Noise modelling and environmental risk assessment of a geophysical survey and its impact on herring and minke whales in Irish coastal waters

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Noise modelling and environmental risk assessment of a geophysical survey and its impact on herring and minke whales in Irish coastal waters

Final Report

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Prepared for: Marine Institute / Foras na Mara
Represented by Dr Colm Lordan & Dr Cormac Nolan

Contact person:	Magda Chreptowicz, mchr@dhigroup.com, +48 608 382 003
Project Manager:	Magda Chreptowicz
Quality Supervisor:	Frank Thomsen
Author:	Frank Thomsen, Matthias Ram, Magda Chreptowicz, Marta Nocoń, Irmina Balicka
Project No.:	11830271
Approved by:	Nicola Balbarini
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Nomenclature

Term	Definition
Effect	Changes caused by sound exposure that are deviations from a prior state, condition, or situation, which is called the ‘baseline’ condition
Impact	Effects that reflect a change whose direction, magnitude, and/or duration might be sufficient to have consequences for the fitness of individuals or populations of individuals
Noise	Sound that is not a useful signal or cue, i.e., it has no adaptive value or biological meaning for the receiver, and may either be neutral or may have adverse effects
Sound	The acoustic energy radiated from a vibrating object, with no reference to its function or potential effect

List of Abbreviations

Abbreviation	Definition
dB	Decibel – a logarithmic measure of sound intensity/pressure. Decibel value for acoustic pressure is 10 log10 (P^2/P_o^2) where P = actual pressure and P_o = reference pressure
Hz	Hertz – a unit of frequency, where 1 Hz = 1 cycle per second, 1 kHz is 1000 cycles per second
LF	Low Frequency
LF-weighted SEL	Sound exposure level with the low frequency weighting function in accordance with the susceptibility of hearing damage of low frequency cetaceans caused by noise (NMFS 2018 applied)
NOAA	National Oceanic and Atmospheric Administration
PTS	Permanent Threshold Shift due to a physical injury of hair cells in the ears of cetaceans and seals as a result of exposure to noise
PTS (single strike)	A permanent threshold shift resulting from of a single sparker/ air-gun pulse
PTS (cum.)	A permanent threshold shift resulting from a cumulative noise dose from sparker/ air-gun pulses
RAM	Range-dependent Acoustic Model
RL	Received Level
R_{mean}	Mean radius of impact calculated across all simulated transects
rms	root mean square
R_{max}	Maximum radius of impact calculated across all simulated transects
SEL	The Sound Exposure Level (SEL) is a measure of the amount of sound energy received integrated along a specific time interval and is commonly used to establish noise level thresholds.
SEL_{cum}	Cumulative noise exposure level; summing up the noise exposure levels of many subsequent events. Calculated as: $SEL_{cum} = SEL + 10 \log_{10} n$ n = number of sparker/ air-gun pulses
SL	Sound source level – sound pressure at a standard reference distance of 1 m; in dB units re 1 µPa at 1 m
SPL	Sound pressure level [dB re 1µPa] – sound pressure expressed in decibels [dB] relative to a reference pressure P_{ref}=1µPa
SPL_{peak}	Peak sound pressure level (signal amplitude maximum value)
TL	Transmission Loss
TTS	Temporary Threshold Shift - a temporary threshold shift resulting from exposure to sound; the threshold will return to the pre-exposure state after some time

Abbreviation	Definition
TTS (single strike)	Temporary threshold shift resulting from a single sparker/ air-gun pulse
TTS (cum.)	Temporary threshold shift resulting from a cumulative noise dose from sparker/ air-gun pulses
UAS	Underwater Acoustic Simulator
µPa	Micro pascal – a unit of pressure

1 Executive summary

This study aimed to conduct a summarised risk assessment of the impact of underwater noise generated during a geophysical survey planned in the Celtic Sea on marine mammals and fish. In order to provide representative data on the possible effects on baleen whales and fishes where the swim bladder is involved in hearing (primarily pressure detection), two species were chosen – the common minke whale (*Balaenoptera acutorostrata*) and the Atlantic herring (*Clupea harengus*). Both are important components of the local marine ecosystem. The investigation was conducted via numerical modelling, based on which noise impact ranges and impact areas were derived. The modelling was performed for one location and included two scenarios with different sound sources: 1) sparker, 2) mini airgun. The results showed that both in the case of the minke whale and the herring, the overall impacts from the planned surveys are predicted to be higher if the airgun is used. For the minke whale, the impact ranges were highest for the cumulative TTS, while for herring – behavioural reactions led to largest impact distances. Based on knowledge about the occurrence of the studied species in the survey region and the biological importance of the area to the analysed animals, it was concluded that geophysical surveys should be taken with caution. The use of the sparker instead of the airgun was recommended, along with the application of additional mitigation measures during the survey activities.

2 Introduction

2.1 Background

The effects of underwater noise on marine life have been studied with increasing intensity in the past decade (see review by Thomsen *et al.* 2021). It is well known that airgun arrays used in large geophysical surveys emit sounds of relatively high intensity that can affect marine life at considerable distances (see review in OSPAR, 2009; Thomsen *et al*. 2021). Less is known about the potential effects of more site-specific surveys using High Resolution Geophysical (HRG) equipment such as sparkers (and as back up mini airguns). The Marine Institute approached DHI to perform an initial and summarised risk assessment of sounds from HRG surveys. The information provided by this work was aimed to guide the environmental management of further surveys undertaken in Irish waters. To achieve this, we modelled the propagation from a geophysical survey in Irish waters, in the southern part of the North Celtic Sea, and present predicted impact ranges of the associated underwater noise for marine mammals and fish.

2.2 Aim of the study

The project aims to undertake noise modelling and environmental risk assessment of geophysical survey sounds and its impact on the minke whale (*Balaenoptera acutorostrata*) and the Atlantic herring (*Clupea harengus*) in Irish waters. Both species are important components of the local marine ecosystem and were chosen for the conducted assessment in order to provide representative data on the possible impact of the planned surveys on two groups of organisms – marine mammals and fish.

The investigation area for the planned activities is located off the south-east coast of Ireland between Cork & Waterford in the North Celtic Sea (Figure 2.1). The water depth of the area ranges from 40 to 80 m.

The study area is located approx. 20 km from Mid-Waterford Coast Special Protected Area (SPA). In the north, the area borders the Natura 2000 area of Hook Head. In the south-east, in approx. 130 km distance, the protected areas of Skomer, Skokholm and the Seas off Pembrokeshire SPA/Sgomer, Sgogwm a Moroedd Penfro are located. To the west, the Natura 2000 area Helvick Head waters is situated at approx. 10 km distance.

