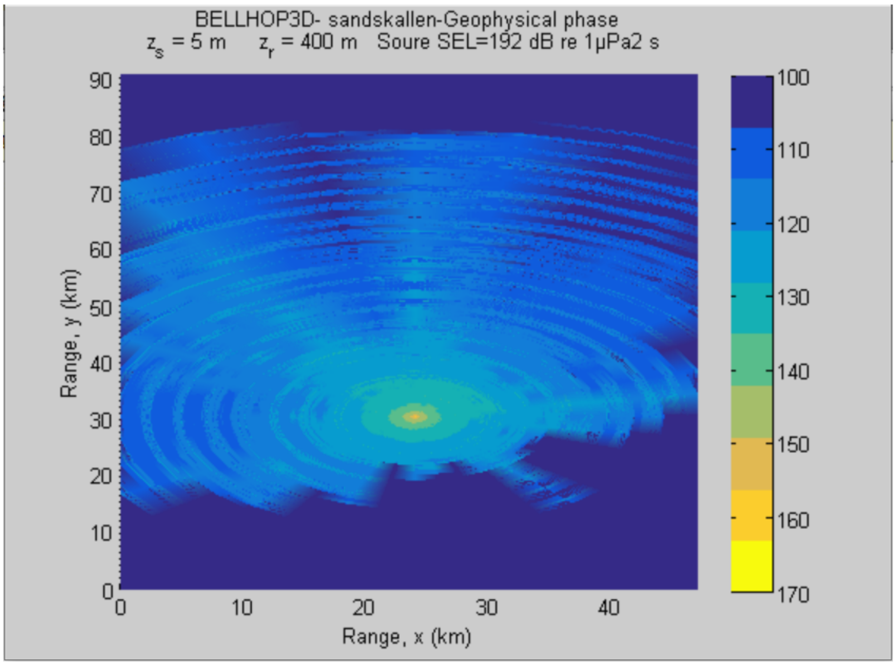

Figure 7.4: Max-over-depth,SEL,Sandskallen,Geophysical Survey Phase,March

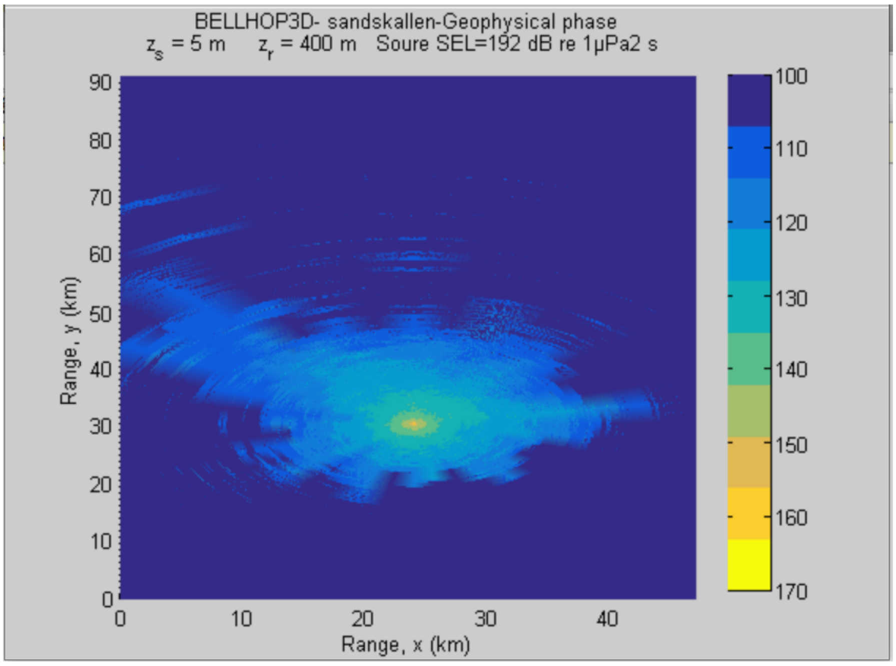

Figure 7.5: Max-over-depth,SEL,Sandskallen,Geophysical Survey Phase,August

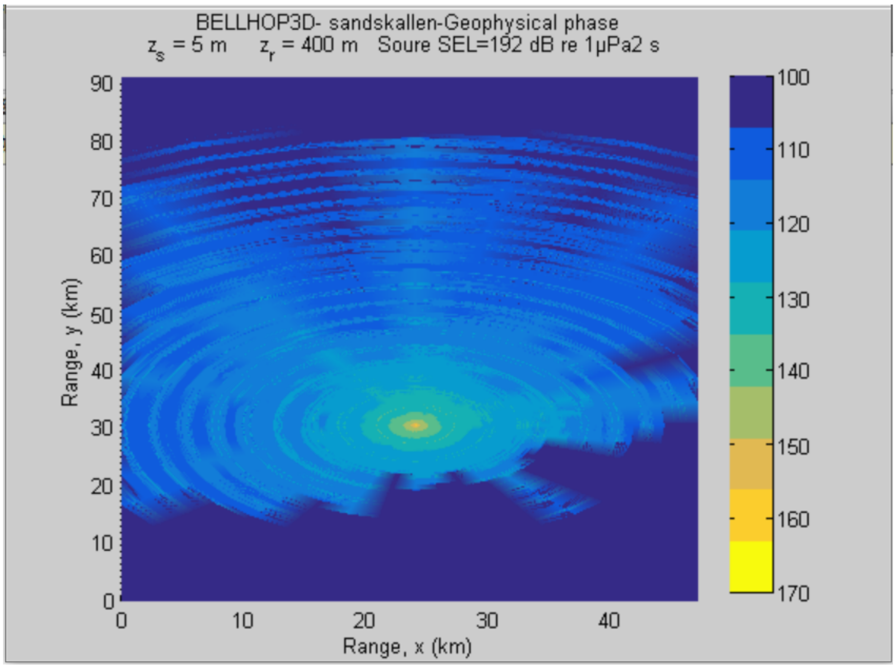

Figure 7.6: Max-over-depth,SEL,Sandskallen,Geophysical Survey Phase,December

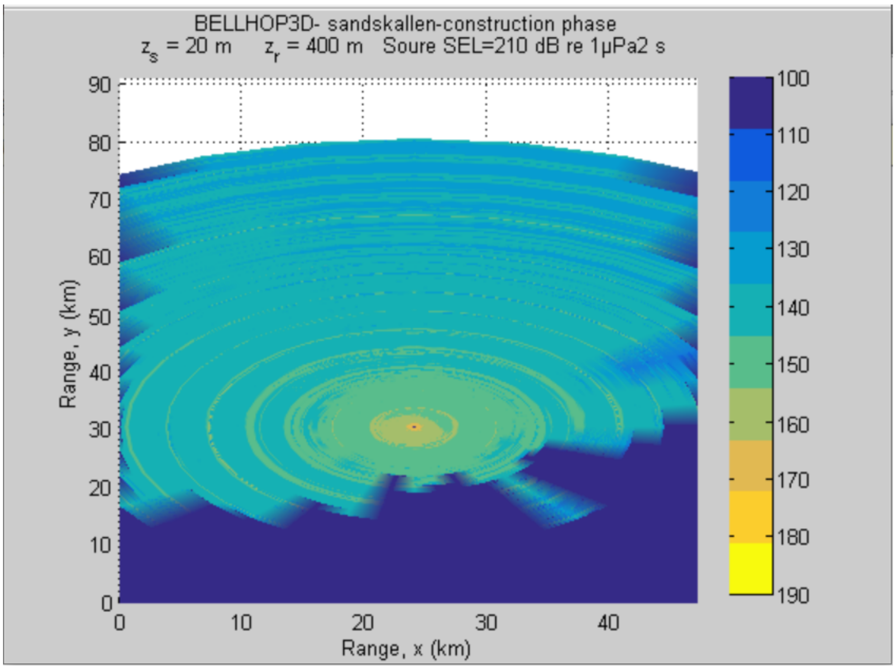

Figure 7.7: Max-over-depth,SEL,Sandskallen,Constructoin Phase,March

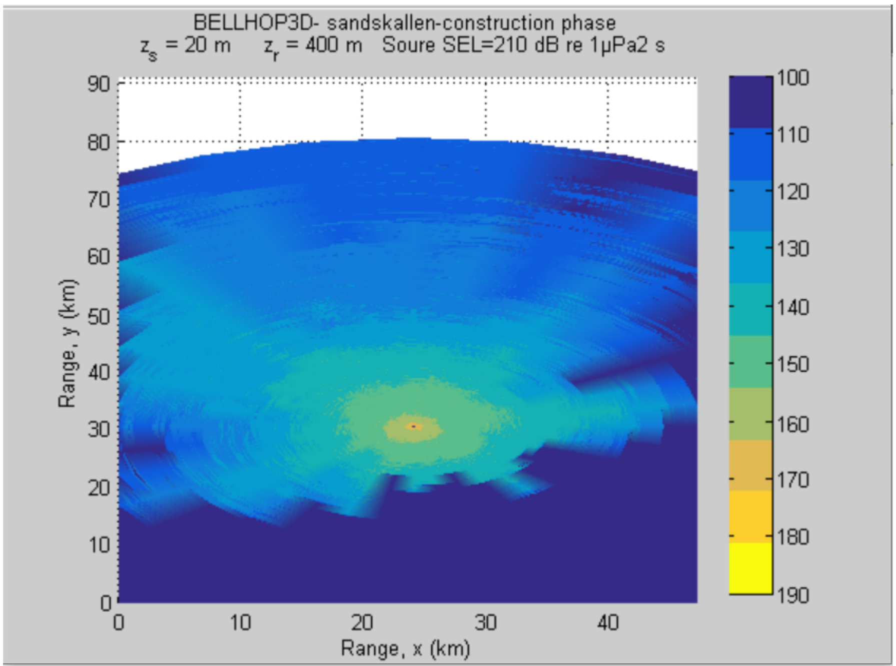

Figure 7.8: Max-over-depth,SEL,Sandskallen,Construction Phase,August

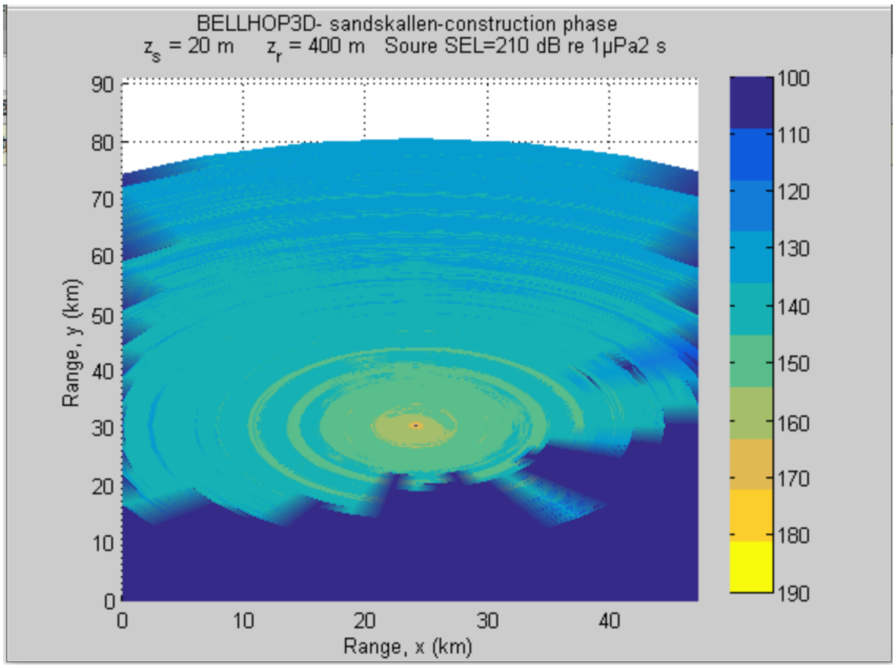

Figure 7.9: Max-over-depth,SEL,Sandskallen,Construction Phase,December

