SUBSEA NOISE TECHNICAL REPORT

GREATER DUBLIN DRAINAGE PROJECT

10028814-RPS-MO-XX-RP-E-RP0085
GDD Subsea Noise
S3 P02
29.08.2025

Document status

Version	Description	Authored by	Reviewed by	Approved by	Review date
S3 P01	Draft for client review	RSP	SM/JM	JM	11/07/2025
S3 P02	Final	RSP	SM/JM	JM	29/08/2025

Contents

Tables

Figures

Appendices

1 INTRODUCTION

1.1 Overview

The Greater Dublin Drainage (GDD) project is the development of a new regional wastewater treatment facility and associated infrastructure to serve the population of Dublin and parts of Kildare and Meath.

The project involves a marine outfall pipe which is to be tunnelled under the north part of Baldoyle Bay, with a transition to buried/trenched pipe installation 5-6 km due east into the Irish Sea.

These activities require information about the ground and sediment conditions and therefore, a site investigation (SI) is proposed, using geophysical and bathymetric surveys and geotechnical survey investigations.

A geotechnical survey, using rotary and/or sonic drilling, is proposed for both the Baldoyle Bay and the Irish Sea portion of the marine outfall route, with a suitable vessel for the depth for each location (<25 m length for shallow locations and <85 m length for deeper locations if not feasible from smaller vessel).

The geophysical and bathymetric survey methods differ between the two portions of the marine outfall route:

Baldoyle Bay:
The bathymetric survey includes (where depth allows):

1. Multibeam Echosounder (MBES)
2. Side Scan Sonar (SSS)
3. Ultra Short Baseline positioning (USBL)

The geophysical survey includes (where depth allows):

4. Parametric Sub-bottom Profiler (P-SBP) or Chirper/Pinger Sub-bottom Profiler (C-SBP)
5. Ultra-High Resolution Seismic (Sparker or Boomer)
6. Small vessel, <25 m

Irish Sea:
The bathymetric survey includes:

1. Multibeam Echosounder (MBES)
2. Side Scan Sonar (SSS)
3. Ultra Short Baseline positioning (USBL)
4. Small vessel, <25 m

1.2 Purpose of the Report

This Subsea Noise Technical Report presents the results of a desktop study considering the potential for Momentary, Brief and Temporary effects[1] of underwater noise on the marine environment from the site investigation works, which include geophysical, bathymetric and geotechnical surveys to map the sediment. The site covers c. 750 ha with c. 715 ha being in the Irish Sea.

The activities necessary to complete the SI emit noise that has the potential to have adverse effects on marine life. At close ranges from a noise source with high noise levels, permanent hearing injury or brief hearing impairment may occur to marine species, while at a very close range, gross physical trauma is possible. At long ranges (several kilometres), the introduction of any additional noise could, for the duration of the activity, potentially cause behavioural changes. For example, changes to the ability of species to communicate and to determine the presence of predators, food, underwater features and obstructions.

This report provides an overview of the potential effects due to underwater noise from the Project on the surrounding marine environment based on the NMFS/NOAA 2024 and Popper et al. 2014 framework for assessing impact from noise on marine mammals and fishes and well as an assessment of likely ranges for behavioural effects.

Consequently, the primary purpose of the subsea noise assessment is to predict the likely range of onset of injury as given in the relevant guidance (Auditory Injury, AUD INJ) and ranges to potential behavioural effects due to anthropogenic noise as a result of the SI.

1.3 Statement of Authority

This report has been prepared by MMRPS on behalf of Uisce Éireann. The technical competence of the authors is outlined below:

[redacted]s a Senior Scientist with RPS. He holds a master's degree in biology, biosonar and marine mammal hearing from University of Southern Denmark.[redacted]has over 10 years' experience as a marine biologist and over 8 years' experience with underwater noise modelling and marine noise impact assessments.[redacted] has co-developed commercially available underwater noise modelling software, as well as developed multiple source models for e.g. impact piling, seismic airgun arrays and sonars. [redacted] is a member of the Institute of Acoustics and a chartered scientist with the Institution of Environmental Sciences.

[redacted]is a Senior Associate in Acoustics with RPS. He holds a BA BAI in Mechanical Engineering from Trinity College Dublin (2004) and a PhD in Acoustics and Vibration from Trinity College Dublin (2008). He is a Chartered Engineer with Engineers Ireland.[redacted]has 20 years' experience in environmental projects including planning applications and environmental impact assessments for a wide range of strategic infrastructure projects.

[redacted]is a Scientist in Acoustics with RPS. He holds a BA (Hons) in Music Technology from Maynooth University and a Postgraduate Diploma in Acoustics and Noise Control from the Institute of

[1] Effects are defined in accordance with the EPA Guidelines on the information to be contained in Environmental Impact Assessment Reports (2022), Table 3.4 Description of Effects, pp.50-52.

Acoustics. He has over two years' experience working in a wide range of environmental areas, including road, rail, offshore wind, industrial, flood relief, underwater noise, and bat acoustics analysis projects. He is an associate member of the Institute of Acoustics and the Institution of Environmental Sciences.

2 ASSESEMENT CRITERIA

2.1 General

To determine the potential spatial range of injury and disturbance, assessment criteria have been developed based on a review of available evidence including national and international guidance and scientific literature. The following sections summarise the relevant assessment criteria and describe the evidence base used to derive them.

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Assessment criteria generally separate sound into two distinct types, as follows:

- **Impulsive sounds** which are typically transient, momentary (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI, 2005; ANSI, 1986; NIOSH, 1998). This category includes sound sources such as seismic surveys, impact piling and underwater explosions. Additionally included here are sounds under 1 second in duration with a weighted kurtosis over 40 (see note below*).
- **Non-impulsive** (and continuous) sounds which can be broadband, narrowband or tonal, momentary, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI, 1995; NIOSH, 1998).This category includes sound sources such as continuous vibro-piling, running machinery, some sonar equipment and vessels. Additionally included here are sounds over 1 second in duration with a weighted kurtosis under 40 (see note below*).
- **Impulse-like** There is scope for some sounds to be classified as both impulsive and non-impulsive following the criteria above. Examples are pulses from sonar-like sources that can contain very rapid rise times (<0.5 ms), sweep a large frequency range and have high kurtosis. However, given that the scientific work carried out to identify impulsive thresholds were done with “pure” impulses (from a near instantaneous event), sonar-like sounds are sometimes not included in this, impulsive, category. This argument ignores that sounds used for establishing the non-impulsive thresholds (often narrowband slowly rising[2] pulses), are markedly less impulsive (lower kurtosis, narrower bandwidth) than what is sometimes seen in pulses from sonar-like sources and are thus also not representative for all sonar-like pulses.

* Note that the European Guidance: “Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications” (MSFD Technical Subgroup on Underwater Noise, 2014) includes sonar as impulsive sources (see Section 2.2 in the reference). However, the guidance suggests that *“all loud sounds of duration less than 10 seconds should be included”* as impulsive.

This contradicts research on impact from impulsive sounds suggesting that a limit for “impulsiveness” can be set at a kurtosis[3] of 40 (Martin, et al., 2020). See examples in Appendix A, Impulsiveness.

This latter criterion (kurtosis >40) has been used for classification of impulsive versus non-impulsive for sonars and similar sources. The justification for departing from the MSFD criterion is that the NMFS 2024

[2] Slowly in this context is >10 ms – slow relative to the integration time of the auditory system of marine mammals.

[3] Statistical measure of the asymmetry of a probability distribution.

and the Popper et al. 2014 frameworks thresholds are based on the narrower definition of impulsive as given in "Impulsive sounds" above.

Given impulsive sound's tendency to become less impulsive with increased range, a minimal range can be established where the noise is no longer impulsive (kurtosis <40) (Appendix A, Impulsiveness). This range is established using raytracing with sources placed at multiple depths to account for variation in final source setup.

The acoustic assessment criteria for marine mammals and fish in this report has followed the latest international guidance (based on the best available scientific information), that are widely accepted for assessments in the UK, Europe and worldwide (Southall, et al., 2019; Popper, et al., 2014; NMFS, 2024).

2.2 Impact Assessment Criteria

2.2.1 Effects on Marine Animals

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Richardson *et al.* (1995) defined four zones of noise influence which vary with distance from the source and level, to which an additional zone has been added "zone of temporary hearing loss". These are:

- **The zone of audibility**: This is defined as the area within which the animal can detect the sound. Audibility itself does not implicitly mean that the sound will affect the animal.
- **The zone of masking**: This is defined as the area within which sound can interfere with the detection of other sounds, such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how animals detect sound in relation to masking levels (for example, humans can hear tones well below the numeric value of the overall sound level). Continuous sounds will generally have a greater masking potential than intermittent sound due to the latter providing some relative quiet between sounds. Masking only occurs if there is a near-overlap in sound and signal, such that a loud sound at e.g., 1000 Hz will not be able to mask a signal at 10,000 Hz[4].
- **The zone of responsiveness**: This is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction. For most species, there is very little data on response, but for species like harbour porpoise there exists several studies showing a relationship between received level and probability of response (Graham IM, 2019; Sarnoci´nska J, 2020; BOOTH, 2017; Benhemma-Le Gall A, 2021). This zone is quantified here with the use of behavioural thresholds (Table 2-2, section 2.2.2.1 & Table 2-3, section 2.2.3).
- **The zone of temporary hearing loss**: The area where the sound level is sufficient to cause the auditory system to lose sensitivity temporarily, causing loss of "acoustic habitat" (the volume of water that can be sensed acoustically by the animal). This hearing loss is typically classified as Temporary Threshold Shift ("TTS", see section 2.2.1 & 2.2.3).

[4] The exact limit of how near a noise can get to the signal in frequency before causing masking will depend on the receivers' auditory frequency resolution ability, but for most practical applications noise and signal frequencies will need to be within 1/3rd octave to start to have a masking effect.

- **The zone of injury / permanent hearing loss**: This is the area where the sound level is sufficient to cause permanent hearing loss in an animal. This hearing loss is typically classified as Auditory Injury ("AUD INJ", see section 2.2.1 & 2.2.3). At even closer ranges, and for very high intensity sound sources (e.g., underwater explosions), physical trauma or acute mortal injuries are possible.

For this study, it is the zones of injury (here "AUD INJ") that are of primary interest, along with estimates of behavioural impact ranges. To determine the potential spatial range of injury and behavioural change, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

Irish Guidance Interpretation

We note that the NPWS/DAHG "Guidance to Manage the Risk to Marine Mammals from Man-made Sound Sources in Irish Waters" 2014 (Department of Arts, Heritage and the Gaeltacht, 2014) contains the following statement:

"It is therefore considered that anthropogenic sound sources with the potential to induce TTS in a receiving marine mammal contain the potential for both (a) disturbance, and (b) injury to the animal."