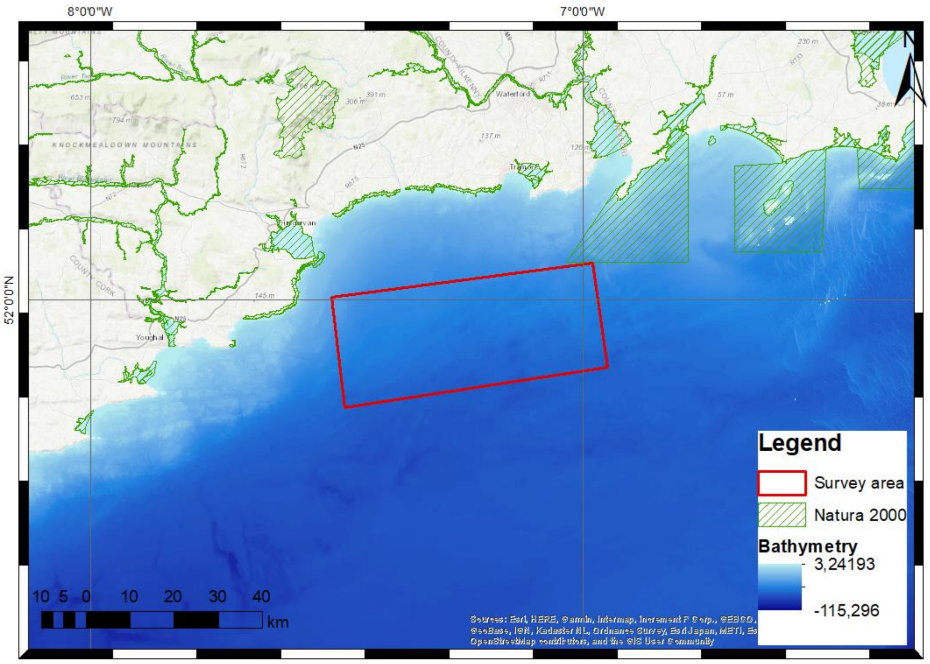

Figure 2.1 Location of the survey area in the North Celtic Sea

2.3 Modelling scope and assumptions

The scope of this study included:

- Numerical underwater noise modelling, including two scenarios conducted for the same location (the deepest station – 72 m), but with different sound sources: 1) sparker, 2) mini-airgun, together with calculation of impact zones for the minke whale (*Balaenoptera acutorostrata*) and Atlantic herring (*Clupea harengus*)
- Summarised Environmental risk assessment of geophysical survey sounds and its impact on the minke whale (*Balaenoptera acutorostrata*) and Atlantic herring (*Clupea harengus*) in the study area and adjacent waters.

2.4 Species

Minke whale *Balaenoptera acutorostrata*

The common minke whale is one of the smallest baleen whales. It has a global distribution in temperate to sub-arctic waters, occurring mostly over continental shelf, but also in deep water and very close to shore (Harris and Yalden, 2008).

In Irish waters, the minke whale is among the most frequently sighted whale species and can be recorded throughout the year, along the entire Irish coast. It is mostly seen over the Irish shelf, as well as in shallower areas like Porcupine and Rockall Banks. The species has a clear seasonal occurrence, with most of the records made along the south and west coasts between May and October (Irish Whale and Dolphin Group; National Biodiversity Data Centre, 2023) (Figure 2.2).

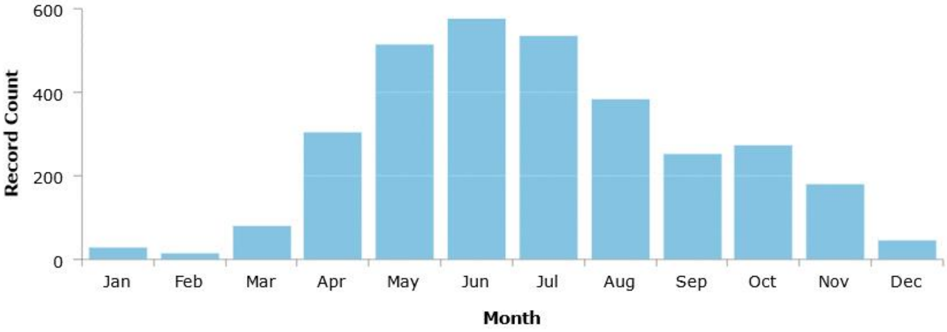

Figure 2.2 Occurrence of minke whales in Irish waters along the year (figure derived from the National Biodiversity Data Centre, Ireland; October 2023)

With regards to acoustic communication, the minke whale is found to use different types of acoustic signals. Among them are for example repetitive, low-frequency (100-500 Hz) pulse trains that may consist of either grunt-like pulses or thump-like pulses (e. Rish *et al.*, 2013). In the hearing classification, the species is grouped as the low-frequency cetacean (NOAA, 2018; NOAA species fact sheet).

Atlantic herring *Clupea harrengus*

The Atlantic herring is a small pelagic fish. It is a key species within the Celtic Sea food web as it helps transferring energy from low to high trophic levels (Peck *et al.*, 2014). It is also an important component of the Irish fishery (Marine Institute, 2013).

The species is highly migratory. During the early life stages, it occupies nursery grounds. This is followed by migration to spawning, wintering and feeding regions in the later life phases (Blaxter and Holliday, 1963). Spawning occurs between October and February, beginning inshore at the western Irish south coast and following eastward movement (Molloy, 2006; O'Sullivan *et al*., 2013). The Celtic Sea stock of herring includes autumn and winter spawning components, with a lower proportion of autumn spawners (Harma *et al*., 2012). Autumn spawning grounds are predominately along the western south coast (Volkenandt *et al.*, 2014). After spawning, the species migrate to offshore feeding grounds. Juveniles have nursing grounds in the Irish Sea, as well as in the bays and inlets along the south and west coasts (Molloy, 2006).

With regards to detection of acoustic signals, herring belongs to the group of fish having its swim bladder involved in hearing and being sensitive primarily to the pressure component of the sound wave (Popper, 2014). The species is most sensitive to the low frequency signals (below 500 Hz) but can detect sounds of up to at least 4 kHz (Enger, 1967; Sivle *et al.*, 2012).

2.5 Noise impact

Underwater noise might affect marine life in in different ways. Depending on the relative distance of the animal to the location of the sound source, several overlapping zones of impacts can be distinguished (Figure 2.3):

- zone of masking: the area where noise interferes with the detection of biologically relevant signals or cues used for communication and navigation;
- zone of behavioural response: the area within which a marine animal changes its behaviour in response to noise, e.g., by swimming away or diving deeper. Repetitive and / or continuous behavioural avoidance can lead to distribution changes of the species in question from the personified area. This can be temporary (e.g. Brandt *et al.*, 2011) or long-term (e.g. Morton and Symonds, 2002);
- zone of impaired hearing: the area in which noise can lead to changes in hearing sensitivity. These changes can be temporary (temporary threshold shift, TTS) or permanent

(permanent threshold shift, PTS). In most cases, TTS and PTS relates to changed sensitivity to certain frequencies;

- zone of physical and/or physiological effects: the zone where tissue damage and physiological effects other than those associated with hearing can occur. In extreme case, the damage can lead to the death of the marine organism.

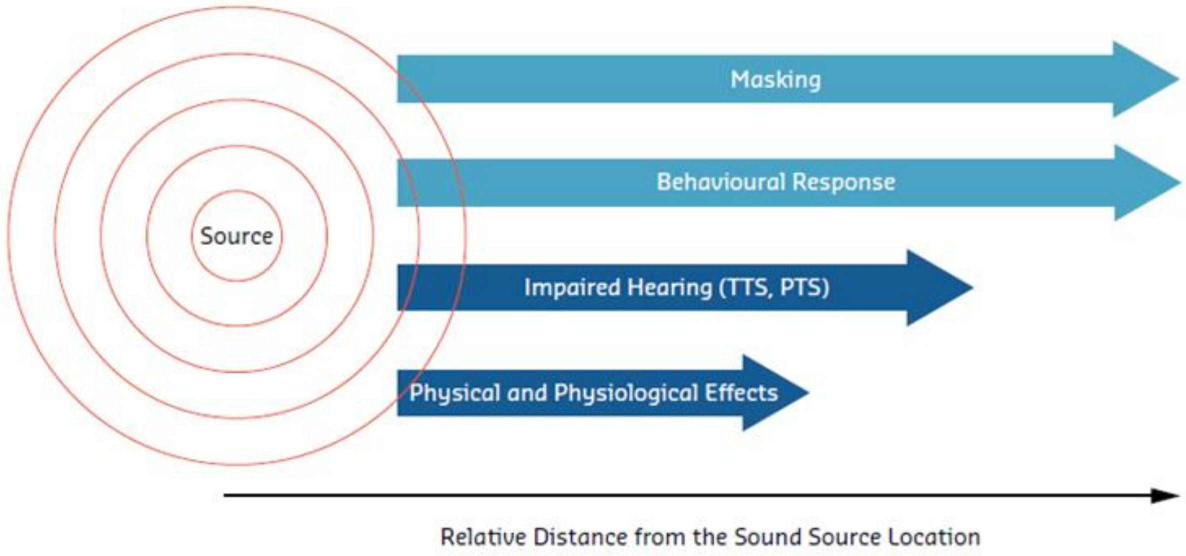

Figure 2.3 Potential effects of noise at different distances from a sound source (taken from Thomsen *et al*. 2021)