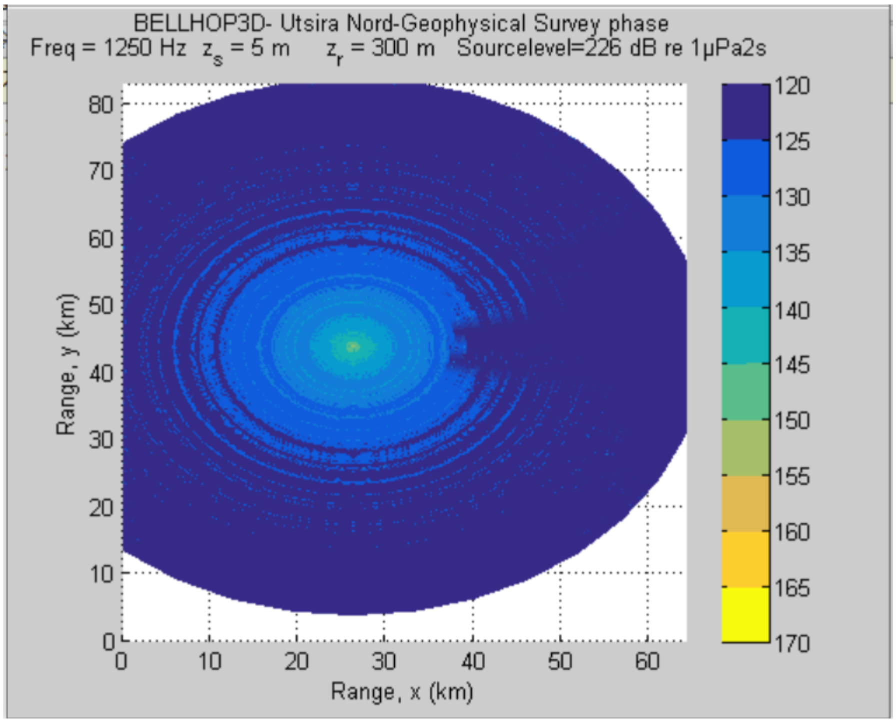

Figure 7.10: Max-over-depth,SEL,Utsira Nord,Geophysical Survey Phase,March

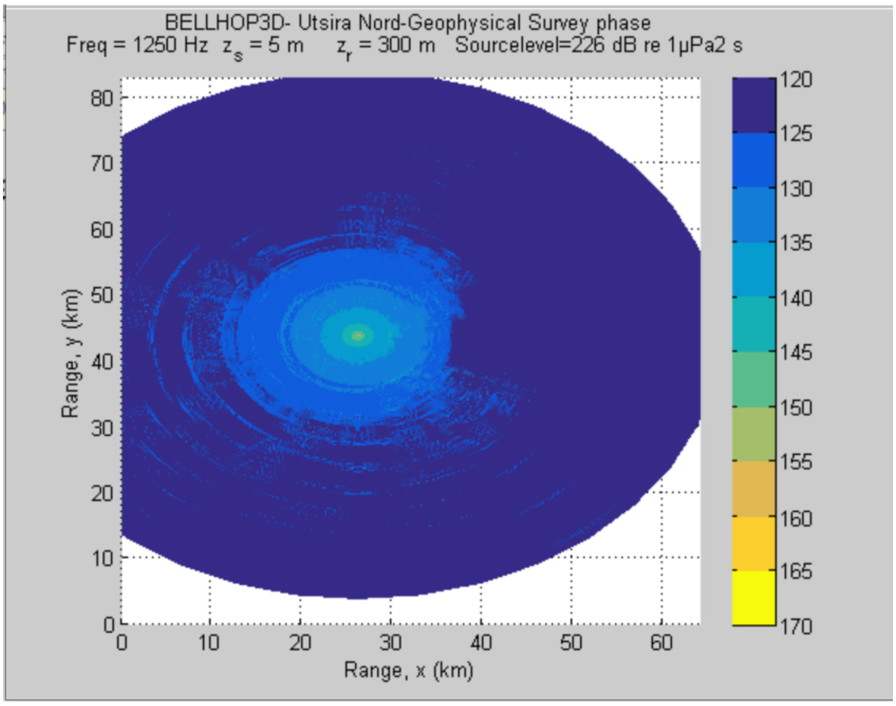

Figure 7.11: Max-over-depth,SEL,Utsira Nord,Geophysical Survey Phase,August

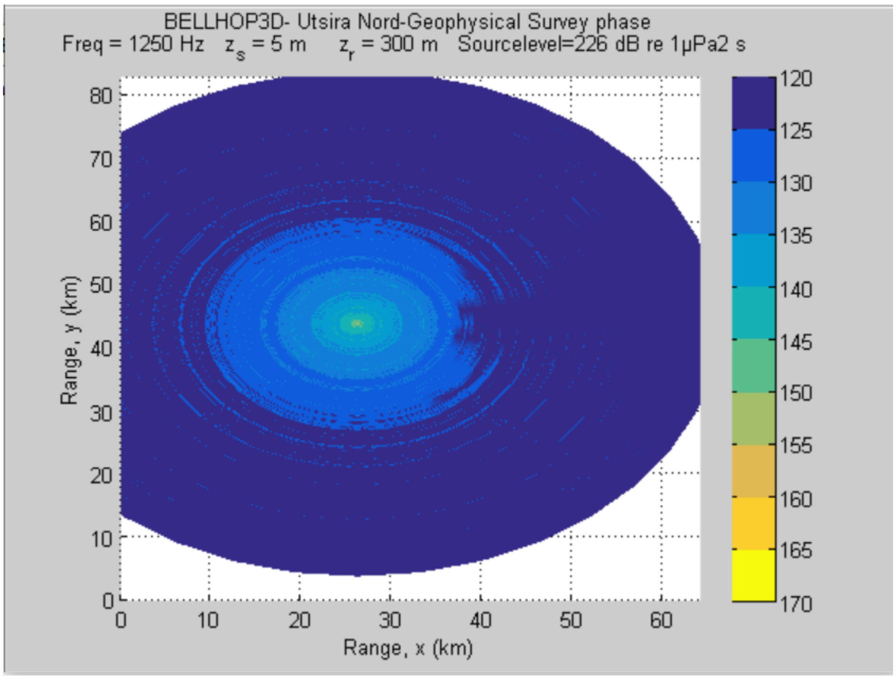

Figure 7.12: Max-over-depth,SEL,Utsira Nord,Geophysical Survey Phase,December

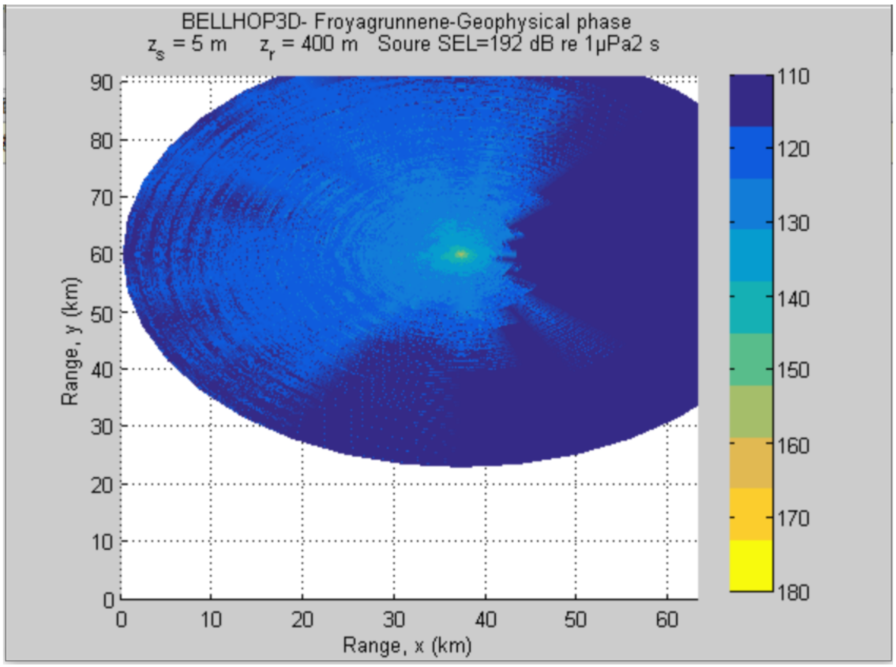

Figure 7.13: Max-over-depth,SEL,Frøyagrunnene,Geophysical Survey Phase,March

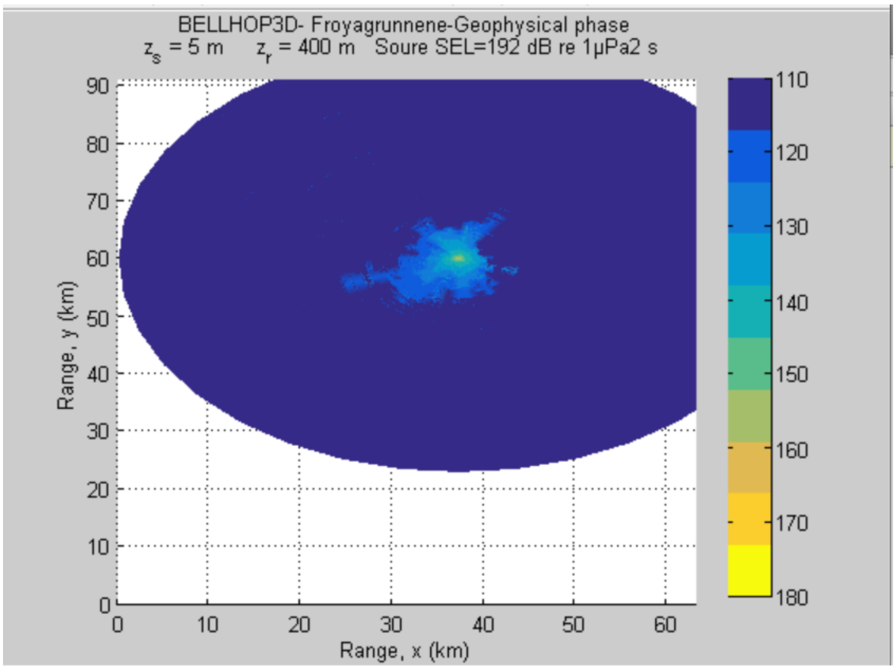

Figure 7.14: Max-over-depth,SEL,Frøyagrunnene,Geophysical Survey Phase,August

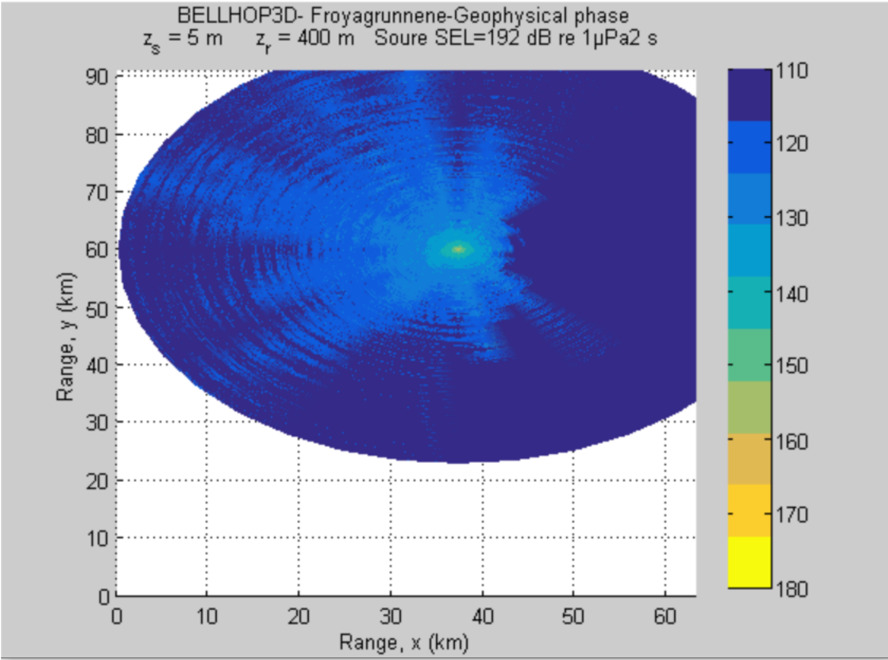

Figure 7.15: Max-over-depth,SEL,Frøyagrunnene,Geophysical Survey Phase,December