This states that TTS constitutes an injury and should thus be the main assessment criteria[5]. However, the guidance goes on to specify the use of thresholds from a 2007 publication (Brandon L. Southall, 2007), which has since been superseded (Southall, et al., 2019; NMFS, 2024) and no longer represents best available science, nor reflects best practice internationally. Thus, the following excerpt from the guidance is relevant:

"The document will be subject to periodic review to allow its efficacy to be reassessed, to consider new scientific findings and incorporate further developments in best practice."

As there has been no such update to date and the guidance clearly states its intention to consider new scientific findings, we have applied the latest guidance (NMFS, 2024), reflecting the current best available method for assessing impact from noise on marine mammals. This means that it is "AUD INJ" (previously "PTS") that is the criteria for injury, not "TTS".

2.2.2 Thresholds for Marine Mammals

The zone of injury in this study is classified as the distance over which a fleeing marine mammal can suffer AUD INJ leading to non-reversible auditory injury. Injury thresholds are based on a dual criteria approach using both un-weighted peak level (L_{pk} – maximal instantaneous SPL) and marine mammal hearing weighted sound exposure level (SEL). The hearing weighting functions are designed to represent the sensitivity for each group within which acoustic exposures can have auditory effects. The categories include:

- **Low Frequency (LF) cetaceans**: Marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*).

[5] Injury being the qualifying limit in the Irish Wildlife Act 1976, section 23, 5c : https://www.irishstatutebook.ie/eli/1976/act/39/enacted/en/print#sec23

- **High Frequency (HF) cetaceans**: Marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales (e.g., bottlenose dolphin *Tursiops truncatus* and white-beaked dolphin *Lagenorhynchus albirostris*).
- **Very High Frequency (VHF) cetaceans**: Marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 kHz) (e.g., harbour porpoise *Phocoena phocoena*).
- **Phocid Carnivores in Water (PCW)**: True seals, earless seals (e.g., harbour seal *Phoca vitulina* and grey seal *Halichoreus grypus*); hearing in air is considered separately in the group PCA.
- **Other Marine Carnivores in Water (OCW)**: Including otariid pinnipeds (e.g., sea lions and fur seals), sea otters and polar bears; in-air hearing is considered separately in the group Other Marine Carnivores in Air (OCA).
- **Sirenians (SI)**: Manatees and dugongs.

These weightings are used in this study and are shown in Figure 2-1. It should be noted that not all of the above hearing groups of marine mammals will be present in the Project area, but all hearing groups are presented in this report for completeness.

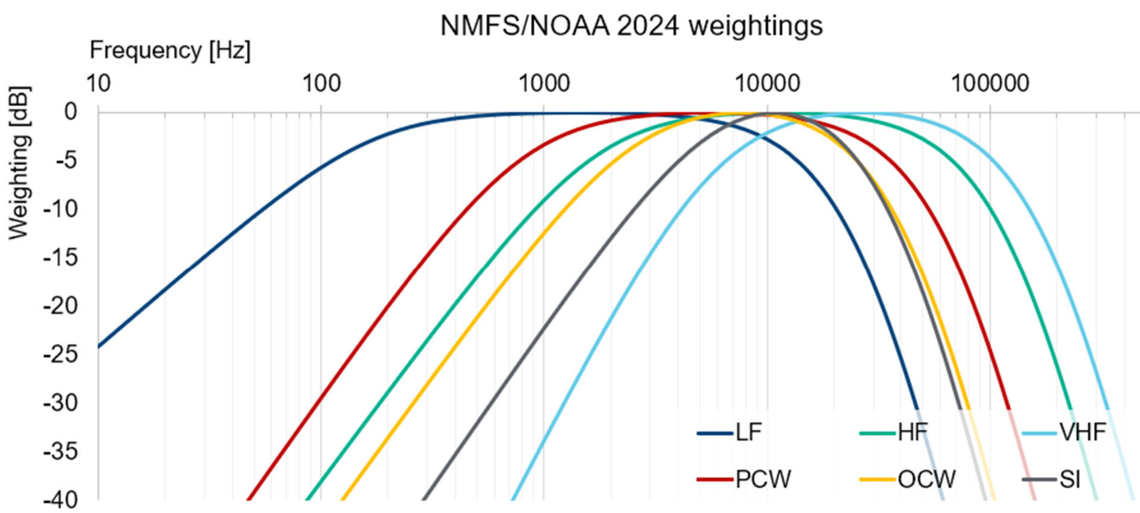


Figure 2-1 Auditory weighting functions for seals, whales and sirenians (NMFS, 2024).

The criteria for impulsive and non-impulsive sound are relevant for this study, given the nature of the sound sources used during the Project. The relevant AUD INJ and TTS criteria proposed by NOAA 2024 are summarised in Table 2-1.

Table 2-1 AUD INJ and TTS thresholds (NMFS, 2024)

Hearing Group	Parameter	Impulsive [dB]		Non-impulsive [dB]	
		AUD INJ	TTS	AUD INJ	TTS
Low frequency (LF) cetaceans	L_{pk}, (unweighted)	222	216	-	-
	SEL, (weighted)	183	168	197	177
High frequency (HF) cetaceans	L_{pk}, (unweighted)	230	224	-	-
	SEL, (weighted)	193	178	201	181
Very high frequency (VHF) cetaceans	L_{pk}, (unweighted)	202	196	-	-
	SEL, (weighted)	159	144	181	161
Phocid carnivores in water (PCW)	L_{pk}, (unweighted)	223	217	-	-
	SEL, (weighted)	183	168	195	175
Other marine carnivores in water (OCW)	L_{pk}, (unweighted)	230	224	-	-
	SEL, (weighted)	185	170	199	179
Sirenians (SI)	L_{pk}, (unweighted)	225	219	-	-
	SEL, (weighted)	186	171	186	180

2.2.2.1 Disturbance to Marine Mammals

The noise thresholds for disturbance of marine mammals are not as mature as the AUD INJ and TTS thresholds and several different approaches exist. A conservative but realistic approach based on a review of Danish and UK guidance documents, as well as scientific reviews has been applied.

The general approach reflects the approach recommended by the Danish guidance (Danish Centre for Environment and Energy, 2021), by a review submitted to the JNCC (Joint Nature Conservation Committee) of the UK (Nedwell, et al., 2007) and by a review for Natural Resources Wales (Sinclair, et al., 2023). These all recommend or acknowledge the use of a weighted received level along with a hearing group specific threshold.

Using 21 suitable studies from these reports, we have arrived at hearing group specific thresholds (Table 2-2) to determine behavioural disturbance levels for non-impulsive noise (here understood to be noise with a kurtosis <40). These thresholds are compared to the range where the hearing group weighted received level exceeds the relevant threshold.

Table 2-2 Disturbance criteria for marine mammals used in this assessment, based on Danish, UK and USA guidance.

Effect	Non-Impulsive Threshold [SPL]	Impulsive Threshold
Low frequency (LF) cetaceans	118	160 dB SEL $_{single\ impulse}$ or 1-second SEL (NOAA level B-harassment)
High frequency (HF) cetaceans	83	
Very high frequency (VHF) cetaceans	74	
Phocid carnivores in water (PCW)	107	

Other marine carnivores in water (OCW)	114

Given the considerable variation in the data (up to 40 dB where both mild disturbance and severe disturbance was included), we have opted to select a conservative value of either the 10th percentile value or the minimal value, whichever is greater[6] (Figure 2-2).

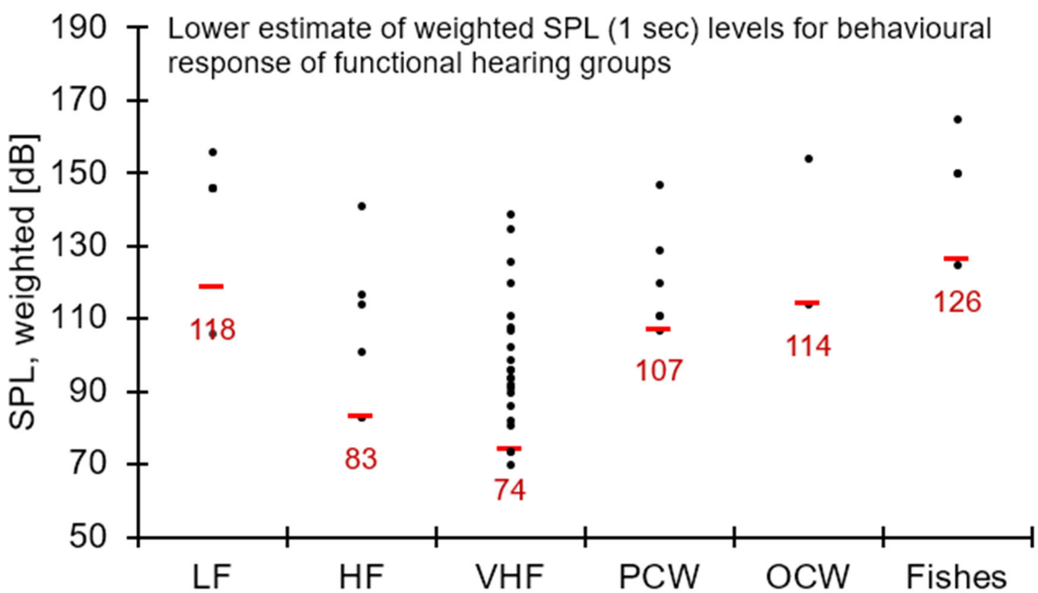


Figure 2-2 Data and behavioural disturbance thresholds.
Red lines/values are 10th percentile values or the minimal value, whichever is greater.

2.2.3 Injury and Disturbance to Fishes

The injury criteria used in this noise assessment are given in Table 2-3 and Table 2-4 for impulsive noises (L_{pk}) and continuous noise (SEL) respectively. L_{pk} and SEL criteria presented in the tables are unweighted.

It is important to clarify that this lack of weighting for fishes reflects a lack of scientific consensus about the best method for applying frequency dependence to received levels for fishes, rather than a statement that fishes can hear all frequencies equally. Thus, fishes generally cannot hear above 10 kHz, and if they can, the sensitivity is generally very poor (Figure 2-3, (Nedwell, et al., 2004)).

[6] Where there is large data variation, the 10th percentile of the equivalent normal distribution can get smaller than the minimal value, in these cases we have used the minimal value observed to cause disturbance.