3 Methodology

This chapter outlines the methodology of the underwater noise propagation model and the assessment of noise impact from geophysical surveys.

3.1 Noise propagation modelling

The numerical noise propagation modelling was performed using a parabolic equation and the in-house MIKE by DHI Underwater Acoustic Simulator (UAS) (MIKE DHI, 2021). The model focuses on noise propagation in the far field, intending to provide a basis for conducting a risk investigation of environmental noise effects. MIKE UAS is based on the method of the parabolic equation developed by (Collins, 1993) and considers the following processes:

- UAS accounts for the change in speed of sound and volume attenuation in the water;
- UAS includes sound propagation in the seabed.
- specific 1/3 octave bands with centre frequencies from 10 Hz to 4 kHz were modelled for the airgun while bands with centre frequencies of 125 Hz to 4 kHz were considered for the sparker. Higher frequencies of up to 20 kHz are based on the model results at 4 kHz but corrected in accordance with frequency dependant attenuation.
- sound propagation is calculated at discrete angular directions, every 5°, of the selected source location, thus producing 72 individual transects extending up to 70 km from the source (Figure 3.1). Spatial maps are then derived by integrating the results across all transects.

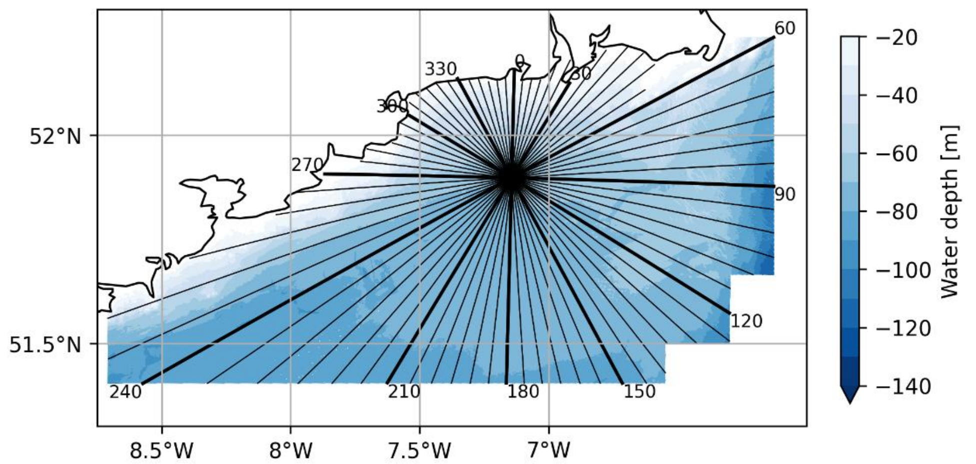

Figure 3.1 Map of transects used in the sound propagation

Simulations were carried out considering the following simplified conditions and specific assumptions:

- The sea surface is treated as a simple, horizontal, perfectly reflecting boundary ignoring the sea states, where in addition to waves, the upper ocean will have an infusion of air bubbles which has a significant impact on the speed of sound in the surface part of the water column.
- The code is a 2D model ignoring 3D effects due to the horizontal refraction of sound rays reflected by a sloped sea bottom. E.g., when the sea floor is shoaling, as is the case for the ocean over a sloping beach and the continental slope, and around seamounts and islands, a ray travelling obliquely across the slope experiences the phenomenon of horizontal refraction.
- Near-field effects are neglected in the present study, which is judged to have a minor effect on the far-field sound pressure level. At impact ranges of interest (e.g., > 100 m), the sound intensity effects and oblique radiated sound waves dominating the near field are diluted significantly.

- Based on the calculations, noise maps of the sound pressure field as a function of distance are provided.
- As both study species are expected to use in principle the full depth of the water column, the maximum received sound level over the water column at any given range is reported.

3.2 Input data

Several parameters are required for the model setup, including sound source spectra and location, seabed and water column characteristics. For this study, such information was obtained from various sources, including data provided by the client, publicly available data, as well as information gathered from literature.

Sound source location

The survey area is located in the north part of the Celtic Sea, approximately 9-20 km from the Irish coastline (Figure 3.2). In the vicinity of the of the survey area several Natura 2000 areas are designated (IE0000764, IE0000707, IE0004193, IE0004027, IE0000671, IE0000665, IE0004192, IE0004032, IE0004032).

The source point location has been identified in the southern part of the research area, at a local depth of -72 m, which was considered as the “worst-case” scenario regarding potential impacts in the whole project area because it was expected that noise would spread farthest from this point. The coordinates for the noise modelling location are provided in Table 3.1. The depth at the source was obtained from the high-resolution bathymetry dataset provided by the client.

The tow depth of the sound source was specified as 0.3 m for the sparker. For the mini airgun a tow depth of 6 m was assumed (Jiménez-Arranz *et al*., 2020).

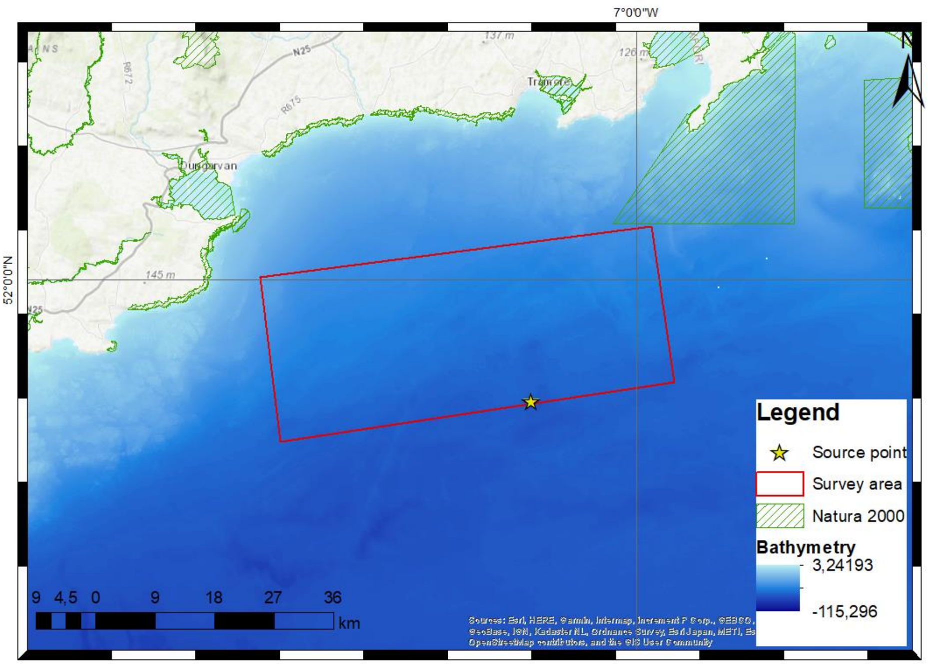

Figure 3.2 Survey area

Table 3.1 Noise modelling location

Longitude	Latitude	Easting [m UTM 29N]	Northing [m UTM 29N]	Water depth [mMSL]
7°8'37.1292"W	51°53'52.98"N	627723.632	5751327.589	-72.7

Sound source spectrum

Two different seismic sound sources have been investigated: An electrode sparker *Applied Acoustics Dura-Spark 400+400* and the *Sercel Mini G* airgun. For both devices, the relevant source spectra were determined.