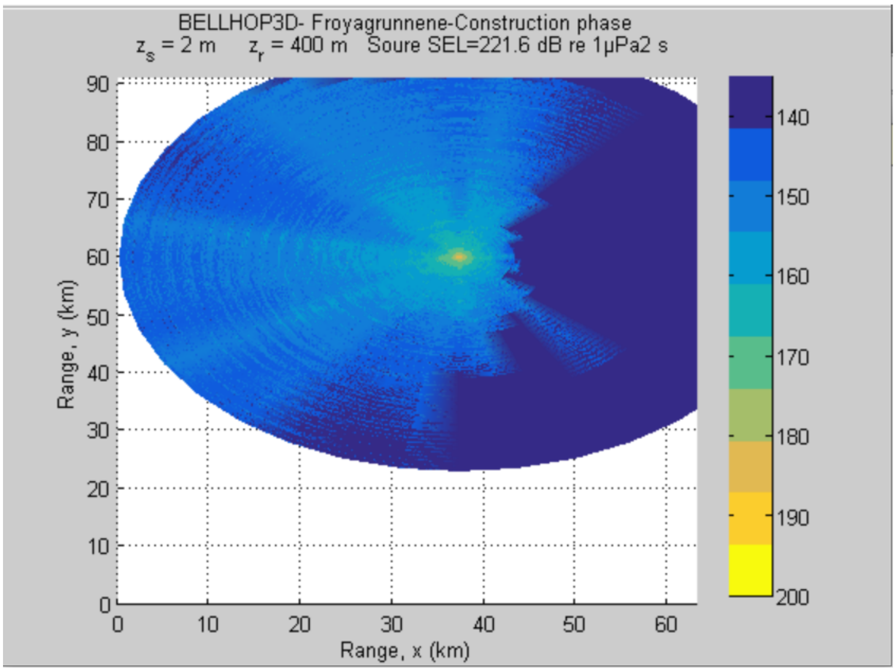

Figure 7.16: Max-over-depth,SEL,Frøyagrunnene,Construction Phase,March

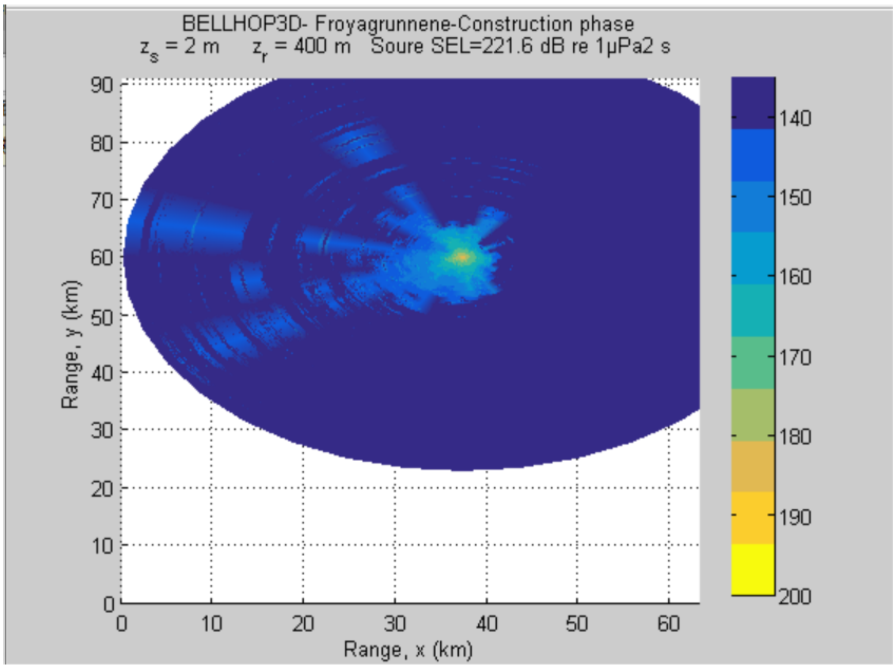

Figure 7.17: Max-over-depth,SEL,Frøyagrunnene,Construction Phase,August

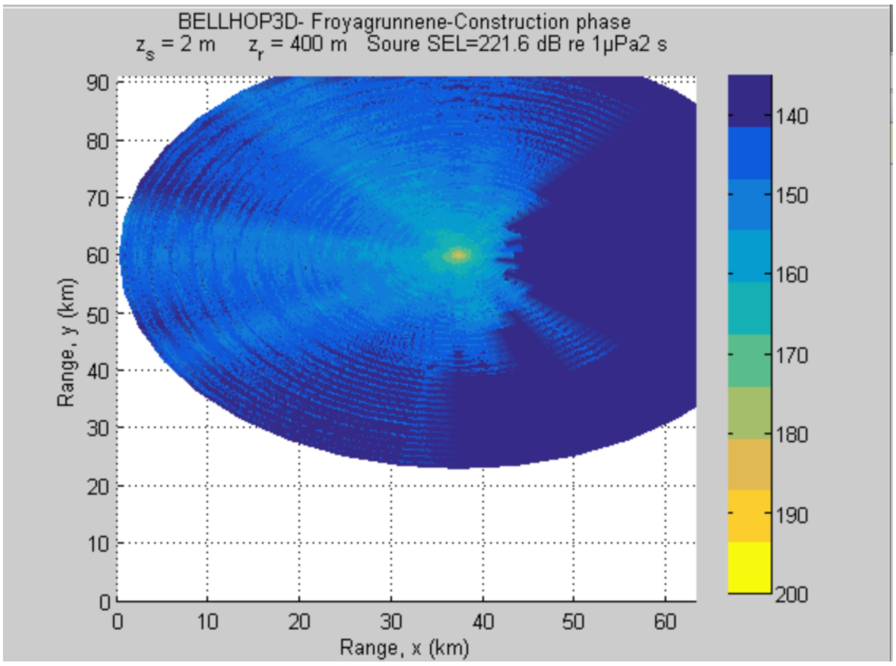

Figure 7.18: Max-over-depth,SEL,Frøyagrunnene,Construction Phase,December

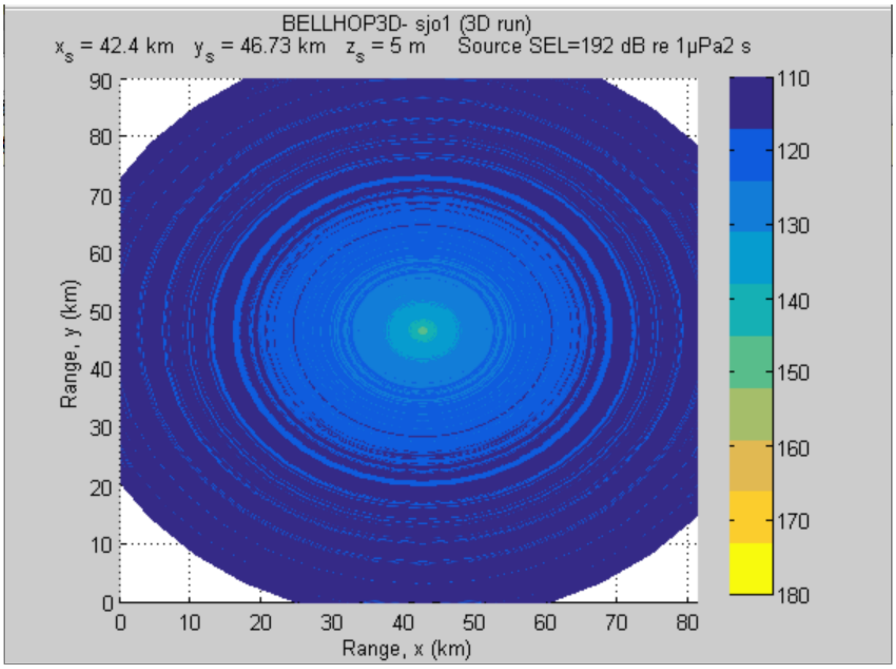

Figure 7.19: Max-over-depth,SEL,Sørlige Nordsjø I,Geophysical Survey Phase,March

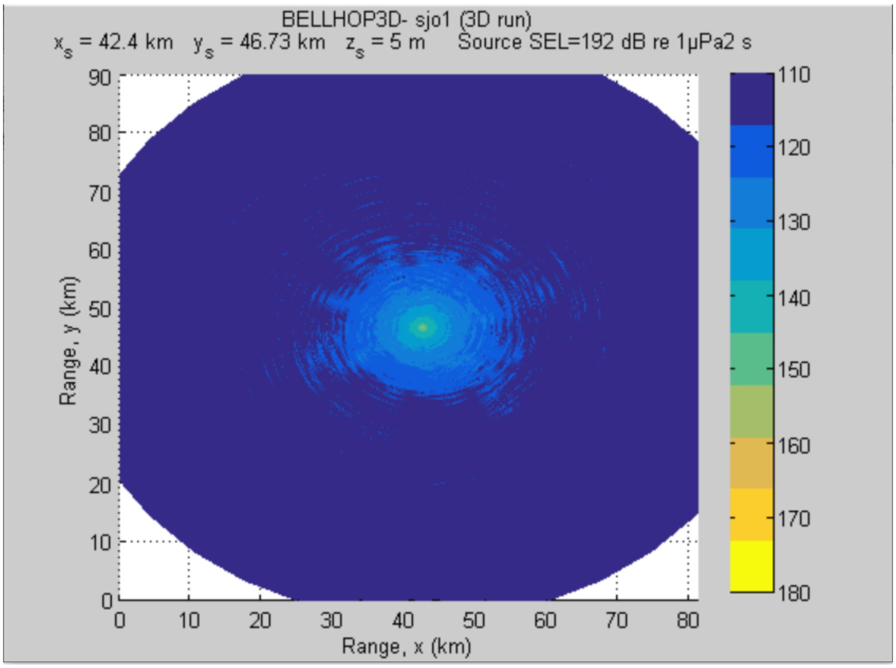

Figure 7.20: Max-over-depth,SEL,Sørlige Nordsjø I,Geophysical Survey Phase,August

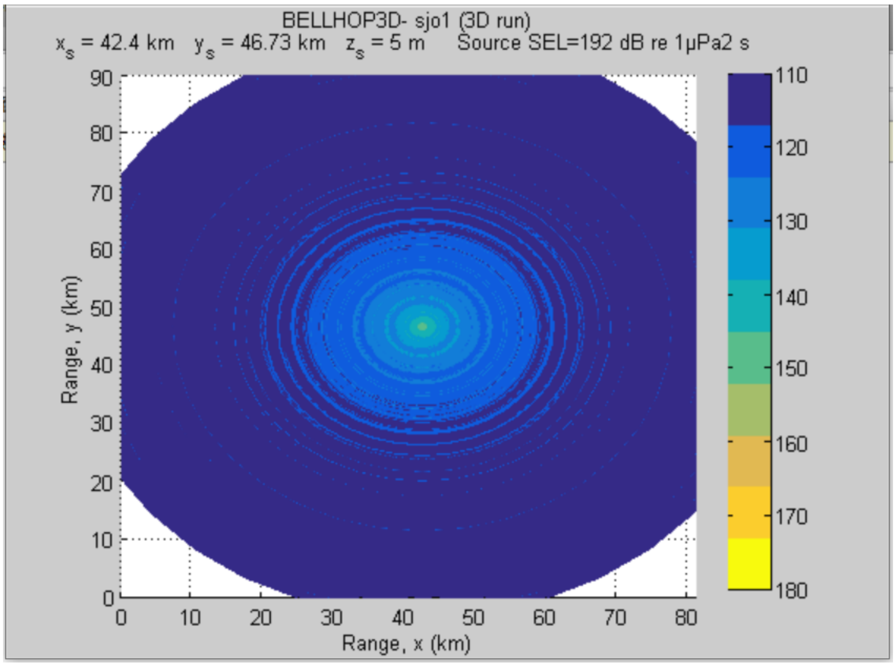

Figure 7.21: Max-over-depth,SEL,Sørlige Nordsjø I,Geophysical Survey Phase,December