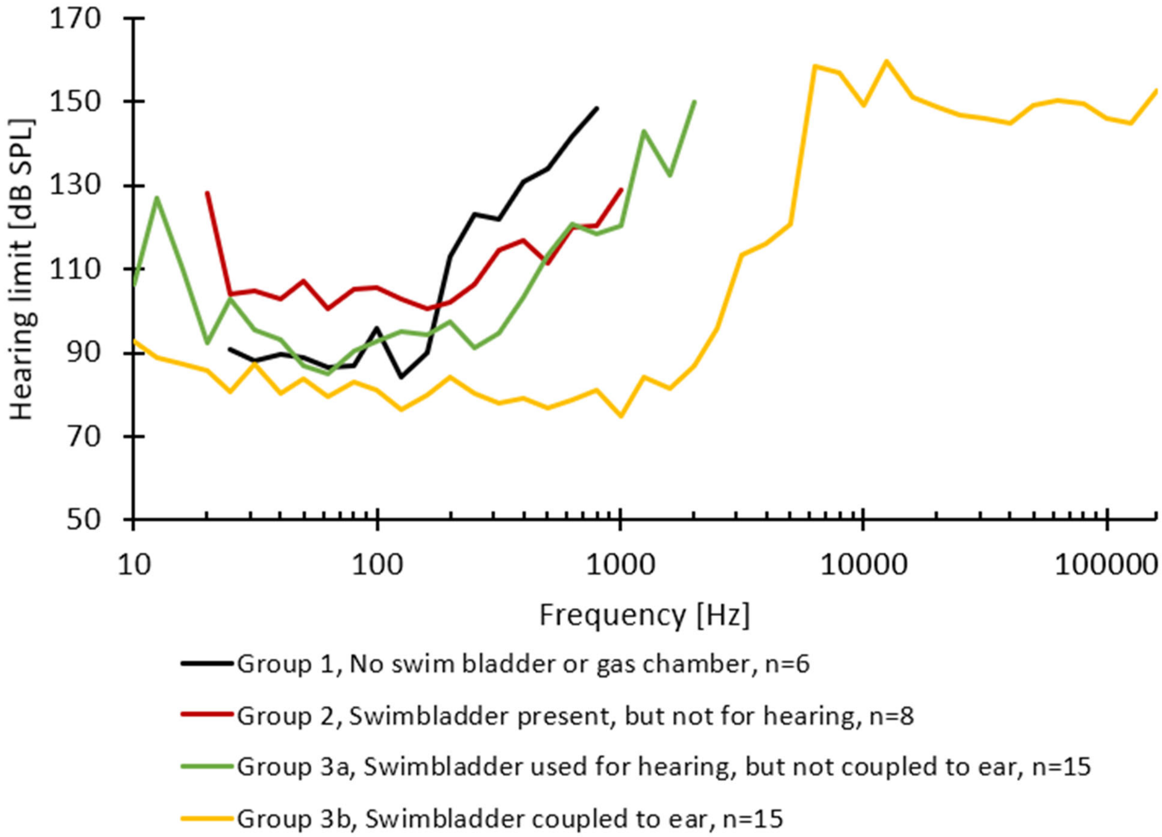


Figure 2-3 Generalised hearing thresholds for fishes grouped by the presence of a swim bladder and its role in hearing.

Physiological effects relating to injury criteria are described below (Popper, et al., 2014):

- **Mortality and potential mortal injury**: Either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g., a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect upon animal populations, especially if it affects individuals close to maturity.

- **Recoverable injury (“AUD INJ” in tables and figures)**: Tissue damage and other physical damage or physiological effects, that are recoverable, but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.

  The AUD INJ term is used here to describe this more serious impact, even though it is not strictly permanent for fish. This is to better reflect the fact that this level of impact is perceived as serious and detrimental to the fish.

- **Temporary Threshold Shift (TTS)**: Short term changes (minutes to few hours) in hearing sensitivity may, or may not, reduce fitness and survival. Impairment of hearing may affect the ability of animals to capture prey and avoid predators, and also cause deterioration in communication between individuals, affecting growth, survival, and reproductive success. After termination of a sound that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of sound exposure.

Popper et al. 2014 does not set out specific TTS limits for L_{pk} and for disturbance limits for impulsive noise for fishes. Therefore publications "Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual" (WSDOT, 2020) and "Canadian Department of Fisheries and Ocean Effects of Seismic energy on Fish: A Literature review" (Worcester, 2006) on effects of seismic noise on fish are used to determine limits for these:

- The criteria presented in the Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual (WSDOT, 2020). The manual suggests an un-weighted sound pressure level of 150 dB SPL (assumed to be duration of 95 % of energy) as the criterion for onset of behavioural effects, based on work by (Hastings, 2002). Sound pressure levels in excess of 150 dB SPL are expected to cause temporary behavioural changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. The document notes that levels exceeding this threshold are not expected to cause direct permanent injury but may indirectly affect the individual fish (such as by impairing predator detection). It is important to note that this threshold is for onset of potential effects, and not necessarily an 'adverse effect' threshold. The threshold is implemented here as either single impulse SEL or 1 second SEL, whichever is greater.
- The report from the Canadian Department of Fisheries and Ocean "Effects of Seismic energy on Fish: A Literature review on fish" (Worcester, 2006) found large differences in response between experiments. Onset of behavioural response varied from 107-246 dB L_{pk}, the 10th percentile level for behavioural response was 160 dB L_{pk} (rounded to nearest 5 dB to reflect large variation in data).

Thus, the behavioural threshold for fishes for impulsive sound is 160 dB L_{pk}, and for non-impulsive sound 150 dB SPL.

Note that while there are multiple groups of fish presented, we have used the thresholds of the more sensitive group for all fish thus covering all fishes (203/186 AUD INJ/TTS for impulsive sound & 222/204 AUD INJ/TTS for non-impulsive sound). These lower thresholds also cover "Eggs and Larvae".

Table 2-3 Criteria for onset of injury to fish and sea turtles due to impulsive noise. For this assessment the lowest threshold for any group is used for all groups (shown in bold).

Type of Animal	Unit	Mortality and Potential Mortal Injury [dB]	Recoverable Injury (AUD INJ) [dB]	TTS [dB]	Behavioural [dB]
Fish: no swim bladder (particle motion detection) Example: Sharks.	SEL	219[1]	216[1]	186[1]	150[3]
	L_{pk}	213[1]	213[1]	193[2]	160[2]
Fish: where swim bladder is not involved in hearing (particle motion detection). Example: Salmonoids.	SEL	210[1]	203[1]	186[1]	150[3]
	L_{pk}	207[1]	207[1]	193[2]	160[2]
Fish: where swim bladder is involved in hearing (primarily pressure detection). Example: Gadoids (cod-like).	SEL	207[1]	**203[1]**	**186**	**150[3] [SPL]**
	L_{pk}	207[1]	**207[1]**	**193[2]**	**160[2]**
Sea turtles	SEL	210[1]	(*Near*) High* (*Mid*) Low (*Far*) Low	-	-
	L_{pk}	207[1]		-	-
Eggs and larvae	SEL	210[1]	(*Near*) Moderate (*Mid*) Low (*Far*) Low	-	-
	L_{pk}	207[1]		-	-

[1] (Popper et al. 2014) table 7.4, [2] (Worcester, 2006), [3] (WSDOT, 2020)

* Indicate (range) and risk of effect, e.g., "(Near) High", meaning high risk of that effect when near the source.

Where Popper et al. 2014 present limits as ">" 207 or ">>" 186, we have ignored the "greater than" and used the threshold level as given.

Relevant thresholds for non-impulsive noise for fishes relating to AUD INJ, TTS, and behaviour are given in Table 2-4.

Table 2-4 Criteria for fish (incl. sharks) due to non-impulsive noise from Popper et al. 2014, Table 7.7.

Type of Animal	Unit	Mortality and Potential Mortal Injury [dB]	Recoverable Injury (AUD INJ) [dB]	TTS [dB]	Behavioural [dB]
All fishes	SEL	(Near) Low (Mid) Low (Far) Low	222†	204†	126 [SPL]*

*Based on review in Section 2.2.2.1, also Figure 2-2.

†Based on 48 hours of 170 dB SPL and 12 hours of 158 dB SPL

3 SITE, SURVEY METHOD AND ENVIRONMENT

3.1 Site Location

Two sites are included in this study, Baldoyle Bay and a part of the Irish Sea stretching from Portmarnock Beach Lifeguard Station to c. 6 km offshore north of Ireland's Eye (Figure 3-1).

The sediment in the Baldoyle Bay is fine and the area is intertidal, with much of it only being submerged near high tide. In the Irish sea the sediment is coarser (sand to gravel), and water depths ranges from 0-25 m within the project area.

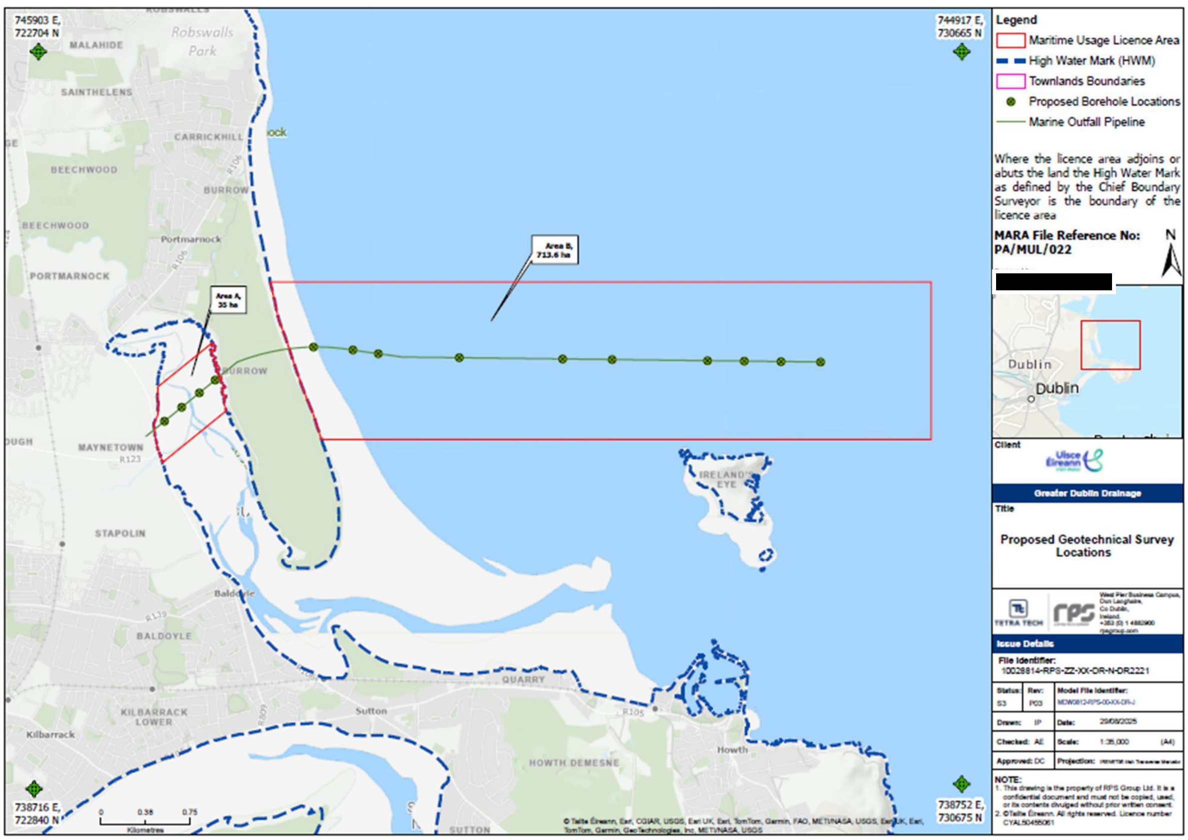


Figure 3-1 Proposed MUL outline and proposed Geotechnical sampling locations.