The primary source is the sparker. It has a typical operational bandwidth of 300 Hz to 1.2 kHz and typical source level of 226 dB re 1 µPa (Applied Acoustics, 2020).

The source spectrum shown in Figure 3.3 was derived based on measurement data published in Crocker & Fratantonio (2016). Since virtually no systematic differences in broadband levels, bandwidth or recorded time domain data could be observed between energy levels of 2000 J and 2400 J, as well as the superior quality of available data at 2000 J, the 2000 J time domain data was chosen as representative input data for the worst-case scenario, in terms of resulting source levels.

Since the data were acquired by measurements under operational conditions, it includes reflections from the sea surface. These reflections are a property of the noise propagation in the medium, rather than a property of a source. The reflections and the resulting gains and losses in the sound transmission are included in the propagation model and thus, must not be part of the source spectrum itself. The final spectrum was thus not directly obtained from the measurement data but synthesised using ideal gaussian pulses in such a manner, that it matches the third-octave averaged spectrum of the measurement very closely when reflections from the sea surfaces are analytically accounted for.

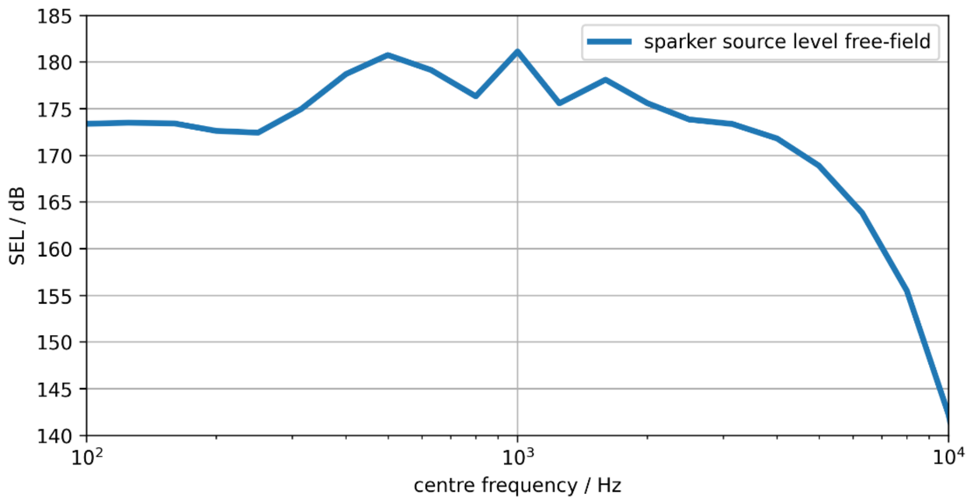

Figure 3.3 Source spectrum @ 1 m Dura-Spark 400+400, 2000 J

The secondary sound source is the seismic airgun. Airguns can reach very high sound levels and their spectral peaks are reached at low frequencies below 100 Hz (Ziolkowski, 1970). The signal is not only characterised by the initial pulse but heavily influenced by the periodic bubble oscillations following the discharge. An analytic solution of the governing equations is possible and gives very accurate results as initially outlined in Ziolkowski (1970). To derive the omnidirectional source spectrum of a single airgun however, such detailed modelling is not required. Instead, available data for other airgun models is scaled to match the characteristics of the investigated model.

The output pressure signal is governed by two parameters: the chamber volume V_{ag} and pressure p_{ag}. Its amplitude p_{pk} scales approximately linearly with the chamber pressure and proportional to the cube root of the chamber volume (Jiménez-Arranz *et al*., 2020), while the bubble oscillation frequency can be estimated by the Rayleigh-Willis equation:

$$f \approx k \frac{(10 + z_{ag})^{\frac{5}{6}}}{\sqrt[3]{p_{ag} V_{ag}}},$$

where z_{ag} denotes the depth of the airgun below the sea surface and k is a constant.

Using the relations above, the source spectrum shown in Figure 3.4 was derived, where the defining parameters have been assumed as $V_{ag} = 60\ \mathrm{in}^3$, $p_{ag} = 3000\ \mathrm{psi}$ and $z_{ag} = 6\ \mathrm{m}$.

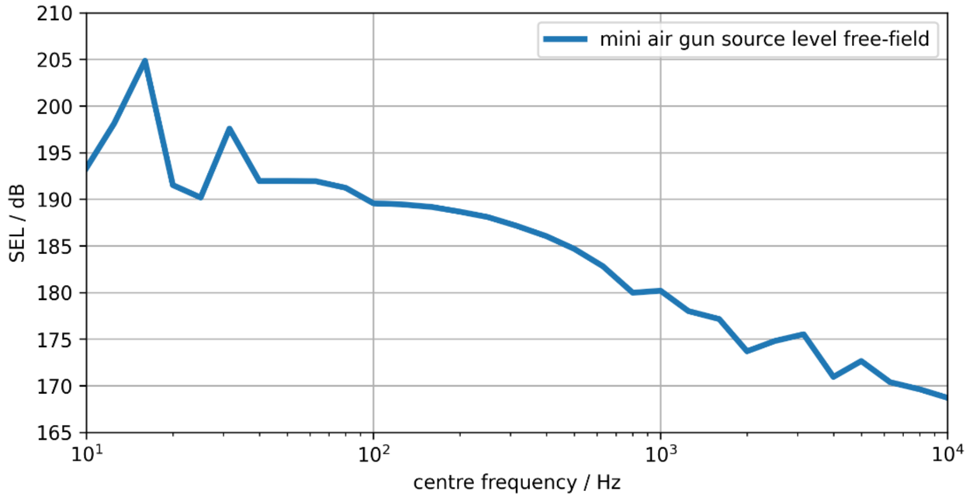

Figure 3.4 Source spectrum @ 1 m Sercel Mini G assuming 60 in³ and 3000 psi

Seabed geo-acoustic properties

The geological profile has been created based on data provided by the client (bottom sediments) and supplemented by information derived from a geological map of the research area (Nymphe Bank sheet, 2023). Geo-acoustic properties of each soil layer were estimated based on standard literature values (Jensen *et al*., 2011). The summary of the seabed profile and geo-acoustic properties of the layers is presented in Table 3.2.

Table 3.2 Overview of seabed profile used for the underwater noise modelling

Cp = compressional wave speed, α = attenuation of compressional waves, ρ = density

Depth below seafloor [m]	Thickness [m]	Layer	vp [m/s]	ρ [kg/m³]	Compressional attenuation $Alpha_p$ [dB/Lambda]
0-5	5	Sand	1650	1900	0.8
5-50	45	Sedimentary rocks	2950	2200	0.2

Water column characteristics

Sound propagation in seawater is influenced by the depth-dependent sound velocity profile and the frequency-depended volume attenuation, which in turn is influenced mostly by the acidity (pH value) and to a lesser extent by the salinity and temperature (Jensen *et al*., 2011).