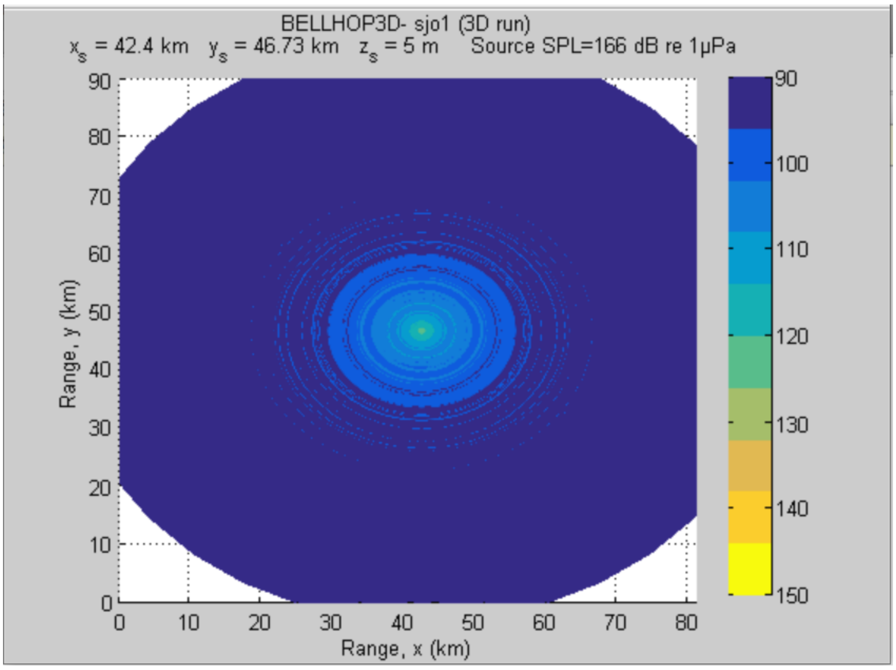

Figure 7.22: RMS SPL,Frøyagrunnene,Sørlige Nordsjø I, Operation Phase,March

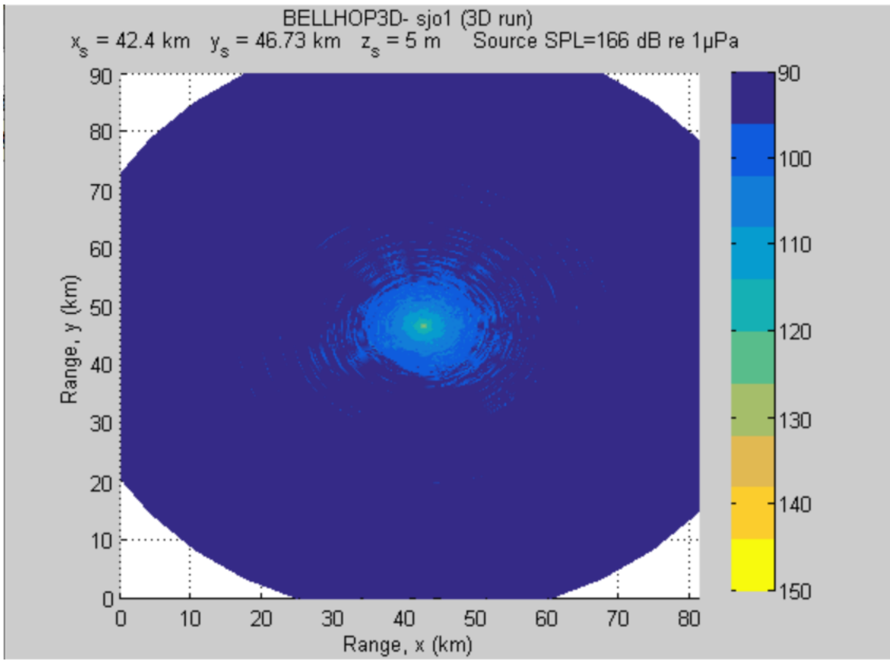

Figure 7.23: RMS SPL,Frøyagrunnene,Sørlige Nordsjø I, Operation Phase,August

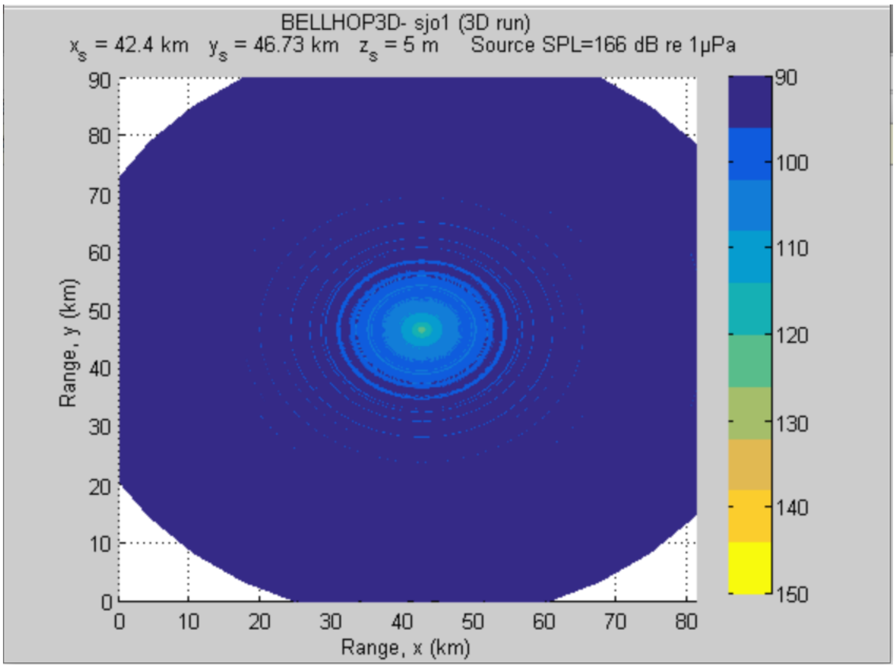

Figure 7.24: RMS SPL,Frøyagrunnene,Sørlige Nordsjø I, Operation Phase,December

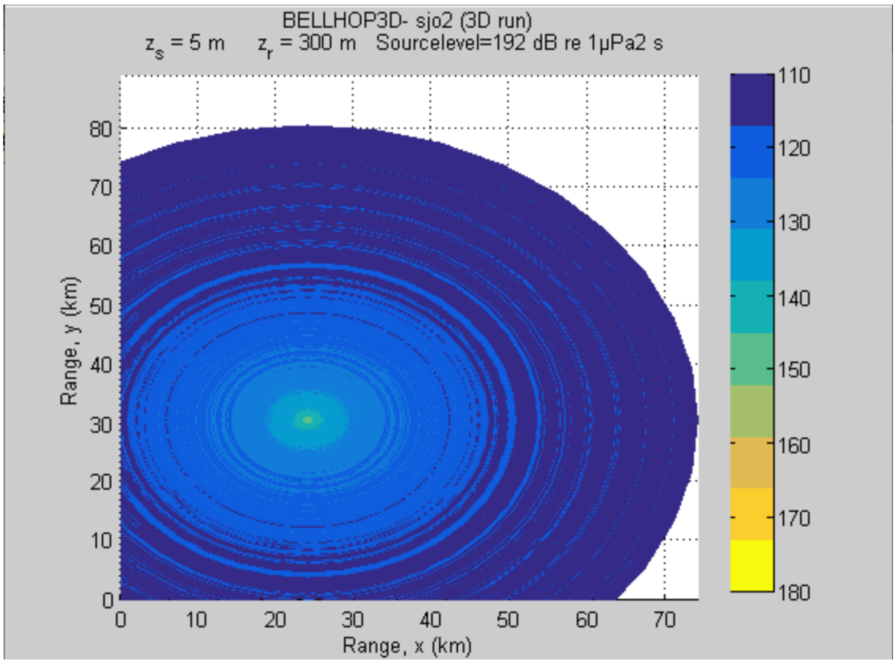

Figure 7.25: Max-over-depth,SEL,Sørlige Nordsjø II,Geophysical Survey Phase,March

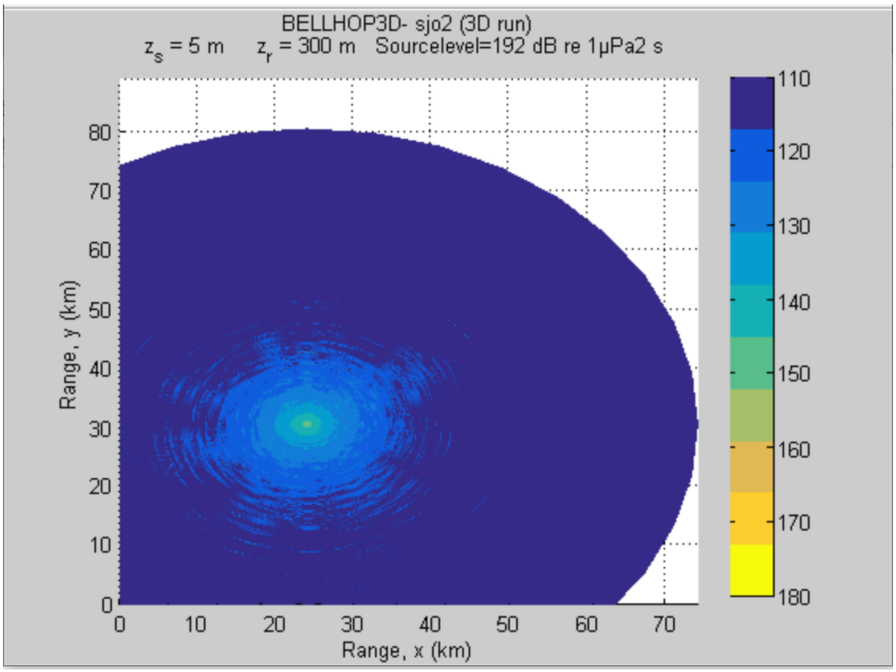

Figure 7.26: Max-over-depth,SEL,Sørlige Nordsjø II,Geophysical Survey Phase,August

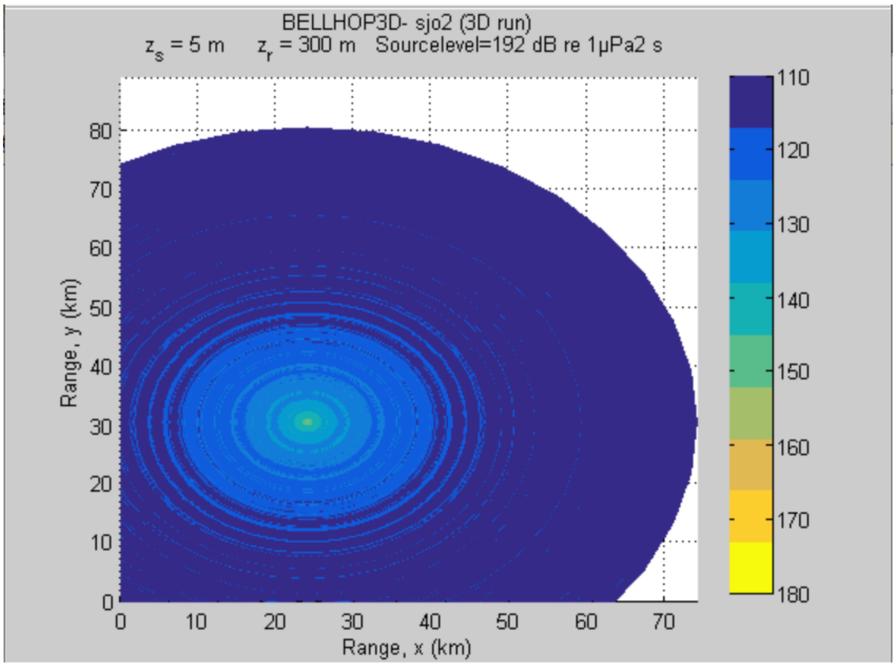

Figure 7.27: Max-over-depth,SEL,Sørlige Nordsjø II,Geophysical Survey Phase,December