3.2 Surveys

Three principal activities are covered by this assessment:

- A bathymetric survey for depths (MBES) and sediment structure (SSS) as derived by acoustic means. Irish Sea only.

- A geophysical for depths (MBES), sediment structure (SSS) and in-sediment properties (P-SBP, C-SPB and UHRS). Baldoyle Bay only.
- A geotechnical survey using invasive methods to characterise the sediment. Both Baldoyle Bay and Irish sea.

3.2.1 Bathymetric Survey – Irish Sea

A single vessel of <25 m length will be using a multibeam echosounder (MBES) and a side scan sonar (SSS) with an ultrashort baseline (USBL) positioning system deployed. The vessel is assumed to move at c. 4 knots while surveying.

3.2.2 Geophysical and Bathymetric Survey – Baldoyle Bay

A single vessel of <25 m length will be using a multibeam echosounder (MBES) a side scan sonar (SSS) with an ultrashort baseline (USBL) positioning system deployed.

Additionally, sub-bottom profiling equipment will be deployed where there is sufficient depth. This will be a combination of either a parametric sub-bottom profiler or a chirper/pinger sub-bottom profiler and a sparker or boomer type seismic source.

The vessel is assumed to move at c. 4 knots while surveying. A depth of 2.5 m has been assumed as worst case for high tide conditions. Higher depths are conservative. This depth is representative for the SI in the middle of the bay and where there is line-of-sight from source to receiver with a minimal water depth of 2.5 m.

Note that given the shallowness of the survey site, part of this survey will likely be carried out using equipment deployed by walkover surveys or from a suitable vehicle. Where there is no free water over the sediment, the results from this study do not apply.

3.2.3 Geotechnical Survey

For the geotechnical survey, two systems are modelled:

1. A single vessel of up to 25 m length using DP thrusters deploying rotary and sonic drilling equipment. This also covers the case of use of Jack-up Barge (JUB) and tug in place of a geotechnical vessel.
2. A single vessel of up to 85 m length using DP thrusters deploying rotary and sonic drilling equipment. This will only be used for depths >15 m in the Irish Sea.

3.3 Environment

3.3.1 Water Properties

Water properties were determined from historical data for the area. Where values differ between e.g. seasons and tidal states, the values resulting in the lowest transmission loss were chosen for a more conservative assessment (more noise at range). Thus, this also covers seasonal variation.

- Temperature: 10 °C – data from seatemperature.org for water temperatures near Dublin. Representative for winter conditions.

- Salinity: Set at 20 psu for Baldoyle Bay (No measurements available – lower salinity is more conservative) and 35 psu for the Irish Sea.
- Soundspeed profile: Assumed uniform given high mixing as a result of tidal flows. A uniform soundspeed profile is conservative compared to the likely downward refracting soundspeed profiles seen during summer months (higher temperature in the surface leads to higher soundspeeds).

3.3.2 Sediment Properties

Sediment properties are taken from the previous geotechnical survey campaign, report titled "Greater Dublin Drainage – Offshore Site Investigation of Outfall Pipeline, Report No 15-664". A sediment model (Ainslie, 2010) was used to derive the acoustic properties of the sediments from the grain size/sediment type. An "acoustically harder" sediment (higher density and soundspeed) will be conservative, in that it will improve sound propagation in the water column.

There was no direct sediment information from Baldoyle Bay. From site images, the sediment looks to be muddy or fine silt. We have assumed "Coarse silt" as a worst-case assumption (this is an acoustically "harder" sediment).

Table 3.1 Sediment properties

Location A-D	ISO (14688-1:2017)	Density [kg/m³]	Soundspeed [m/s]	Grain size [mm] (nominal)
A, Baldoyle Bay	Coarse silt	1646	1583	0.022
B, Irish Sea coastal/shallow, depth c. 5 m	Coarse Sand	2272	1873	0.71
C, Irish Sea mid, depth c. 15 m.	Fine Gravel	2780	2128	5.7
D, Irish sea deep, depth c. 25 m.	Fine Gravel	2780	2128	5.7

4 SOURCE NOISE LEVELS

Underwater noise sources are usually quantified in dB scale with values generally referenced to 1 µPa as if measured at a hypothetical distance of 1 m from the source (called the Source Level). In practice, it is not usually possible to measure at 1 m from a source, but the metric allows comparison and reporting of different source levels on a like-for-like basis.

For a large sound source, this imagined point at 1 m from this acoustic centre does not exist, the energy is distributed across the source and does not all emanate from this imagined acoustic centre point, rather it’s the position in space that would lead to the equivalent received level at range (usually from ranges greater than the larges dimension of the source). Therefore, the stated sound pressure level at 1 m does not exist for large sources. For such large source, in the acoustic near field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the back-calculated source level (Figure 4-1).

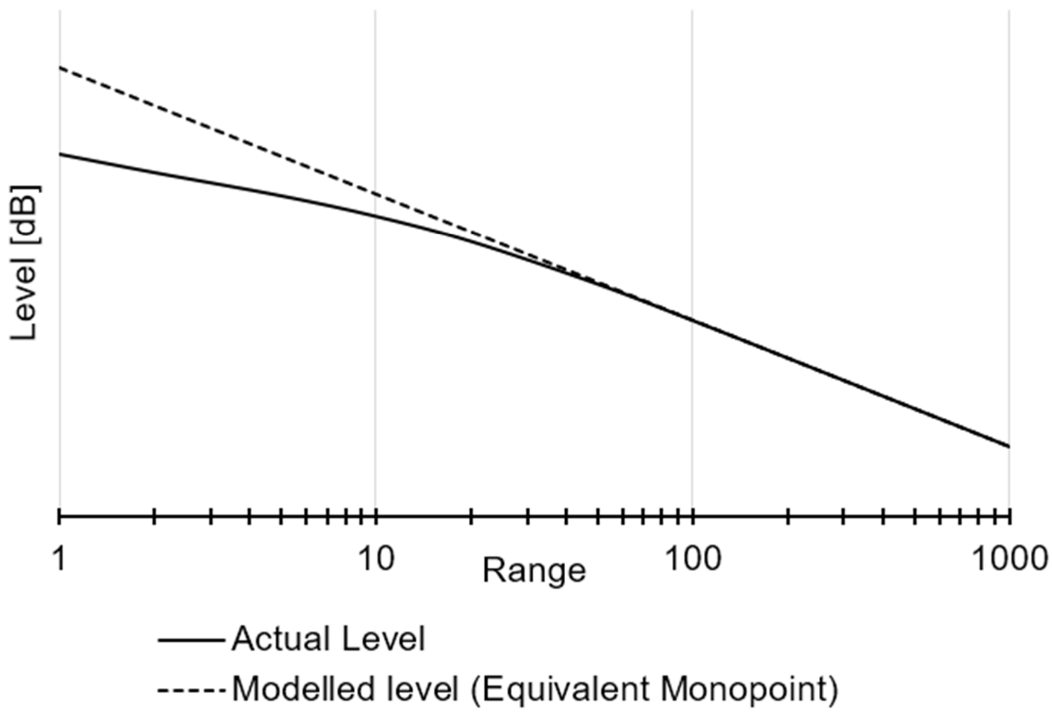


Figure 4-1 Schematic of the actual received level trend from a source of 50 m length versus the modelled level assuming an equivalent monopoint source.

4.1 Source Models

The noise sources and activities investigated during the subsea noise assessment study are summarised in Table 4.1.

Source levels for the active equipment were combined to produce a “combined” source that represents the total noise emissions from the activity.

Note that as source levels have all been converted to 1-second SPL equivalents, the levels vary depending on the location to reflect changes in depth and sediment properties (repetition rate of emitted pulses and sediment absorption affects the modelled source level).

Multibeam echosounders have been included in the assessment even though their main frequencies lie well above the hearing range of the VHF hearing group. This is because, given the way the signals are produced some spectral leakage (energy “leakage” into other frequencies due to the acoustic properties of the transducer) will occur, resulting in significant acoustic energy to frequencies audible to both dolphins and porpoises.

As sonars and echosounder have narrow beams and therefore “sweep” through the water body, they are harder to model for expected received level. For the assessment, the energy in the beam has been converted to an equivalent spherical source (of lower spherical SPL than the in-beam level) to ensure that a randomly positioned receiver would receive the same energy as one occasionally “hit” by a beam. Note that while extremely narrow beams (0.1-1 degree) are often stated for sonars and echosounders, this is the width of the beam where the received level drops by a set amount, usually 3 dB (if stated at all). There is a significant amount of acoustic energy outside the beam, which has been included in the assessment.

The parametric sub-bottom profilers have quite narrow beams directed vertically down, with levels attenuating rapidly as the angle away from vertical increases. For exposure modelling [dB SEL], the source level at an angle corresponding to the specular reflection of the sediment[7], has been used for the assessment. This means there will be a cone within which we will underpredict the impact for animals. As risk ranges tend to be larger than the radius of this cone, and animals will be able to hear the vessel approaching with time to evade this cone, this does not translate to an increased risk for the animals.

For the peak pressure level [dB L_{pk}] propagation modelling, the actual directivity of common SBPs, sparker and boomers have been used.

[7] There is still reflection at steeper angles, but also a large loss to the sediment, meaning rapid attenuation, with increasing number of surface-bottom reflections.