The characteristics vary with location and season and thus must be chosen accordingly. The sound velocity profile shown in Figure 3.5 was derived from measurements supplied by the client. A subset of 199 individual measurements out of more than 2500 datapoints was chosen based on location, season, and data quality. The final sound velocity profile was then calculated as the average of the samples.

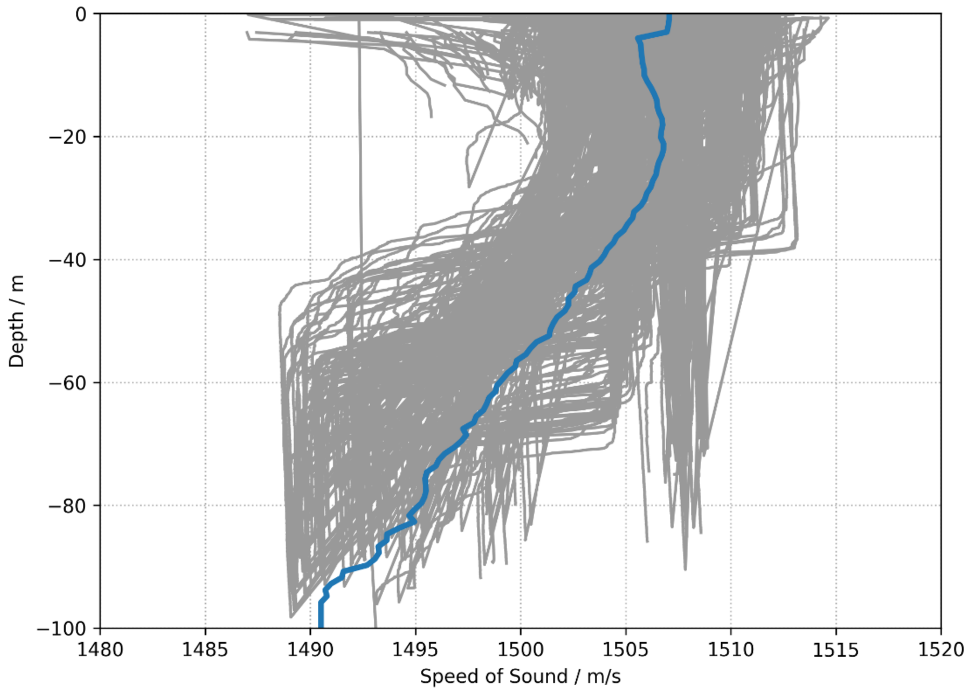

Figure 3.5 Sound velocity profile for the Celtic Sea in autumn
(grey: individual measurements, blue: averaged profile)

The remaining parameters, acidity, salinity and water temperature given in the Table 3.3, have been assumed as constant over depth. The error in the overall transmission loss resulting from the neglection of their variability with water depth, and resulting variations in the volume attenuation coefficient, is assumed to be negligible. This assumption is justified, since the variation of the parameters is small and volume attenuation in the water column is only one loss mechanism, contributing to transmission losses besides bottom reflection loss and scattering loss, both of which are also subjected to uncertainty.

Table 3.3 Depth-independent parameters of the water

pH [-]	S [psu]	T [°C]
8.1	33	10

3.3 Thresholds for noise impact

Noise criteria describe received levels of noise, which should not be exceeded in order not to cause harm to marine life. For the need of the modelling study conducted for this report, thresholds for noise impact were chosen based on international criteria, as well as on information from available studies.

For marine mammals, the most comprehensive set of criteria was defined by US regulators (NMFS, 2018) and updated by Southall *et al.*, 2019. In both documents, threshold values are based on frequency weighting, with consideration that animal hearing sensitivity is frequency dependant. With regards to the minke whale, in the conducted modelling, TTS and PTS thresholds set for Low Frequency Cetaceans (LFC) were used. In the case of behavioural response, the criteria set by NMFS/ NOAA were applied (Table 3.4).

With regards to herring, TTS and PTS thresholds used in the model were based on an expert review by Popper *et al.* (2014). The criteria chosen for the behavioural response was derived from a field study by Hawkins *at al.* (2014) (Table 3.4).

Table 3.4 Overview of noise exposure criteria used to calculate the impact ranges

Reference	Group of animals	Effect	Sound type modelled	Sound Exposure Level/ Sound Pressure Level
Popper et al., 2014	Fish with swim bladder involved in hearing - herring	PTS	Single pulse and 1 h cumulative	203 dB re 1µPa (non-weighted SEL)
		TTS		186 dB re 1µPa (non-weighted SEL)
Hawkins et al., 2014	Fish with swim bladder - herring	Behavioural reaction	Single pulse	135 dB re 1µPa (non-weighted SEL)
NMFS, 2018	Low-frequency cetacean – minke whale	PTS	Single pulse and cumulative (cumulation up to 24 h)	183 dB re 1µPa (LF-weighted SEL)
		TTS		168 dB re 1µPa (LF-weighted SEL)
		Behavioural reaction	Single pulse	160 dB re 1µPa (rms)

3.4 Estimation of impact zones

The impact zones for PTS, TTS and the behavioural response of the minke whale and Atlantic herring, were derived based on the numerical noise modelling described in the Section 3.1, and using the noise criteria defined in Section 3.3. The key features and assumptions of the model are:

- For this exemplary modelling study, we chose one location for each of the emitted sounds which means that the noise source and the receivers (animals) are considered static. The modelling results for single pulses are considered accurate within the bounds of the model.
- The impact ranges for multiple pulses, also defined as the cumulative noise exposure are subjected to high uncertainty due to the static nature of the modelling. Under natural conditions, one would expect animals to move away from the source and the source will move as well. Thus, a maximum exposure time of one hour is assumed, which is considered a conservative estimate for cumulative noise exposure.
- Ambient noise is considered as a lower bound. A generic ambient noise spectrum with a broadband level of approximately 105 dB re 1 µPa is assumed and accumulation of noise exposure is only considered where ambient noise levels are exceeded.
- To compute the cumulative sound exposure levels for 1 h, a duty cycle of 1.5 s was assumed for the sparker whereas 10 s were assumed for the airgun.

4 Results

This chapter presents the results of the sound propagation modelling. The noise impact ranges are shown for two scenarios of the geophysical survey: when it is performed with a sparker (1) and with the mini airgun (2).

4.1 Sound levels

The influence of bathymetry on the noise propagation is mostly small due to the relatively flat sea bottom in the survey area. A slightly slower decline of sound levels towards the southern direction can be observed where the depth remains nearly constant over a considerable range. As could be expected due to the higher source levels, the sound exposure levels in the survey area are considerably elevated when the airgun (Figure 4.1) is operated instead of the sparker (Figure 4.2).