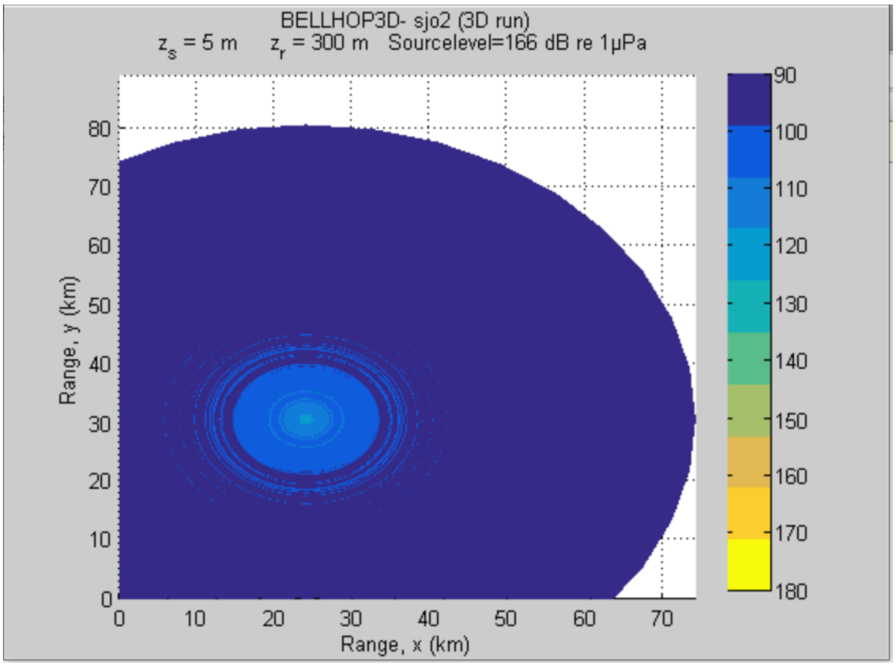

Figure 7.28: RMS SPL,Sørlige Nordsjø II, Operation Phase,March

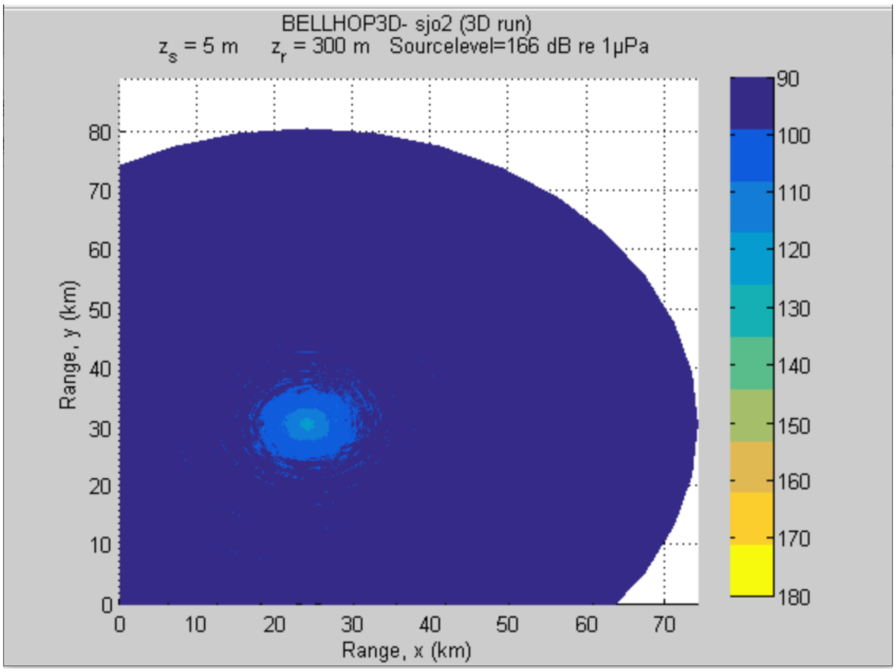

Figure 7.29: RMS SPL,Sørlige Nordsjø II, Operation Phase,August

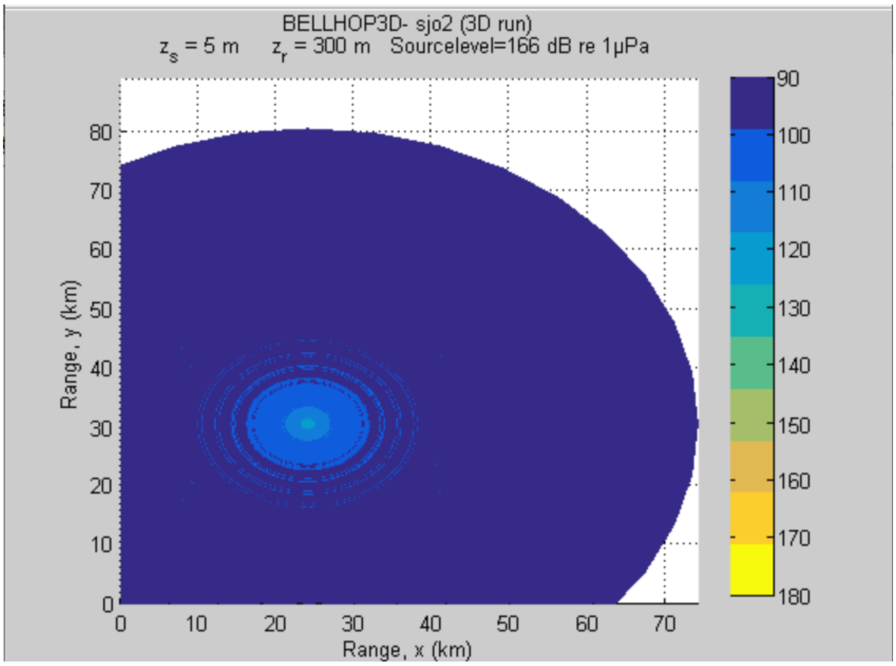

Figure 7.30: RMS SPL,Sørlige Nordsjø II, Operation Phase,December

APPENDIX 2 Sound Pressure Levle and Sound Exposure Level Vertical distribution

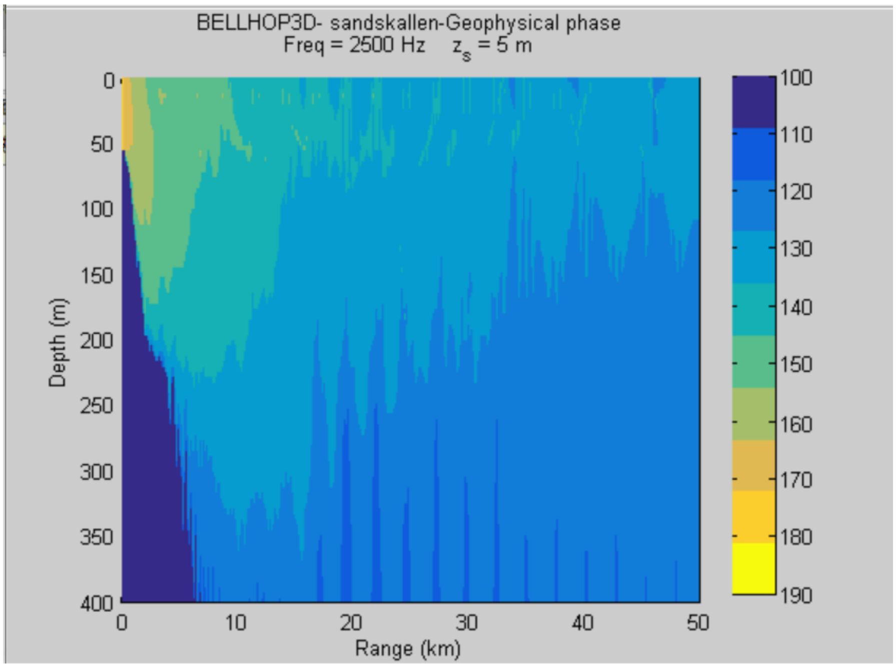

Figure 7.31: SEL,Sandskallen,Geophysical Survey Phase, March

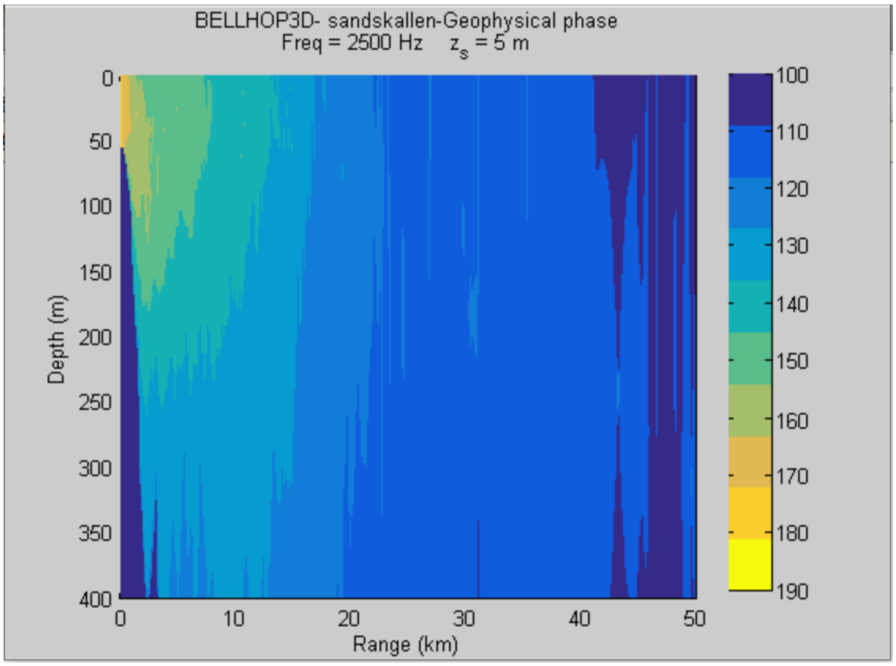

Figure 7.32: SEL,Sandskallen,Geophysical Survey Phase, August

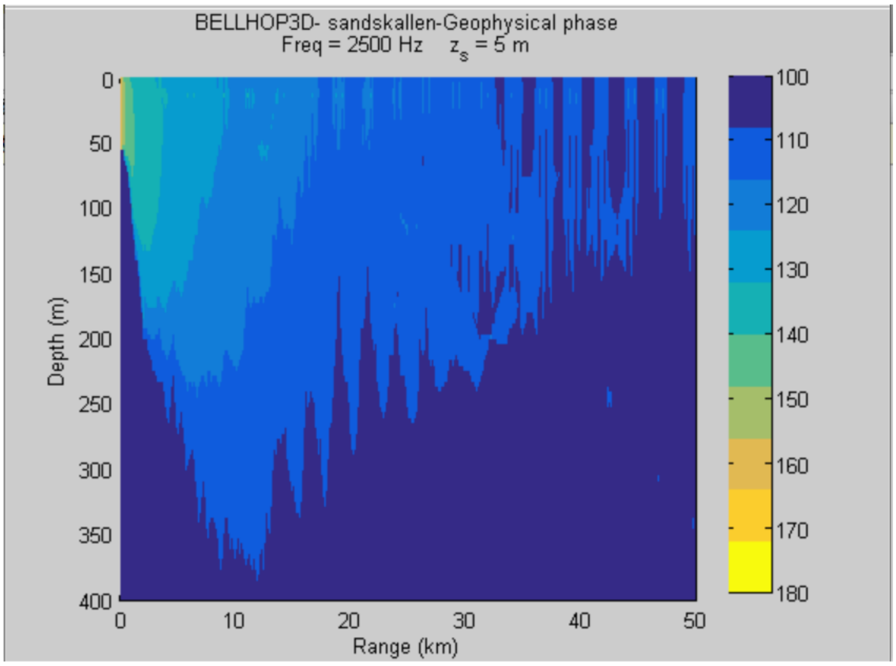

Figure 7.33: SEL,Sandskallen,Geophysical Survey Phase, December

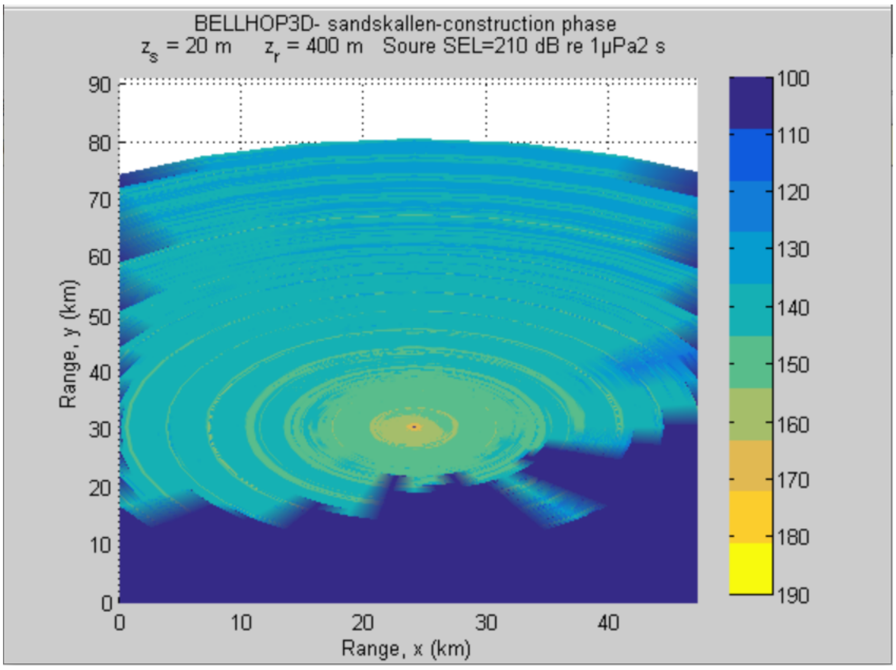

Figure 7.34: SEL,Sandskallen,Construction Phase, March