Table 4.1 Summary of Noise Sources and Activities Included in the Subsea Noise Assessment

Equipment	Source level [SPL]	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
Survey vessel Geophysical and Bathymetric survey Vessel length <25 m	165 dB SPL	10-16,000 Hz	(Wittekind, 2014; Simard, et al., 2016; Heitmeyer, 2001)	Non-impulsive
Survey vessel (or tug and JUB) Geotechnical survey Vessel length <25 m depths <15 m	165 dB SPL	10-16,000 Hz	(Wittekind, 2014; Simard, et al., 2016; Heitmeyer, 2001)	Non-impulsive
Survey vessel Geotechnical survey Vessel length <85 m Depths >15 m	196 dB SPL	10-40,000 Hz	(Wittekind, 2014; Simard, et al., 2016; Heitmeyer, 2001)	Non-impulsive
Multibeam echosounder	190 dB SPL (ping rate dependent, equivalent spherical level)	200,000 – 400,000 Hz	Source levels based on von Hann windowed FM or CW pulses at max SPL as given by manufacturer.	Non-impulsive after 10-25 m*
Side Scan Sonar	165 dB SPL (ping rate dependent, equivalent spherical level)	100,000 – 900,000 Hz	Source levels based on von Hann windowed FM or CW pulses at max SPL as given by manufacturer.	Non-impulsive after 10-25 m*
USBL	190 dB SPL (ping rate adjusted)	8,000 – 40,000 Hz	Generic USBL based on models from Edgetech, ORE offshore, Sonardyne & Ixblue	Non-impulsive after 10-25 m*
Parametric sub-bottom profiler Based on: “Innomar Medium”	206 dB SPL (ping rate and depth dependent, off-axis level)	Primary: 85,000 – 115,000 Hz Secondary: 2,000 – 22,000 Hz	Source levels based on von Hann windowed FM or CW pulses at max SPL as given by manufacturer.	Non-impulsive after 10 m*
Chirper/Pinger sub-bottom profiler	183 dB SPL (ping rate and depth dependent, off-axis level)	2,000 – 20,000 Hz	Source levels based on von Hann windowed FM or CW pulses at max SPL as given by manufacturer.	Non-impulsive after 10 m*
Sparker (UHRS)	184 dB SPL 220 dB L_{pk}	630 – 3600 Hz	Generic model based on GeoSource and Applied Acoustics	Non-impulsive after 10 m*

Equipment	Source level [SPL]	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
			models at 400 J, 1 pulse per second	
Boomer (UHRS)	177 dB SPL 219 dB L_{pk}	160 – 16,000 Hz	Generic model based on Applied Acoustics, Geoforce and GeoBoomer models at 400 J, 1 pulse per second	Non-impulsive after 10 m*
Sonic drilling	189 dB SPL	50 – 16,000 Hz	Based on recorded levels from sonic coring of up to 0.102 m diameter	Non-impulsive
Rotary coring (incl. CPT)	150 dB SPL	10 – 160,000 Hz	Based on recorded levels from drills of up to 0.102 m diameter	Non-impulsive

* Using criteria for impulsiveness as laid out in section 2.1.

4.2 Vessels

An ensemble model, consisting of a combination of numerical models (Wittekind, 2014; MacGillivray, et al., 2021) and empirical models (Heitmeyer, 2001; Simard, et al., 2016; Chion, et al., 2019; Liefvendahl, et al., 2015; Audoly, et al., 2015) was used to calculate representative source band levels of the vessels. Where we did not have exact representative vessels, the 90th percentile value of the ensemble model distribution[8] was used as a conservative estimate.

4.2.1 Small Vessel, <25 m – Irish Sea and Baldoyle Bay.

A vessel of up to 25 m length with a DP system enabled is assumed, travelling at a max speed of 4 knots during the survey. Band levels are presented in Figure 4-2, the broadband level is 165 dB SPL.

This vessel is modelled for all geophysical, bathymetric and geotechnical surveys.

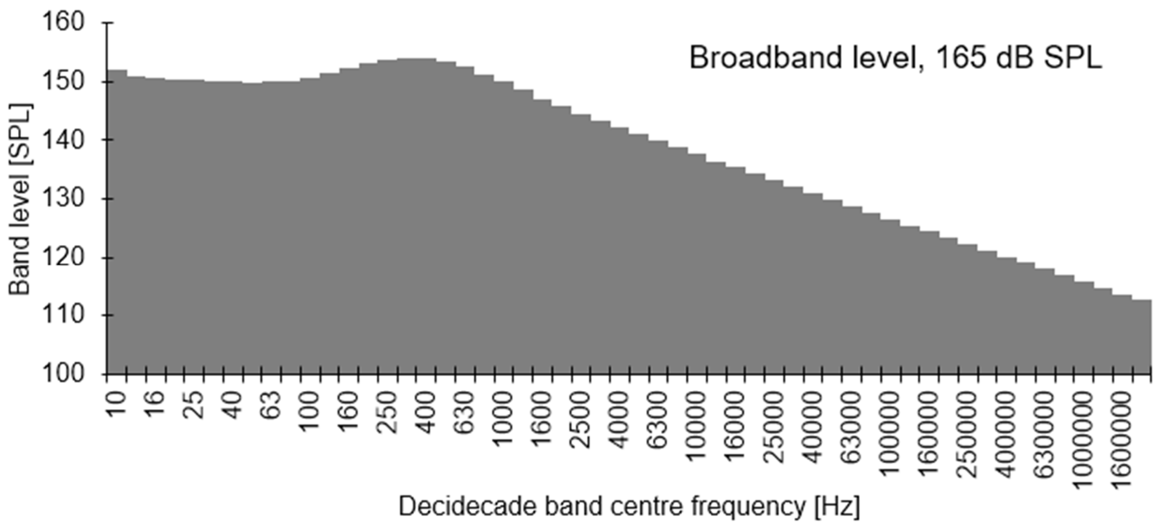


Figure 4-2 Source band levels for small vessel (<25 m).

4.2.2 Large Vessel, <85 m – Irish Sea Geotechnical for depths >15 m

A vessel of up to 80 m length assumed, travelling above the propeller cavitation speed (important for noise emissions). Band levels are presented in Figure 4-3, the broadband level is 196 dB SPL.

This vessel is modelled for geotechnical surveys in the Irish Sea where depths are 15 m or greater.

[8] The 90th percentile value of the normal distribution fitted to the model.

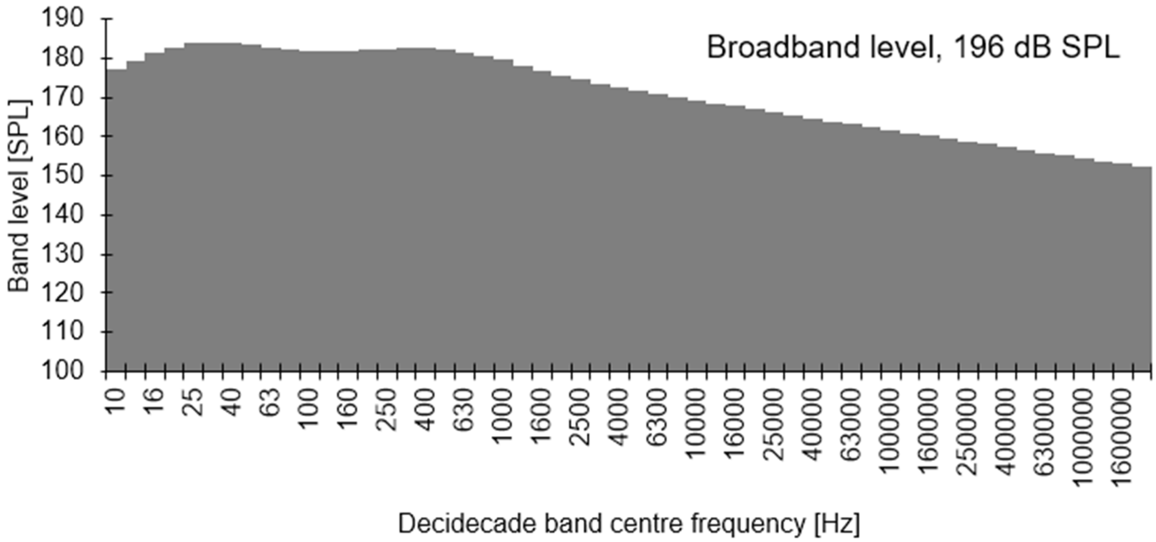


Figure 4-3 Source band levels for the large vessel (<85 m).

4.3 MBES

The MBES source is based off a generic model using data from 24 MBES systems. The system is specified to have nominal frequencies from 200 kHz to 400 kHz. The broadband level is 189 dB SPL, with band levels given in Figure 4-4

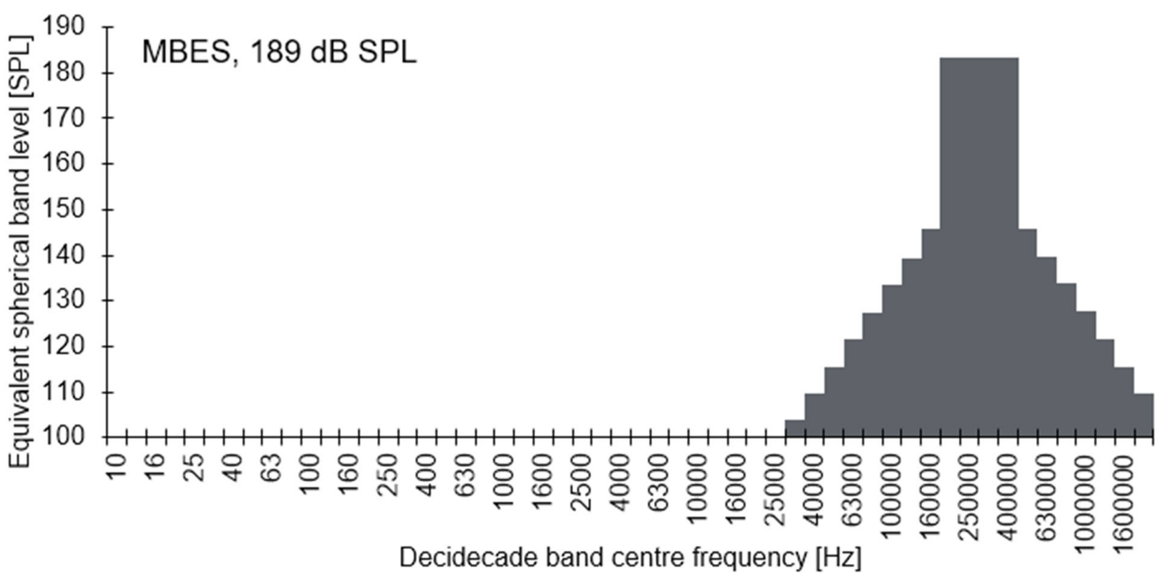


Figure 4-4 Source band levels for the MBES given as spherical equivalent levels.

4.4 SSS

The SSS source is based off a generic model using data from seven common SSS systems. The system is specified to have nominal frequencies from 100 kHz to 900 kHz. The broadband level is 165 dB SPL, with band levels given in Figure 4-4

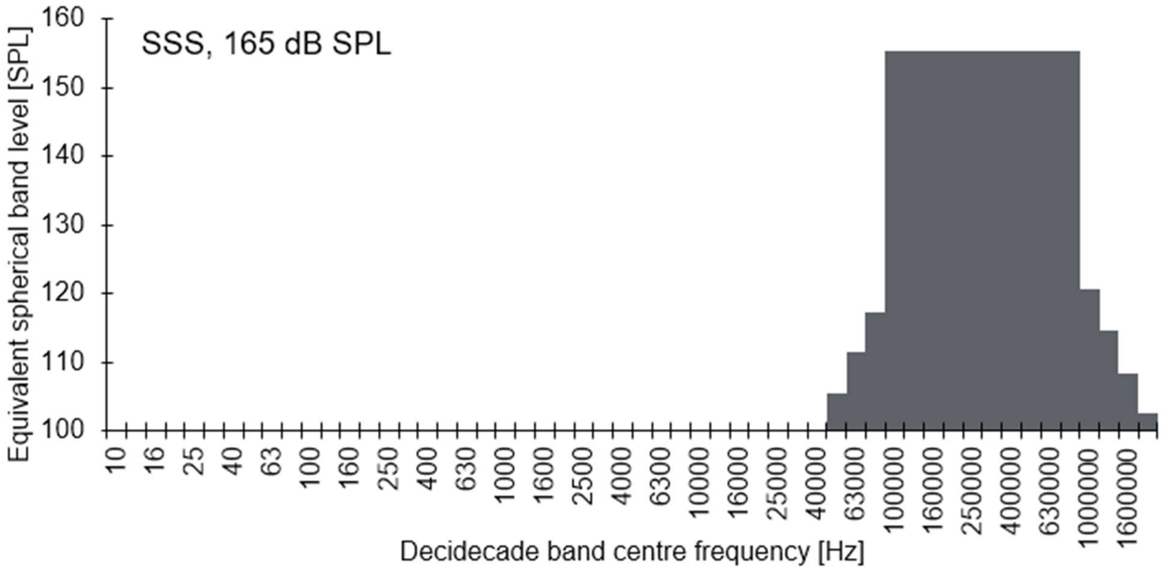


Figure 4-5 Source band levels for the SSS given as spherical equivalent levels.