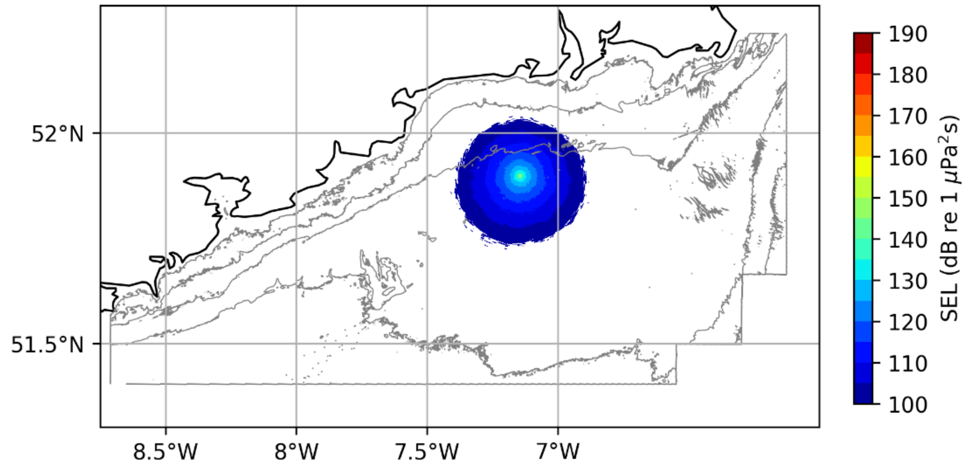

Figure 4.1 SEL related to operation of the sparker in the project area

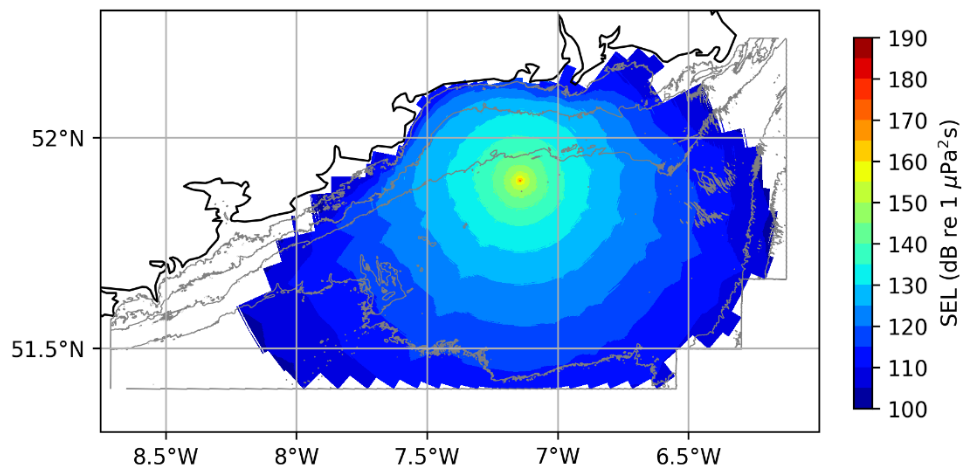

Figure 4.2 SEL related to operation of the mini airgun in the project area

4.2 Impact ranges for minke whales

4.2.1 Sparker

Modelling results obtained for the minke whales showed that in case of TTS and PTS from a single strike, as well as for the cumulative PTS, effects from the sparker are in the short range (up to 0.2 km). Maximum distances found for the cumulative TTS and the behavioural response are also considered low (1.1 km), with impact areas below 3 km^2 (Table 4.1, Figure 4.3 - Figure 4.5).

Table 4.1 Threshold distances and impact areas obtained for the minke whale, resulting from operation of sparker in the study area

Impact on minke whales when the sparker is on operation			
Noise effect	Average distance all transects [km]	Max. distance [km]	Impact area [km²]
Behavioural response	0.9	1.1	2.7
TTS single strike	0.1	0.1	0.03
TTS cumulative	0.9	1.1	2.5
PTS single strike	0.1	0.1	0.03
PTS cumulative	0.2	0.2	0.12

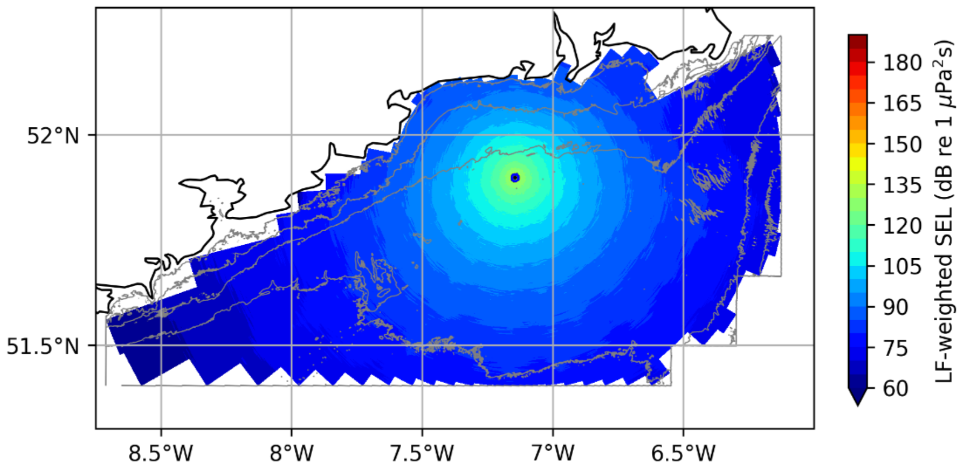

Figure 4.3 LF-weighted SEL related to operation of the sparker in the project area, showing ranges of PTS_{cum} and TTS_{cum} effects on the minke whale (blue line indicates TTS_{cum}, black: PTS cum; cumulation is performed for 1 h)

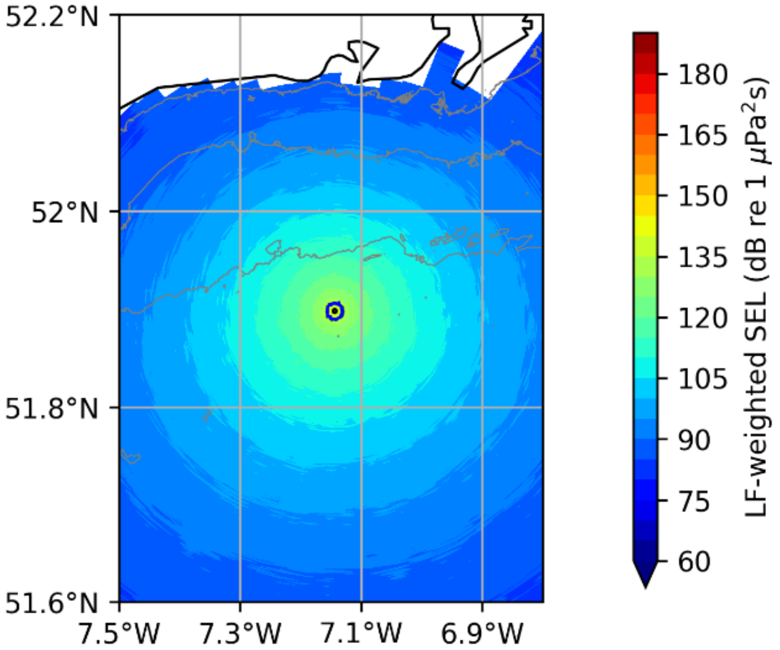

Figure 4.4 Enlarged view of Figure 4.3: LF-weighted SEL related to operation of the sparker in the project area, showing ranges of PTS_{cum} and TTS_{cum} effects on the minke whale (blue line indicates TTS_{cum}, black: PTS cum; cumulation is performed for 1 h)