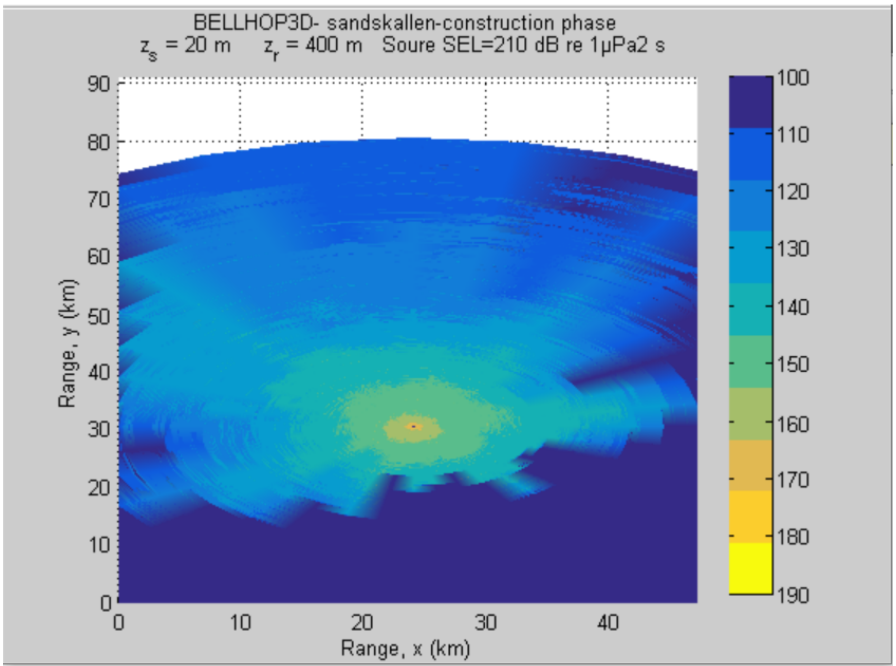

Figure 7.35: SEL,Sandskallen,Construction Phase, August

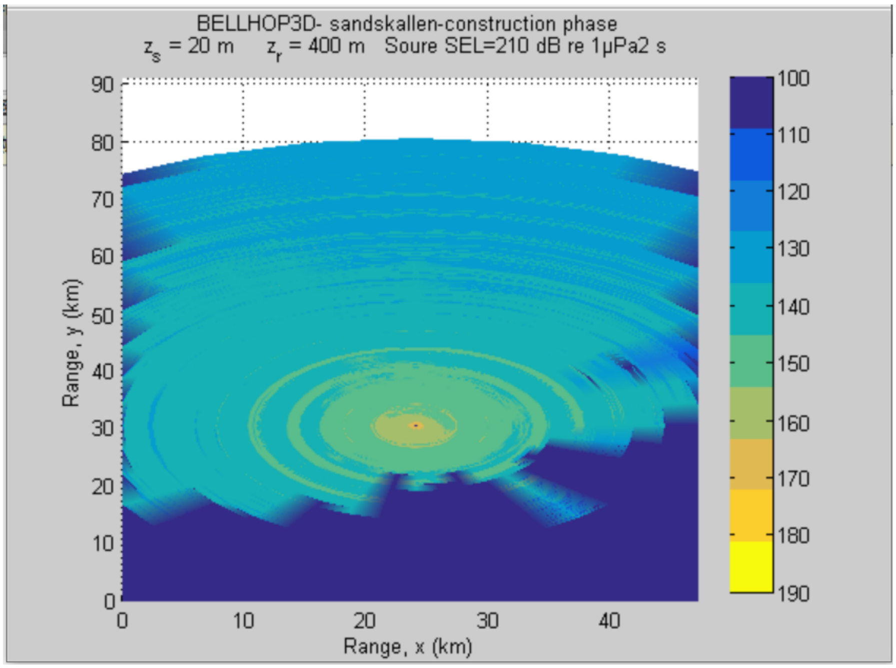

Figure 7.36: SEL,Sandskallen,Construction Phase, December

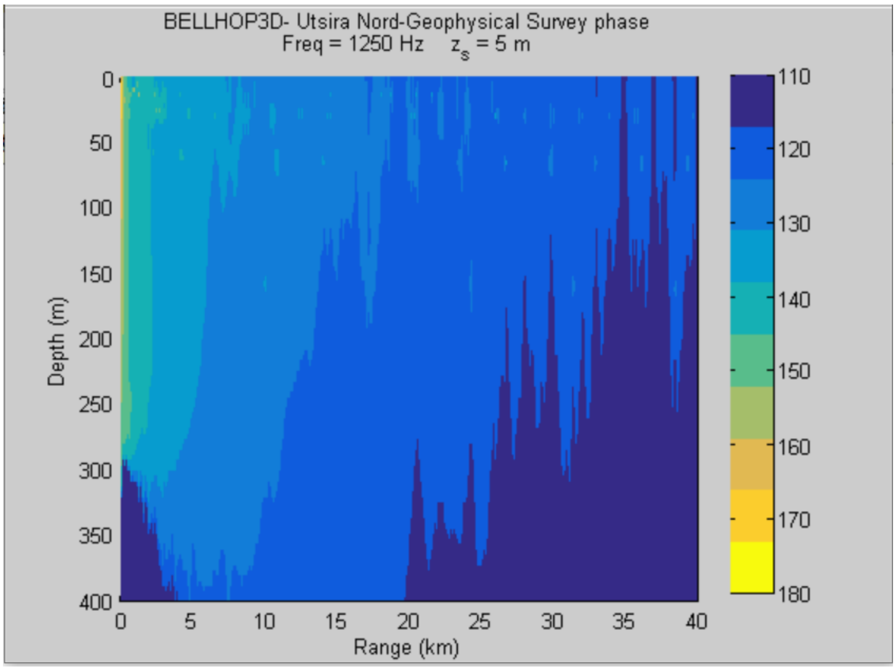

Figure 7.37: SEL,Utsira Nord,Geophysical Survey Phase, March

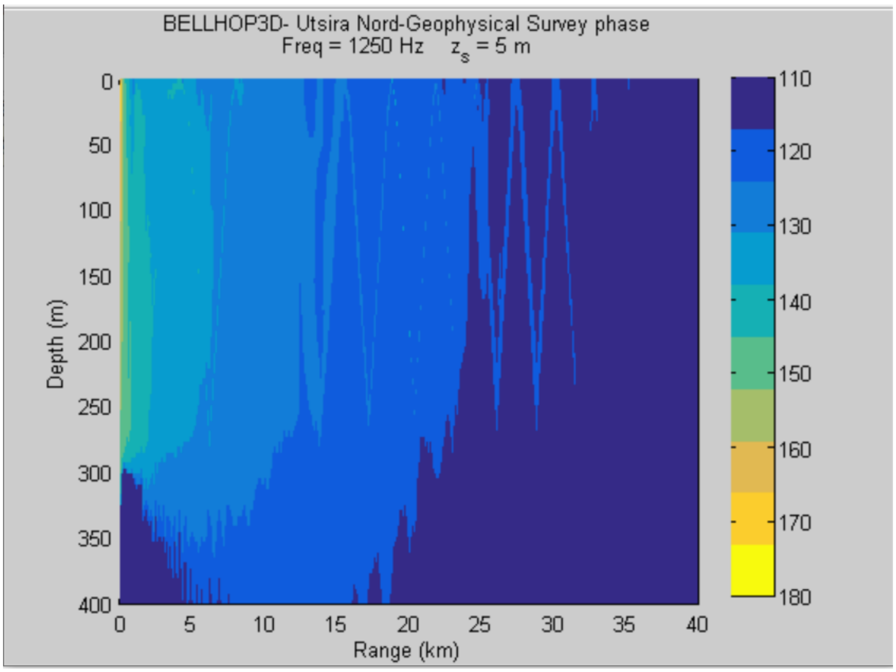

Figure 7.38: SEL,Utsira Nord,Geophysical Survey Phase, August

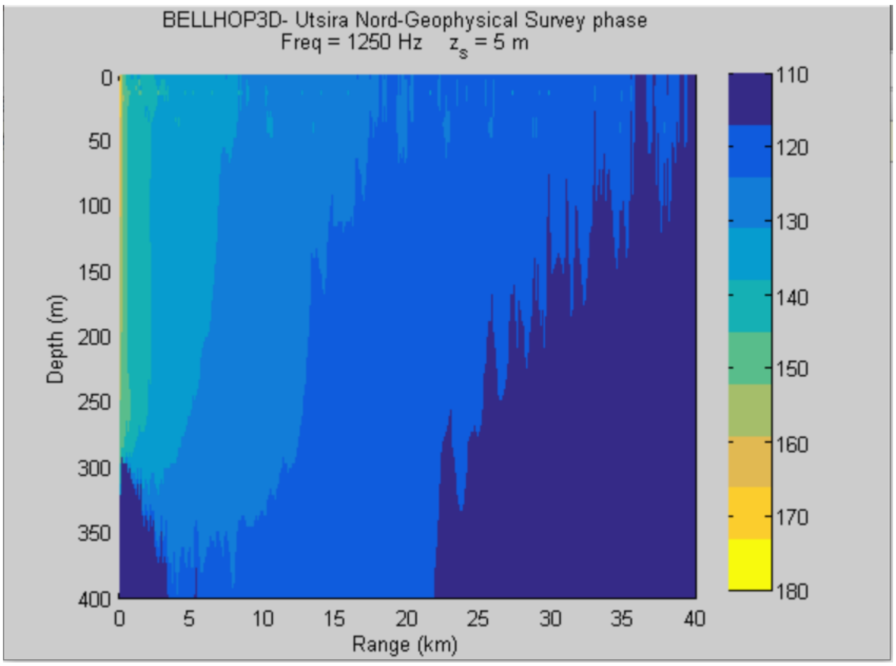

Figure 7.39: SEL,Utsira Nord,Geophysical Survey Phase, December

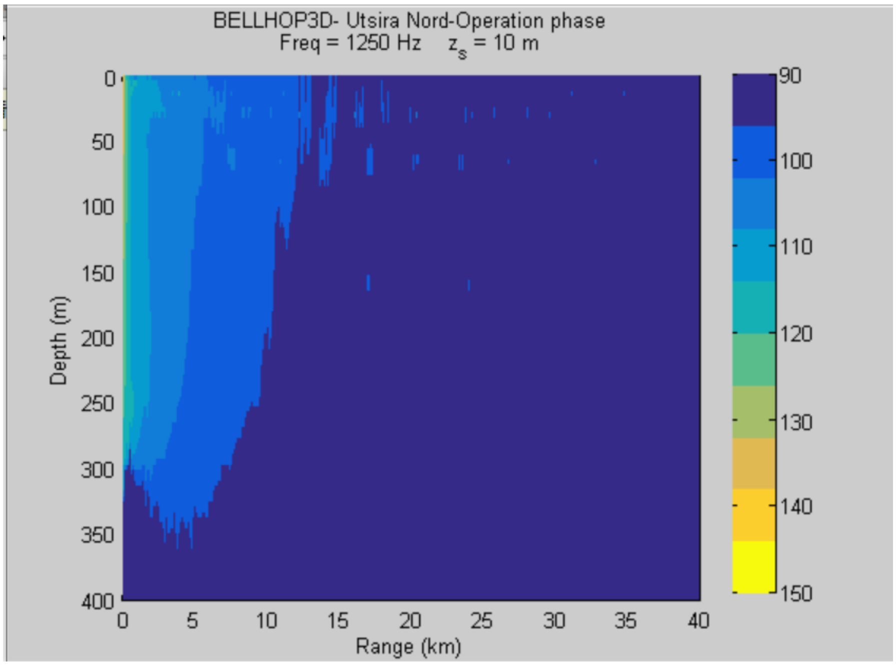

Figure 7.40: RMS SPL,Utsira Nord,Operation Phase, March

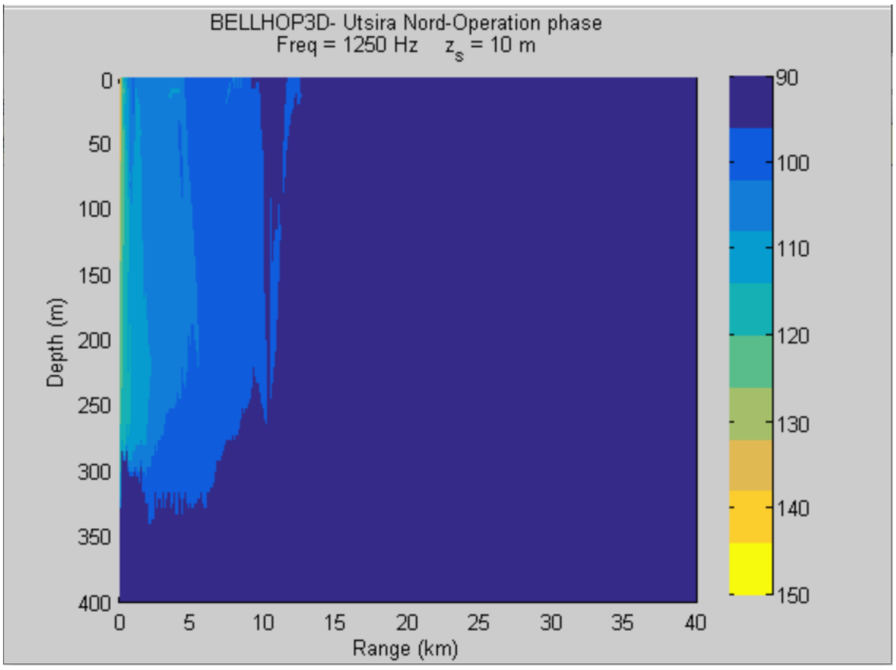

Figure 7.41: RMS SPL,Utsira Nord,Operation Phase, August

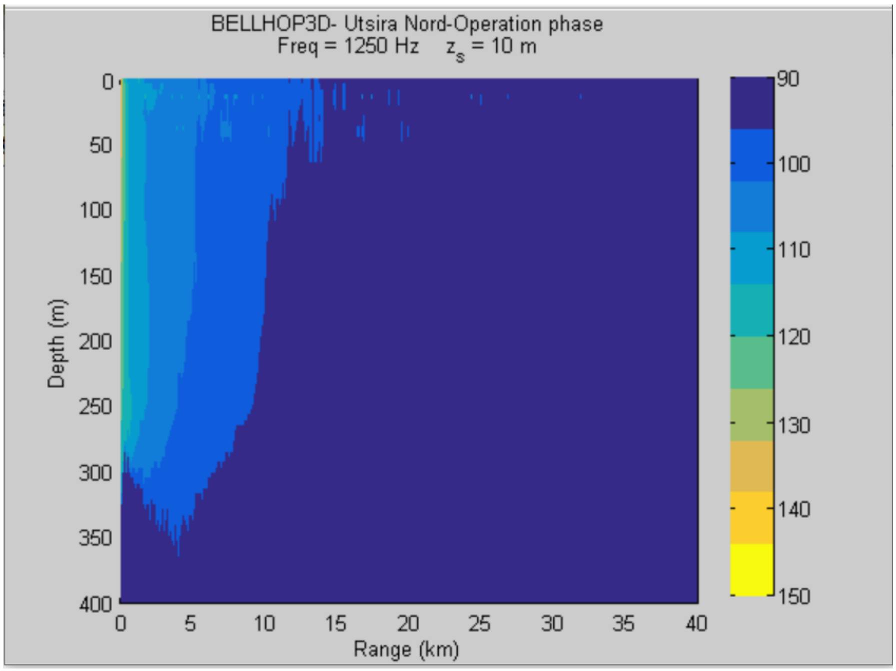