4.5 USBL

The USBL is based on a generic model using data from systems made by Edgetech, ORE offshore, Sonardyne & Ixblue. The band levels are given in Figure 4-6 and the broadband level is 190 dB SPL.

The USBL is used along with deployed equipment when the exact position relative to the vessel is needed, such as during the deployment of towed SSS or C-SBP.

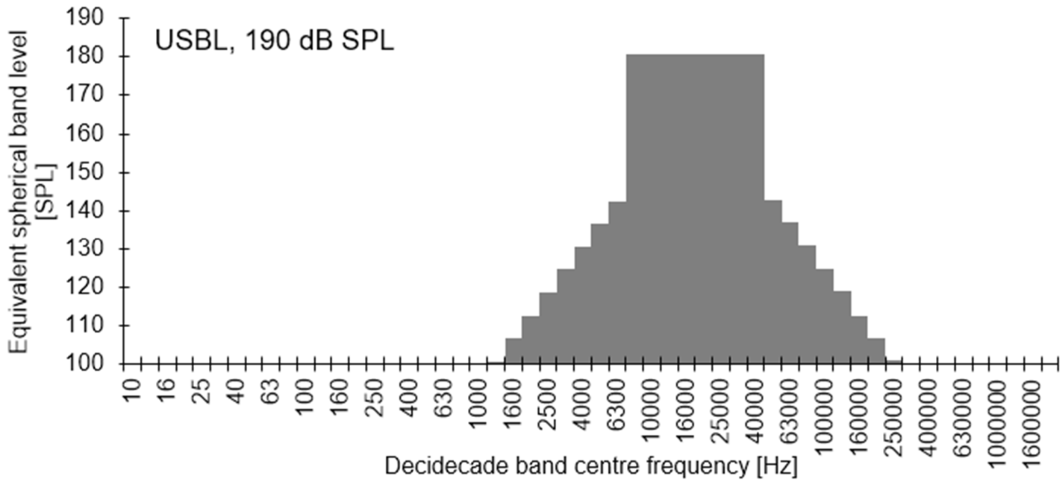


Figure 4-6 Source band levels for the USBL.

4.6 Sub-bottom Profiler, Parametric

The parametric type sub-bottom profiler uses two beams of higher frequencies (85-115 kHz) to generate a very narrow lower frequency beam (using constructive/destructive interference between the higher frequencies) to penetrate the sediment. The hull-mounted Innomar medium is representative for the survey. The broadband level is 206 dB SPL with the higher frequencies being at 206 dB SPL and the lower frequencies at 148 dB SPL (Figure 4-7).

The SBP does not use all these frequencies simultaneously but has been assessed against the potential spread of frequencies that might be emitted.

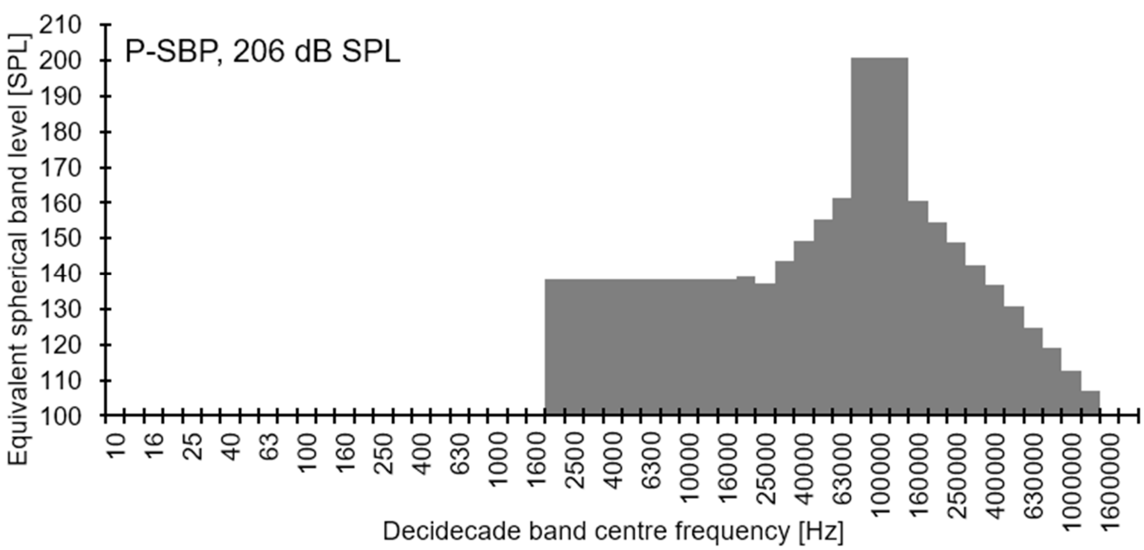


Figure 4-7 Source band levels for the parametric SBP.

4.7 Sub-bottom Profiler, Chirper/Pinger

The C-SBP will be either hull mounted or deployed as towfish. The main frequencies are 2,000 Hz to 20,000 Hz. The broadband level is 183 dB SPL (Figure 4-7).

The SBP does not use all these frequencies simultaneously but has been assessed against the potential spread of frequencies that might be emitted.

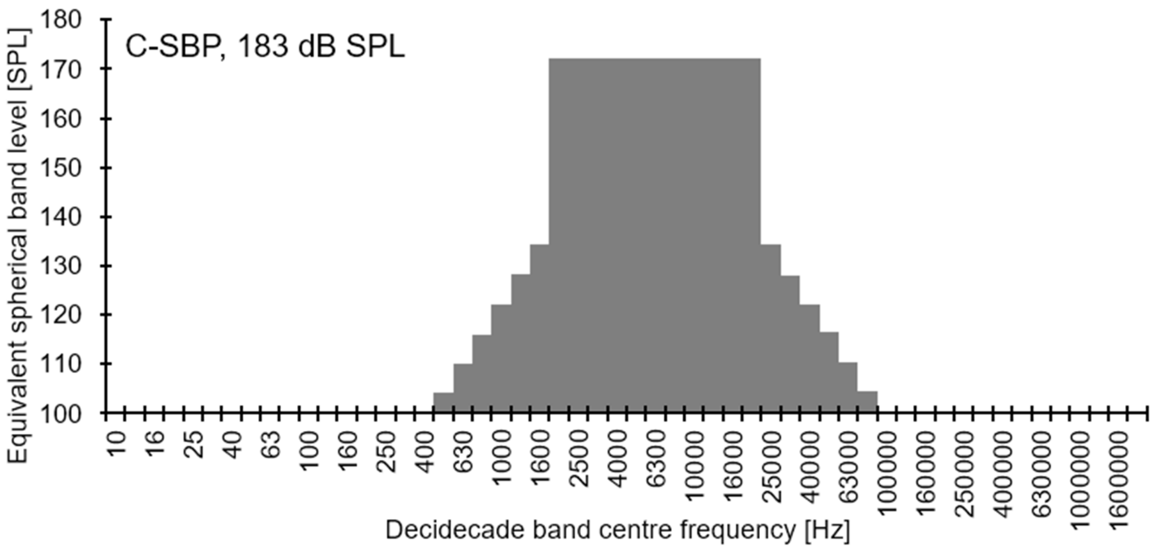


Figure 4-8 Source band levels for the chirper/pinger SBP.

4.8 UHRS, Sparker

The sparker source is based on a 400 J firing at 1 second intervals. The main frequencies are 630 Hz to 6,300 Hz. The broadband level is 184 dB SPL (Figure 4-7).

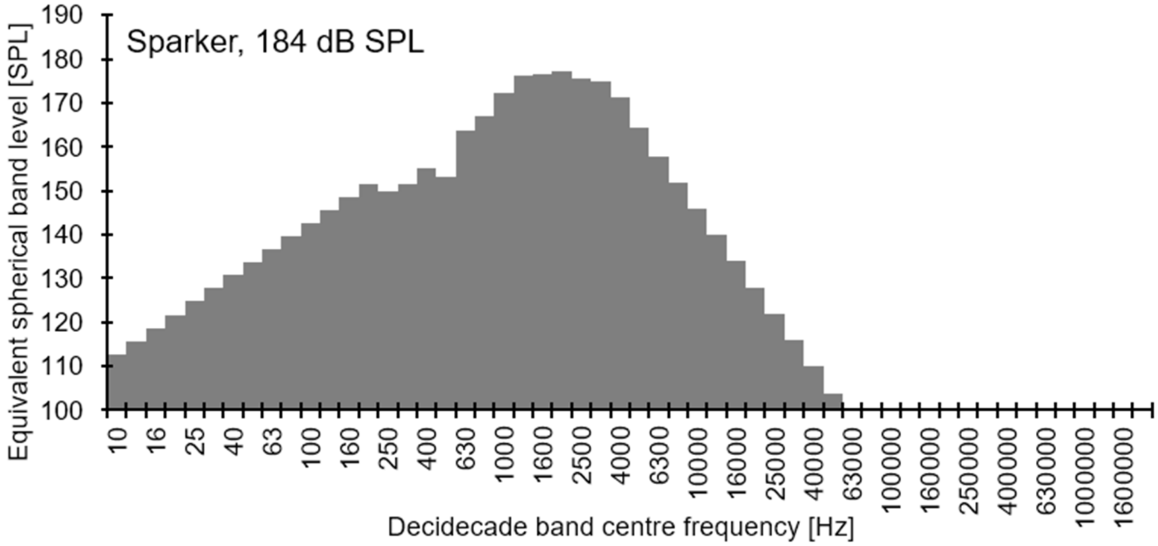


Figure 4-9 Source band levels for the sparker.

4.9 UHRS, Boomer

The boomer source is based on a 400 J firing at 1 second intervals. The main frequencies are 160 Hz to 16,000 Hz. The broadband level is 177 dB SPL (Figure 4-7).