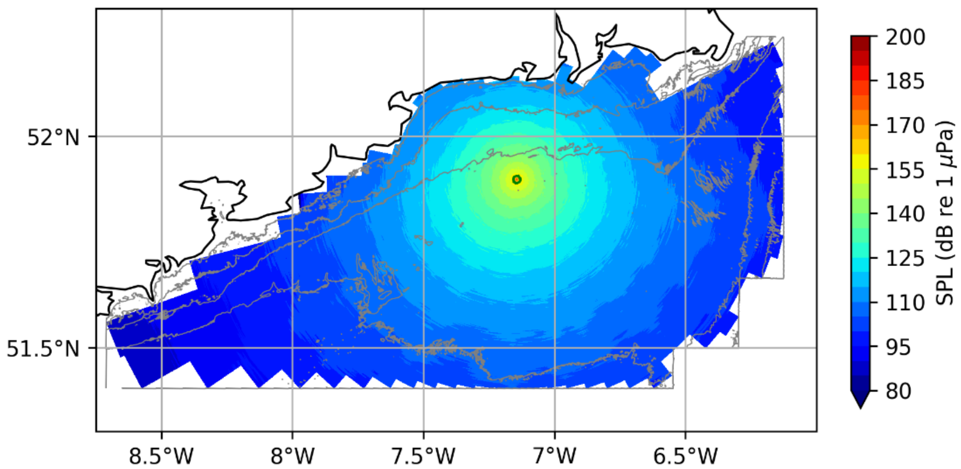

Figure 4.5 SPL related to operation of the sparker in the project area, showing range of the behavioural response effect on the minke whale (green line indicates behavioural response)

4.2.2 Mini airgun

In case of the mini airgun, the effects of TTS and PTS from a single strike, as well as from the cumulative PTS were found not to exceed 0.3 km. When cumulation of noise is considered, effect from TTS reach 2.9 km and the impact area of 19.7 km^2. For the behavioural reaction, impact is predicted to be below 2 km in range and the impact area up to 6.3 km^2 (Table 4.2, Figure 4.6 - Figure 4.7).

Table 4.2 Threshold distances and impact areas obtained for the minke whale, resulting from operation of mini airgun in the study area

Impact on minke whales when the mini airgun is on operation			
Noise effect	Average distance all transects [km]	Max. distance [km]	Impact area [km²]
Behavioural response	1.4	1.9	6.3

TTS single strike	0.1	0.1	0.03
TTS cumulative	2.5	2.9	19.7
PTS single strike	0.1	0.1	0.03
PTS cumulative	0.3	0.3	0.3

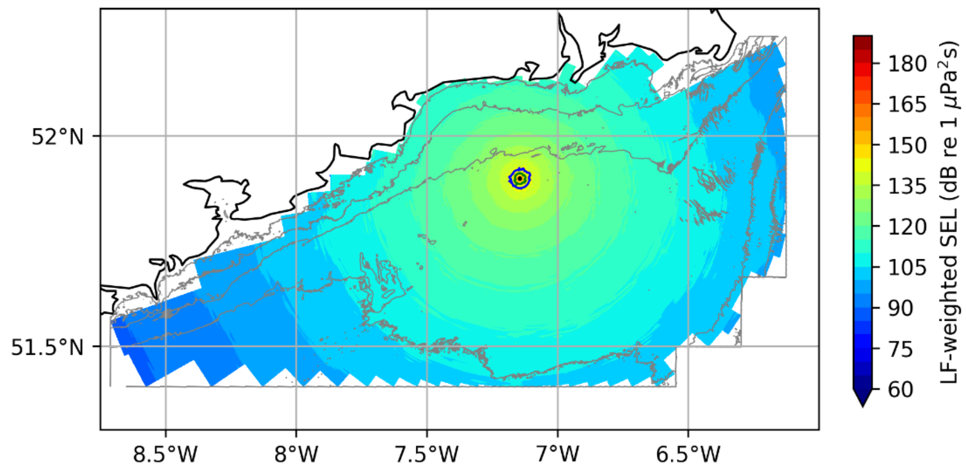

Figure 4.6 **LF-weighted SEL related to operation of the mini airgun in the project area, showing ranges of PTS_{cum} and TTS_{cum} effects on the minke whale** (blue line indicates TTS_{cum}, black: PTS_{cum}; cumulation is performed for 1 h)

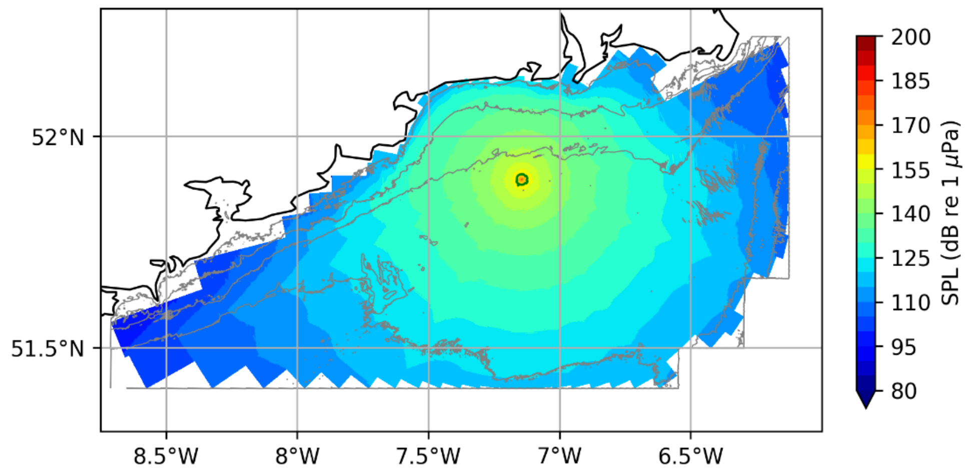

Figure 4.7 **SPL related to operation of the mini airgun in the project area, showing range of the behavioural response effect on the minke whale** (green line indicates behavioural response)

4.3 Impact ranges for herring

4.3.1 Sparker

Modelling conducted for the Atlantic herring indicated that both in case of TTS and PTS (single strike and cumulative), impact of the sparker is in the short range - up to 0.1 km. Values found for the behavioural change are also low, with maximum distance of 1 km and the impact area of 2.2 km^2 (Table 4.3, Figure 4.8).

Table 4.3 Threshold distances and impact areas obtained for the Atlantic herring, resulting from operation of the sparker in the study area.

Impact on herring when the sparker is on operation			
Noise effect	Average distance all transects [km]	Max. distance [km]	Impact area [km²]
Behavioural response	0.8	1.0	2.2
TTS single strike	0.1	0.1	0.03
TTS cumulative	0.1	0.1	0.03
PTS single strike	0.1	0.1	0.03
PTS cumulative	0.1	0.1	0.03

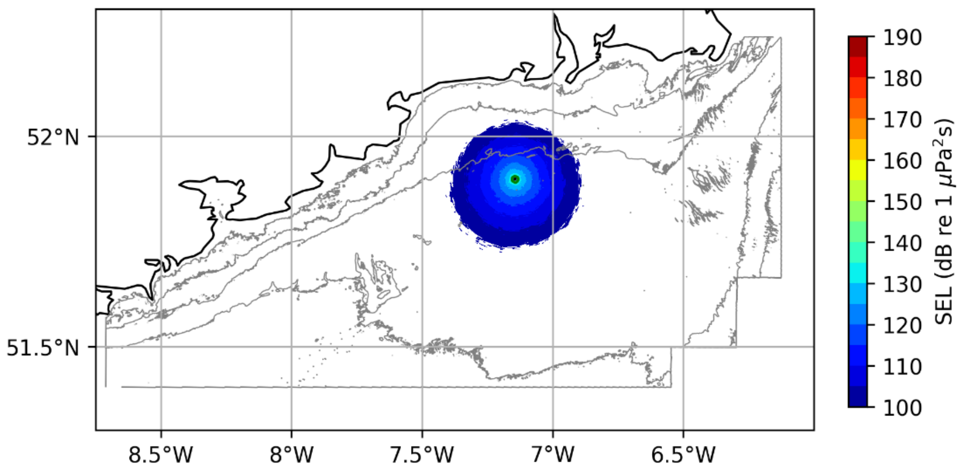

Figure 4.8 Unweighted SEL related to operation of the sparker in the project area, showing ranges of PTS_{cum}, TTS_{cum} and the behavioural response effects on the Atlantic herring (blue indicates TTS_{cum}, black: PTS cum and green: behavioural response; cumulation is performed for 1 h)

4.3.2 Mini airgun

In case of the mini airgun, the effects of TTS and PTS (single strike and cumulative) were also found to be in the low range, with the maximum distance not exceeding 0.7 km. For the behavioural reaction, the range of impact is predicted to be much higher – up to 13.6 km and the impact area of 460.5 km^2 (Table 4.4, Figure 4.9).