Figure 7.42: RMS SPL,Utsira Nord,Operation Phase, December

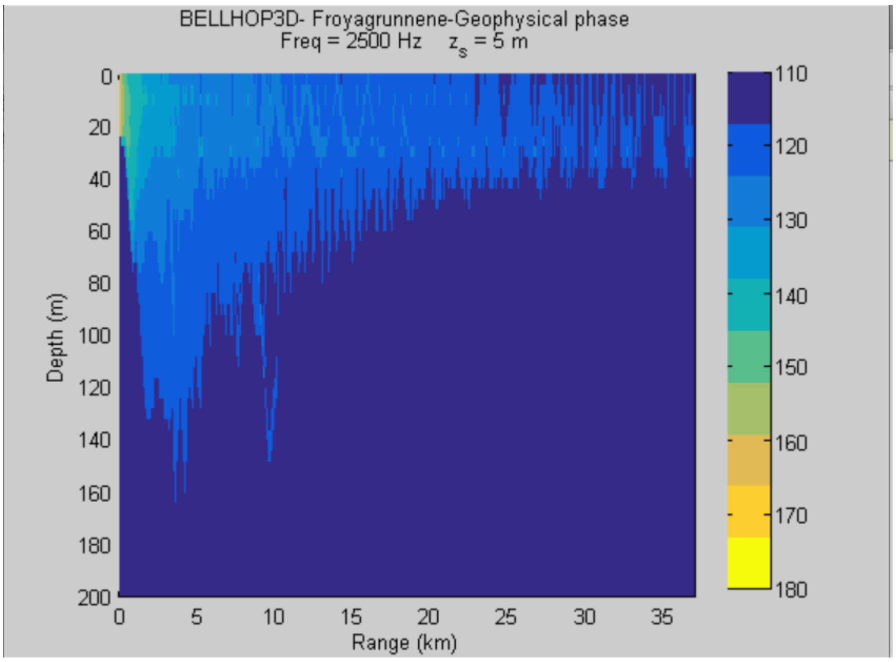

Figure 7.43: SEL,Frøyagrunnen,Geophysical Survey Phase, March

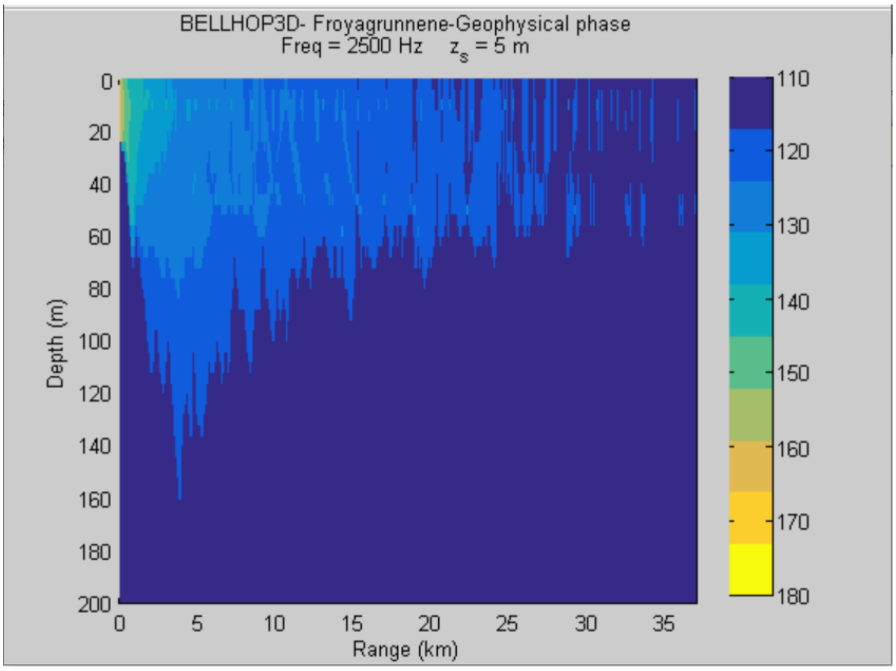

Figure 7.44: SEL,Frøyagrunnen,Geophysical Survey Phase, December

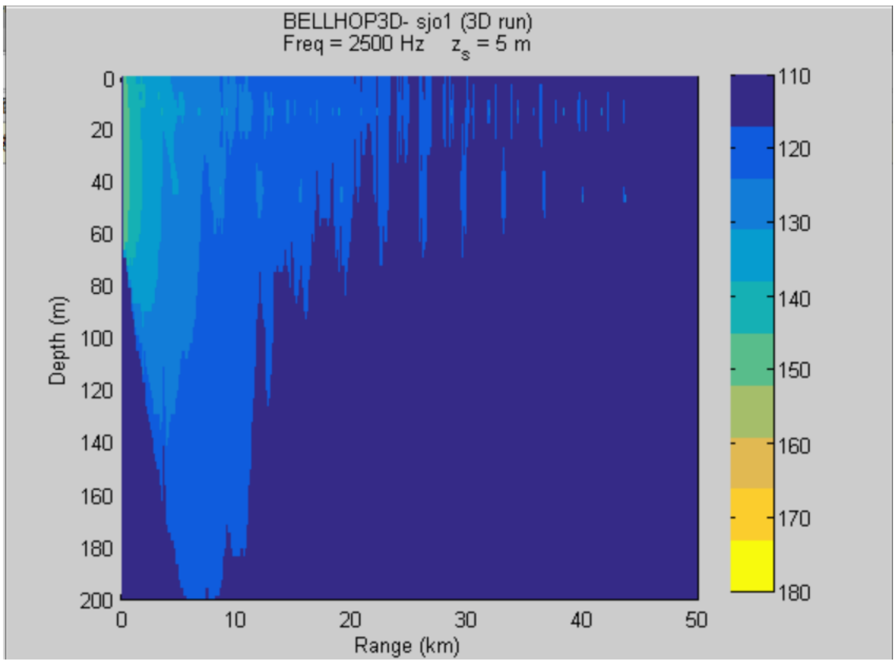

Figure 7.45: SEL,Sørlige Nordsjø I,Geophysical Survey Phase, March

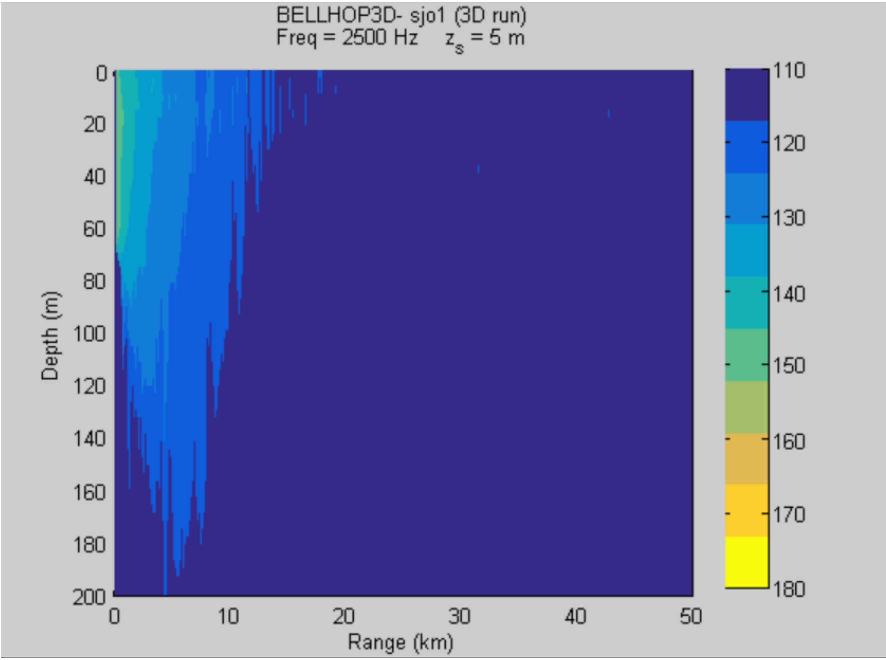

Figure 7.46: SEL,Sørlige Nordsjø I,Geophysical Survey Phase, August

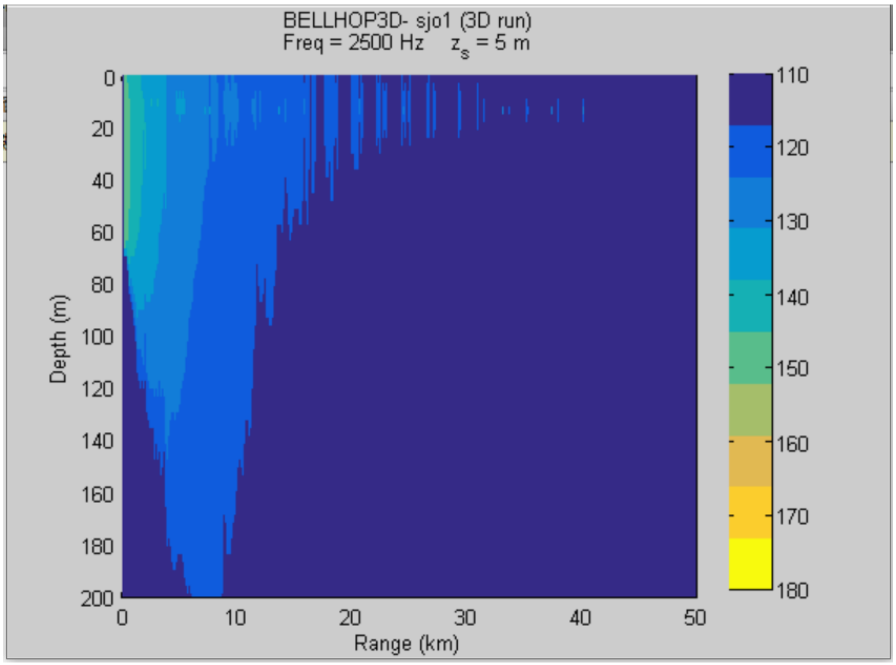

Figure 7.47: SEL,Sørlige Nordsjø I,Geophysical Survey Phase, December

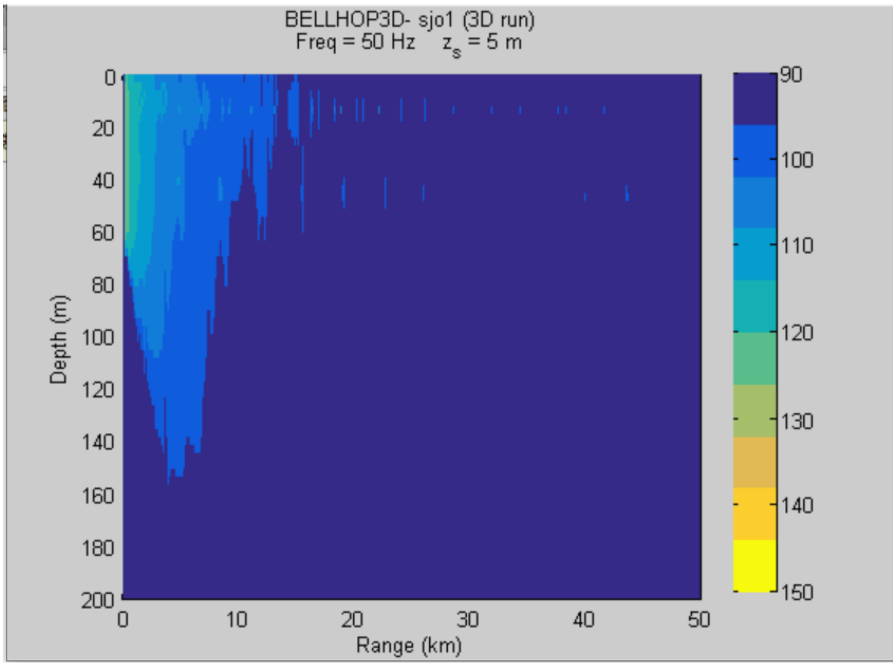

Figure 7.48: RMS SPL,Sørlige Nordsjø I,Operation Phase, March

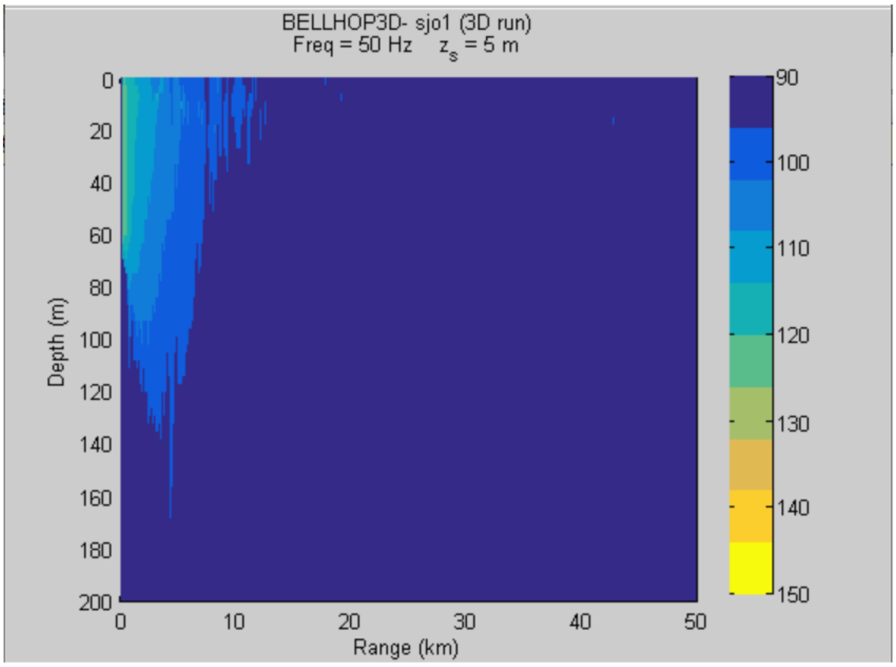

Figure 7.49: RMS SPL,Sørlige Nordsjø I,Operation Phase, August