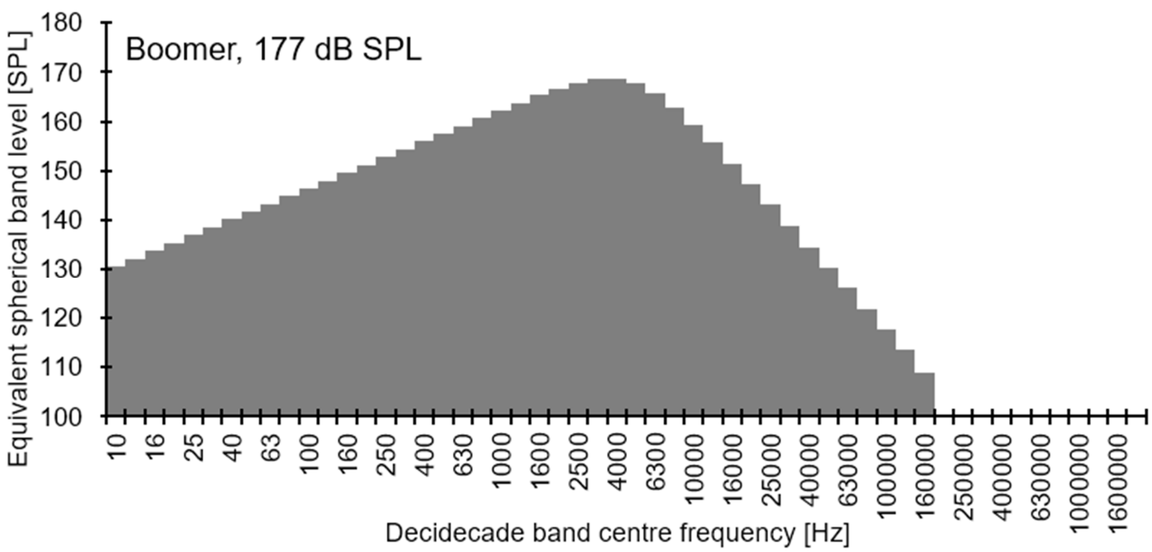


Figure 4-10 Source band levels for the sparker.

4.10 Sonic & Rotary Drilling/Coring

Source band levels for sonic & rotary coring/drilling are based on recordings from these types of activities (Bureau of Ocean Energy Management; Center for Marine Acoustics, 2023; Erbe, et al., 2017; L-F, et al., 2023)

Band levels are given in Figure 4-11, with a broadband level for Sonic drilling of 189 dB SPL and for Rotary drilling of 150 dB SPL.

The rotary drilling/coring also covers any cone penetration testing (CPT).

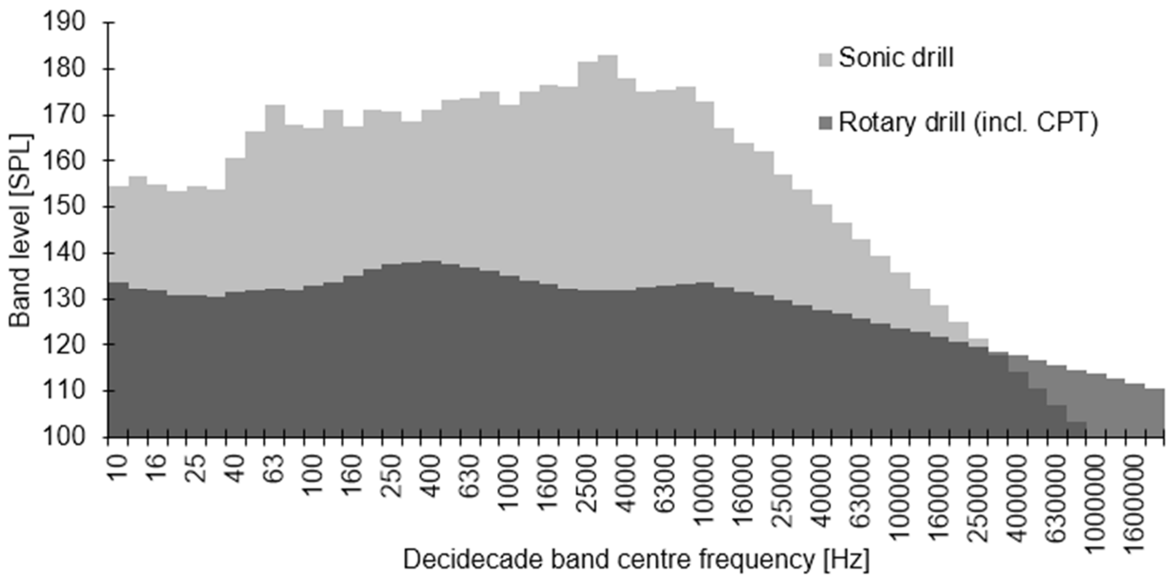


Figure 4-11 Source band levels for sonic & rotary coring/drilling.

4.11 Combined Sources

In the following sections, the four combined source configurations are given for clarity. These represent the sources as modelled and thus account for overlap in noise emissions between sources.

4.11.1 Bathymetric Survey – Irish Sea, no SBP or UHRS

Equipment active:

- Bathymetric Survey vessel up to 25 m length
- MBES
- SSS
- USBL

Broadband level of 193 dB SPL, with band levels shown in Figure 4-12.

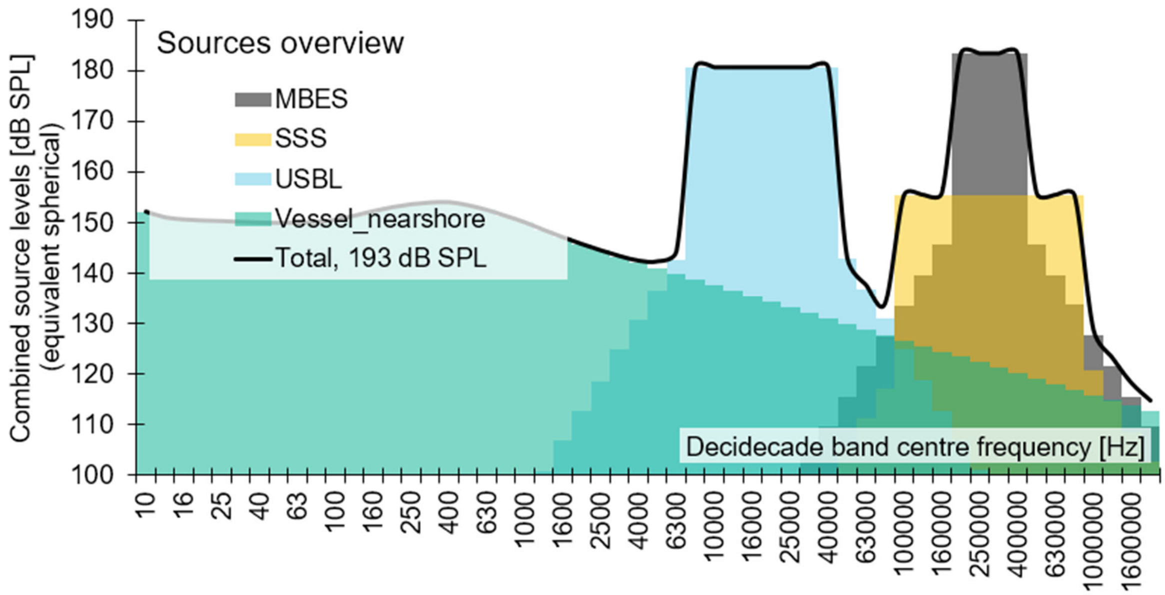


Figure 4-12 Source band levels for bathymetric survey without SBPs or UHRS.

4.11.2 Geophysical and Bathymetric Survey – Baldoyle Bay, incl. SBP & UHRS

Equipment active:

- Geophysical and Bathymetric Survey vessel up to 25 m length
- MBES (Bathymetric)
- SSS (Bathymetric)
- Both SBPs (P-SBP and C-SBP)*
- Both UHRS types (Sparker and Boomer)*

*In the actual surveys only a single SBP and only a single UHRS will be active/used, they are all included in the assessment to provide a wider applicability of the results.

Broadband level of 206 dB SPL, with band levels shown in Figure 4-12.

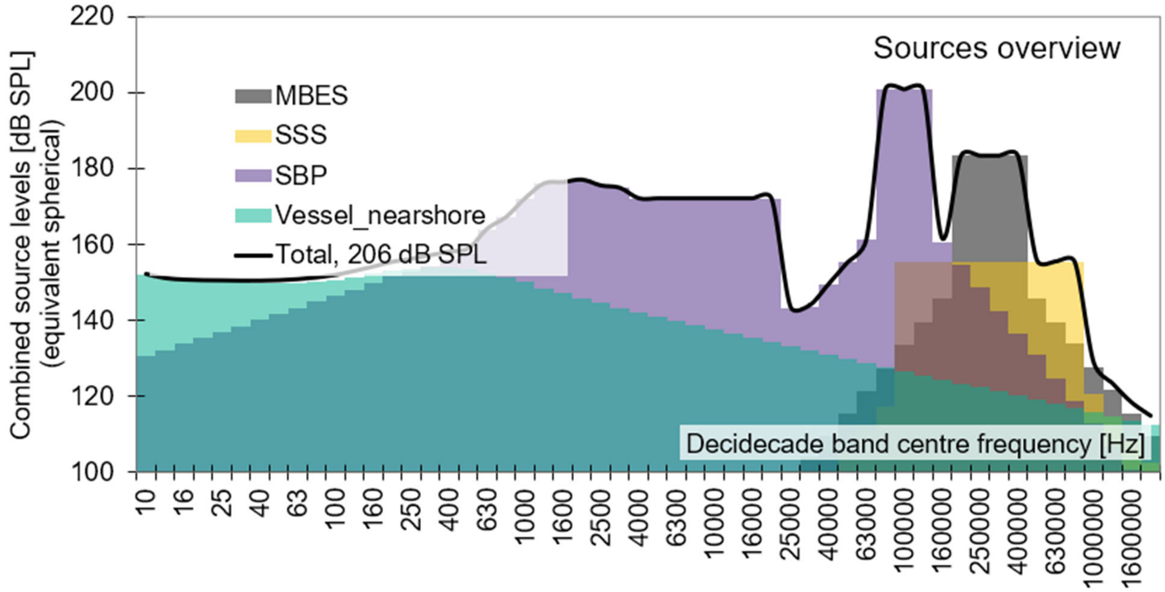


Figure 4-13 Source band levels for geophysical and bathymetric survey with SBPs and UHRS equipment.

4.11.3 Geotechnical Survey – Small vessel

Equipment active:

- Geophysical and Bathymetric Survey vessel up to 25 m length
- Sonic drilling/coring
- Rotary drilling/coring (incl. CPT)

Broadband level of 189 dB SPL, with band levels shown in Figure 4-14.