Table 4.4 Threshold distances and impact areas obtained for the Atlantic herring, resulting from operation of the mini airgun in the study area

Impact on herring when the mini airgun is on operation			
Noise effect	Average distance all transects [km]	Max. distance [km]	Impact area [km²]
Behavioural response	12.1	13.6	460.5
TTS single strike	0.1	0.1	0.03
TTS cumulative	0.6	0.7	1.1
PTS single strike	0.1	0.1	0.03
PTS cumulative	0.1	0.1	0.03

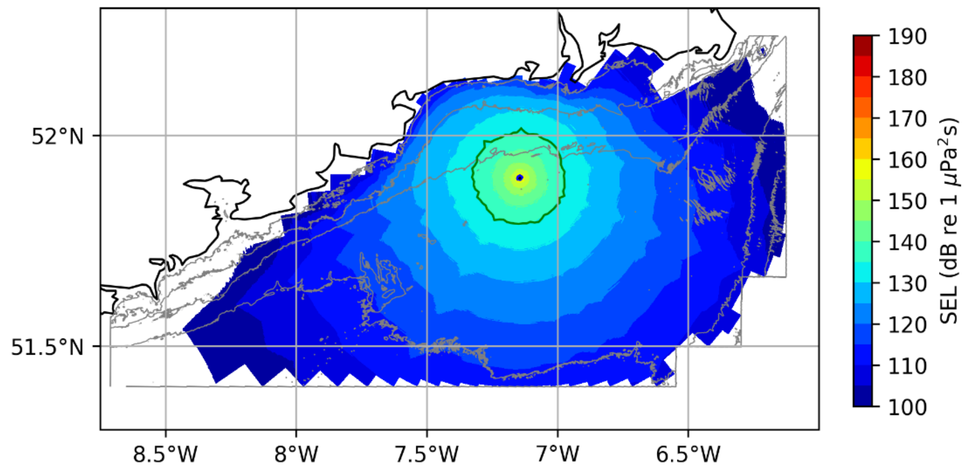

Figure 4.9 Unweighted SEL related to operation of the mini airgun in the project area, showing ranges of PTS_{cum}, TTS_{cum} and the behavioural response effects on the Atlantic herring (blue indicates TTS_{cum}, black: PTS cum and green: behavioural response; cumulation is performed for 1 h)

5 Conclusions

This study aimed to conduct a preliminary risk assessment of the impact of underwater noise generated during geophysical surveys planned in the Celtic Sea. For the assessment, two species of marine organisms were chosen – the common minke whale and the Atlantic herring, both of which are important components of the local marine ecosystem. Both these species rely especially on the low frequency signals in their acoustic communication and thus, might be affected by noise generated during geophysical surveys conducted with a use of the sparker and airguns. The extent of such impact was investigated via numerical modelling.

In case of the minke whale, modelling results have shown that both for the sparker and the mini airgun, effects are short-range when TTS and PTS from a single pulse are considered, as well as for the cumulative effect of PTS. The impact range increases when cumulation of noise is predicted for TTS, with higher values found for the airgun than for a sparker (impact area up to 19.7 km^2 and 2.5 km^2 respectively). The effect of behavioural reactions for the airgun was found to be around twice as large as for the sparker covering an area up to 6.3 km^2.

It should be noted that ranges predicted for the cumulative noise dose should be treated as approximate values. Under field conditions, both the sound source and the receivers are moving and thus, the actual effects on minke whales might be slightly lower than found in this study. Based on data on the minke whale occurrence in the Celtic Sea (National Biodiversity Data Centre, Ireland, 2023; Figure 2.2), the risk of impact is largest from May to August, when the density of animals is highest. The number of sightings is quite high also in the autumn months. Therefore, the surveys should be conducted with caution, provided that minke whales are not in the close vicinity of the sound source operation. The already planned use of the sparker rather than the airguns as the primary source is further supported by this study.

The Irish Guidelines to manage the risk of underwater noise to marine mammals (Department of Arts, Heritage and the Gaeltacht, 2014) specify mitigation measures for the use of geophysical acoustic surveys. The measures suggested in the document include restrictions that no animals are within the range of 1 km from the survey activities. This corresponds to the possible impact ranges modelled for the sparker (the maximum distance was 1.1 km, even under assumptions of noise cumulation for one hour, as well as the static sound source and receiver). Thus, sparker noise impacts on baleen whales can be managed well using the Irish guidelines. A different situation might apply to the airgun, for which the impact distances were found to be higher compared to the sparker. Special attention should be paid to the possible effect of the cumulative TTS, which was predicted to reach the distance of almost three kilometres. If airguns need to be used, it is recommended to specify the survey schedule in detail for a tailor-made risk assessment including the application of the most effective mitigation procedure. This could mean, for example to divide the survey in intervals of shorter than one-hour intervals. Nonetheless, the choice of sparker for the planned survey is safer and recommended.

In case of the Atlantic herring, effects of TTS and PTS from a single pulse, as well as of the cumulative PTS, were found to be of equally short range for the airgun and the sparker. When multiple pulses were considered, TTS ranges were higher for the airgun, but also within relatively small distance from the sound source and a resulting impact area up to 1.1 km^2. In contrast, the effect in form of behavioural reaction predicted for the use of airgun was much higher, reaching 13.6 km and an impact area of 460.5 km^2. In case of the sparker, behavioural changes are predicted within area up to 2.2 km^2.

Similar to the results obtained for the minke whales, it could be expected that under field conditions, impact distances for multiple pulses for the Atlantic herring might be smaller than found in this study. We also have to mention that the behavioural thresholds used in this study are based on results of just one investigation and are thus prone to a high level of uncertainty. However, it should be remembered that the geophysical surveys are planned in the area used by herring for spawning, indicating biological importance of the study site to the species. Behavioural reactions at relatively large distances could be an issue of concern especially during the winter season, when spawning of the Celtic Sea stock predominately takes place (Volkenandt *et al.*, 2014). As fish reactions to noise can vary to a great extent, depending on the individual fitness and the environmental condition (e.g. Kastelein et al., 2008), at this stage of the assessment it is difficult to predict how the animals would react and how it could impact the status of the population. Therefore, it is recommended to use the sparker rather than the airgun whenever possible. Based on the modelling results, it can be assumed that in case of the sparker, a safe distance of 1 km to the spawning area and migration route can be applied. For the airgun, the corresponding distance is approximately 13 km in case of a one-hour survey. As with marine mammals, it is recommended to perform a more detailed risk assessment based on the exact details. It is pointed out though that the best way to keep impacts at safe levels is the use of the sparker instead of the airgun.

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