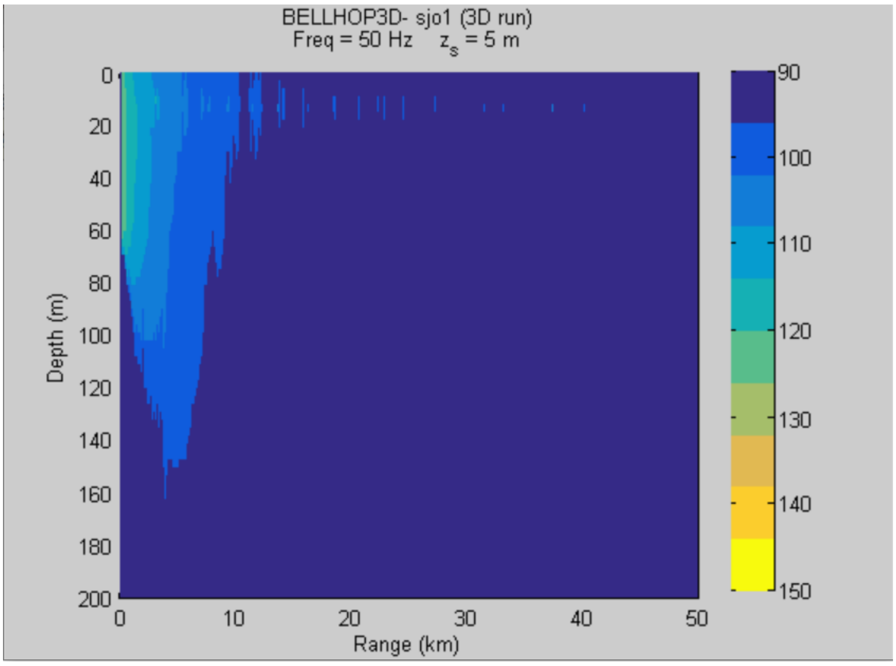

Figure 7.50: RMS SPL,Sørlige Nordsjø I,Operation Phase, December

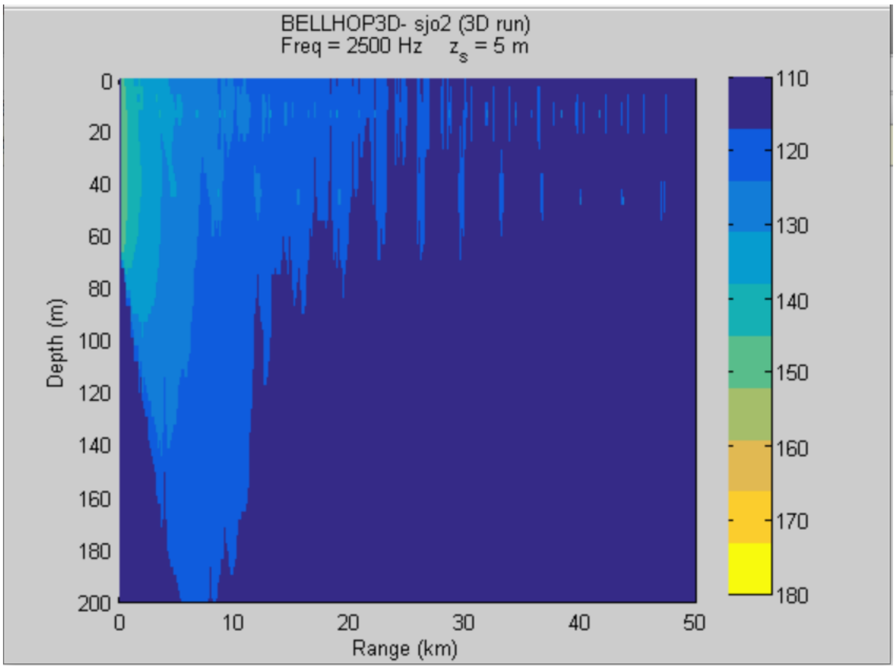

Figure 7.51: SEL,Sørlige Nordsjø II,Geophysical Survey Phase, March

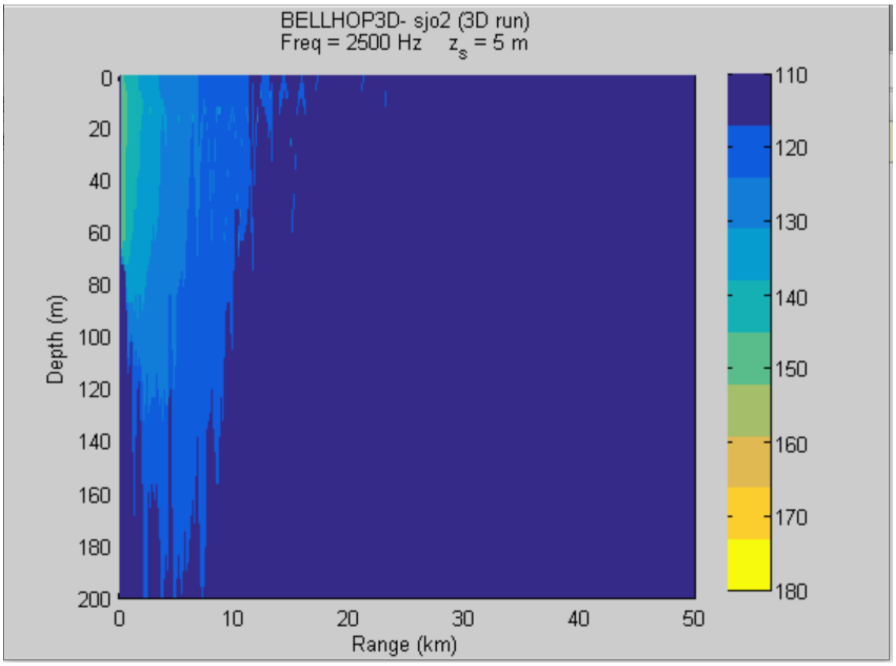

Figure 7.52: SEL,Sørlige Nordsjø II,Geophysical Survey Phase, August

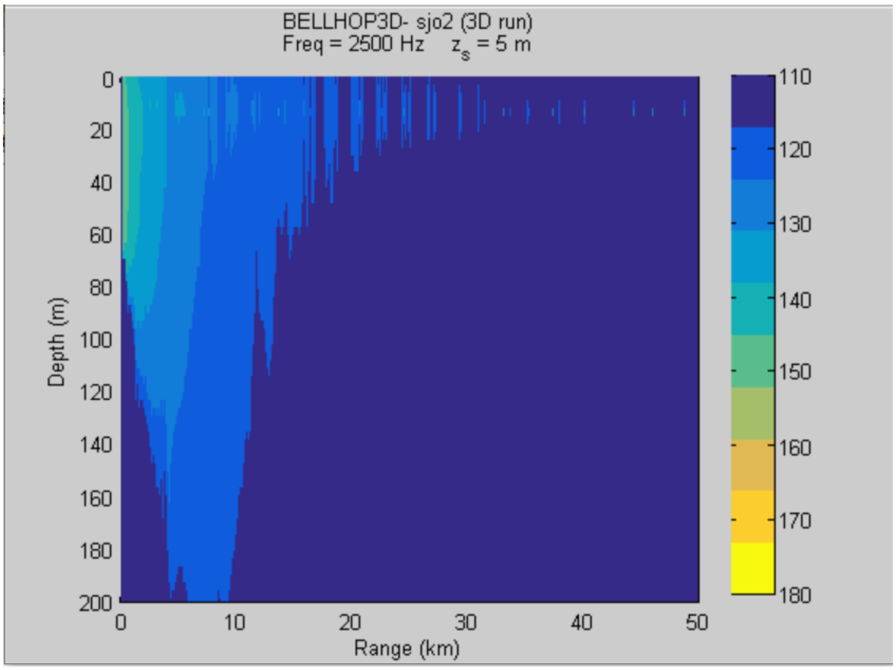

Figure 7.53: SEL,Sørlige Nordsjø II,Geophysical Survey Phase, December

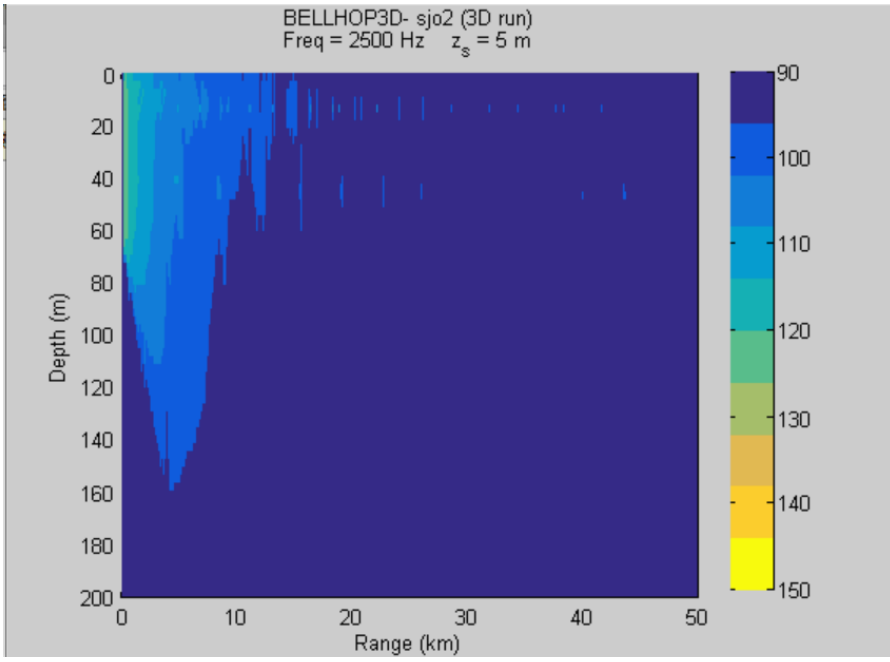

Figure 7.54: RMS SPL,Sørlige Nordsjø II,Operation Phase, March

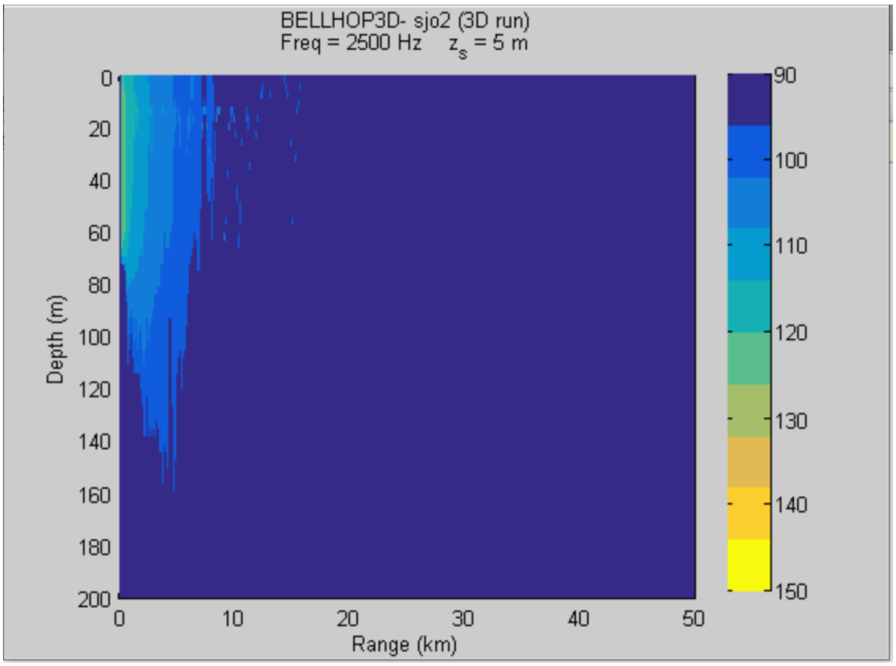

Figure 7.55: RMS SPL,Sørlige Nordsjø II,Operation Phase, August

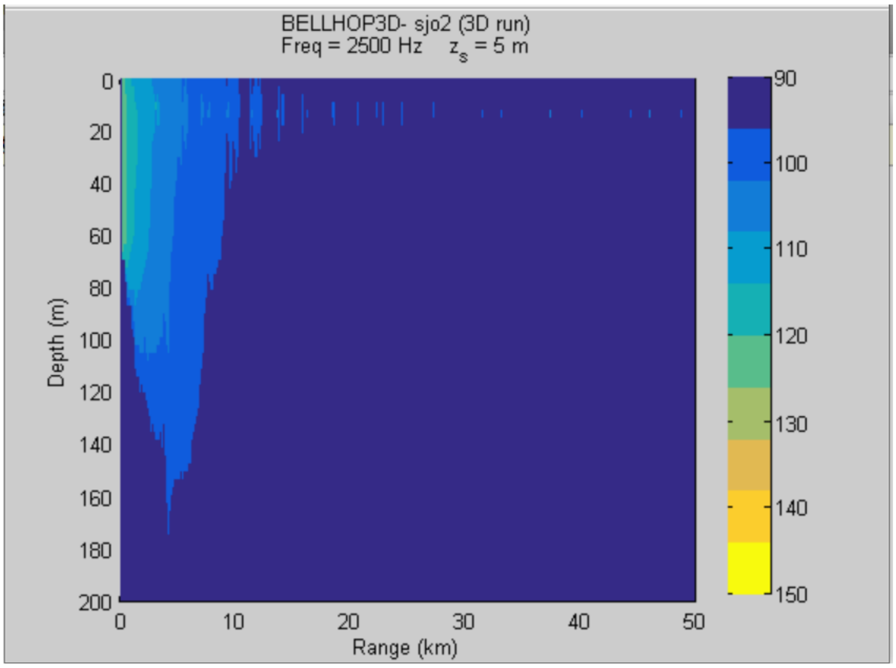

Figure 7.56: RMS SPL,Sørlige Nordsjø II,Operation Phase, December