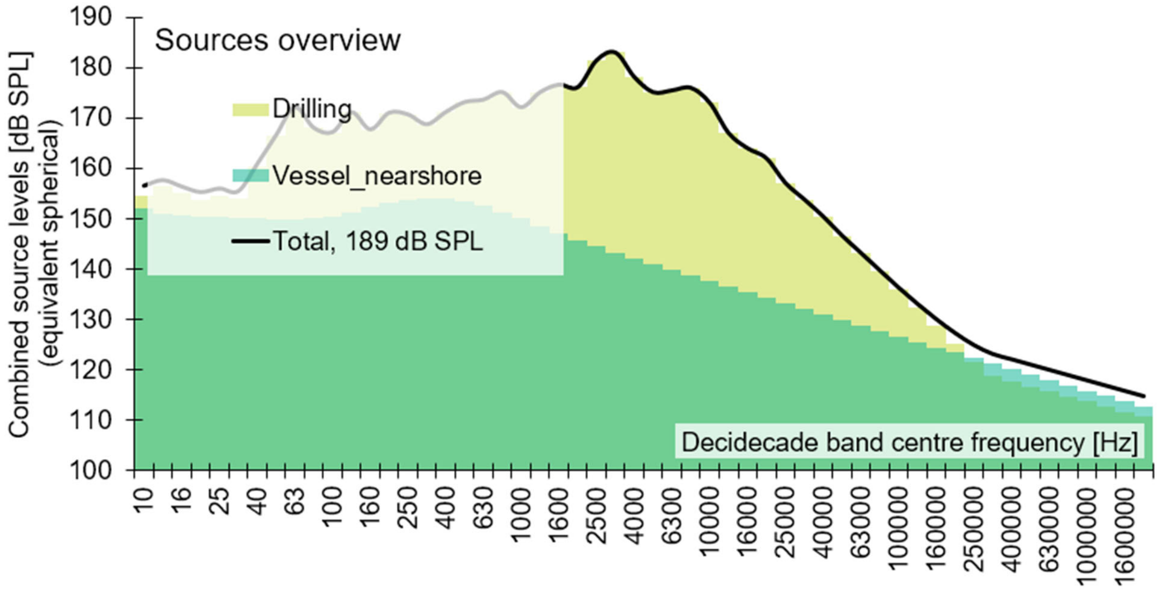


Figure 4-14 Source band levels for geotechnical survey – small vessel.

4.11.4 Geotechnical Survey – Large vessel

Equipment active:

- Geophysical and Bathymetric Survey vessel up to 85 m length with active DP system
- Sonic drilling/coring
- Rotary drilling/coring (incl. CPT)

Broadband level of 189 dB SPL, with band levels shown in Figure 4-14.

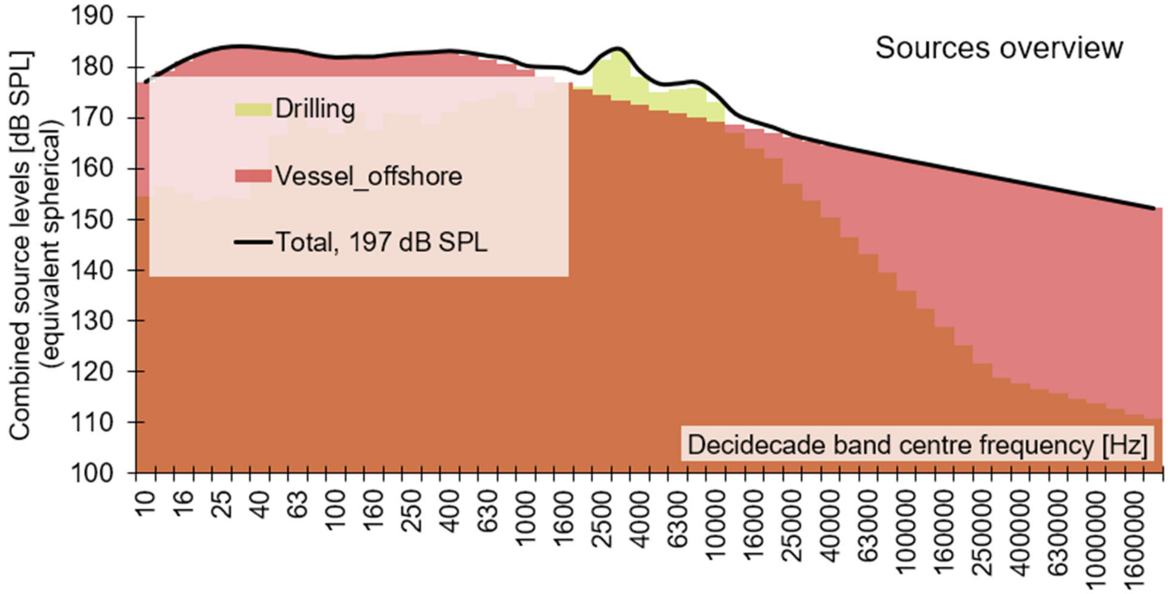


Figure 4-15 Source band levels for geotechnical survey – large vessel.

5 SOUND PROPAGATION MODELLING METHODOLOGY

There are several methods available for modelling the propagation of sound between a source and receiver, ranging from very simple models which simply assume spreading according to a $10\times\log_{10}$(range) or $20\times\log_{10}$(range) relationship, to full acoustic models (e.g., ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available which lie somewhere in between these two extremes in terms of complexity (e.g., (Rogers, 1981; Weston, 1971)).

For simpler scenarios, such as this one, where the sediment is relatively uniform and mostly flat, or where great detail in the sound field is not needed, the speed of these simpler models is preferred over the higher accuracy of numerical models and are routinely used for these types of assessments. For this assessment, we have used the Weston model (Weston, 1971), which is suitable to depths of c. 200 m and non-consolidated sediments.

This model will tend to underestimate the transmission losses (leading to estimates greater than actual impact), primarily due to the omission of surface roughness, wind effects and shear waves in the sediment.

Validation examples of the model can be found in Appendix B

5.1 Modelling Assumptions

The main assumptions made for the modelling are:

1. Animals fleeing the area will not return within a 24-hour period.
2. Animals flee for up to 24 hours.
3. Results assume a transition from impulsive (kurtosis >40) to non-impulsive (kurtosis <40) at some distance from the source. For this assessment, the transition occurs before 25 m from the source. After the transition to non-impulsive noise, the noise is assessed against the non-impulsive thresholds.

   This assumption is also applicable for the assessment of behavioural disturbance.
4. Sources are modelled as point sources.
5. Modelling is done for high tide, being the tidal state with the least transmission loss.

5.2 Exposure Calculations (dB SEL)

To compare modelled levels with the two impact assessment frameworks (NMFS 2024 & Popper et al. 2014) it is necessary to calculate received levels as exposure levels (SEL), weighted for marine mammals and unweighted for fishes. For ease of implementation, sources have generally been converted to an SPL source level, meaning converting to SEL from SPL or from a number of events.

To convert from SPL to SEL, the following relation can be used:

$$SEL = \mathrm{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \qquad (1)$$

Or, where it is inappropriate to convert SEL from one event to SEL cumulative by relating to the number of events as:

$$SEL_{\ n\ events} = SEL_{single\ event} + 10 \cdot Log_{10}(n) \tag{2}$$

And SPL from SEL:

$$SPL = SEL_{single\ event} + 10 \cdot Log_{10}\left(\frac{n}{t_2 - t_1}\right) \tag{3}$$

As an animal swims away from the sound source, the noise it experiences will become progressively more attenuated; the cumulative, fleeing SEL is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation is used to estimate the approximate minimum start distance for an animal in order for it to be exposed to sufficient sound energy to result in the exceedance of a threshold, or to check if a set exclusion zone is sufficient for an activity (e.g. will an exclusion zone of 500 m be sufficient to prevent exceeding an AUD INJ threshold). It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a constant speed. The real-world situation is more complex and the animal is likely to move in a more varied manner. Reported swim speeds are summarised in Table 5-1 along with the source papers for the assumptions.

For this assessment, a swim speed of 1.5 m/s for marine mammals, and 0.5 m/s for fishes (including sharks) is assumed.

For very long fleeing durations, the ambient sound itself can exceed the thresholds, e.g., an ambient sound level of 122.4 dB, weighted for the VHF group, will exceed the non-impulsive TTS threshold of 161 dB SEL after 2 hours' exposure[9]. For this assessment, we consider fleeing durations of 2 hours (7200 seconds, allowing 10800 m of fleeing), meaning that weighted levels of 122.4 dB SPL will exceed the VHF group's non-impulsive TTS threshold in the fleeing model.

Table 5-1 Swim speed examples from literature

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Harbour porpoise	VHF	1.5	Otani *et al.,* 2000
Harbour seal	PCW	1.8	Thompson, 2015
Grey seal	PCW	1.8	Thompson, 2015
Minke whale	LF	2.3	Boisseau *et al.,* 2021
Bottlenose dolphin	HF	1.52	Bailey and Thompson, 2010
White-beaked dolphin	HF	1.52	Bailey and Thompson, 2010
Basking shark	Fish (unweighted)	1.0	Sims, 2000
All other fish groups	Fish (unweighted)	0.5	Popper *et al.,* 2014
Sea turtles	Fish (unweighted)	0.56-0.84 & 0.78-2.8	(F, et al., 1997; SA, 2002)

[9] 122.4 dB SPL + 10*log_{10}(3600 seconds) = 161 dB SEL, TTS non-impulsive threshold for the VHF group is 161 dB SEL.

6 RESULTS AND ASSESSMENT

6.1 Assumptions and Notes on Results

The results should be read while keeping the following in mind:

- Results are rounded up to the nearest two significant digits. This can lead to apparent overlaps in risk ranges.
- The modelling resolution of 10 metres means that, where results are lower than this, “<10” is stated to mean “below 10 metres”.
- As the impulsive noise transitions to non-impulsive noise with increased ranges, the appropriate behavioural threshold for the assessment changes from 160 dB to 74-126 dB (a likely >10-fold increase in range). This means that there are large ranges of disturbance, but these should be considered in relation to, for example, the radiated noise from common vessels, which will exceed this threshold to ranges of 500-10000 m (assuming 160-180 dB SPL source level).
- Animals are modelled as fleeing in straight lines. Where sites are very confined, the maximal modelled risk ranges will be restricted by line-of-sight ranges (and cut short where they meet land).
- Modelling assumes a maximal fleeing time of 24 hours.
- Modelling assumes 6 hours activity in Baldoyle Bay (a generous high-tide window) and 24 hours activity in the Irish Sea.
- Modelling is limited to a range of 20 km from the site boundary.
- Where behavioural disturbance ranges are over 20 km, “>20000 m” is reported.

6.2 Results Tables

6.2.1 Bathymetric Survey – Irish Sea, no SBP or UHRS

The behavioural disturbance ranges are between 13,000 to >20,000 m depending on the hearing group. These ranges should be considered in relation to normal vessel noise in the area, where any vessels closer to the animal than the survey vessel will tend to “drown out” the noise from the survey vessel. The exception to this is a closer range where the higher frequencies from the MBES and P-SBP are still relevant (higher frequencies attenuate rapidly at higher frequencies, see Appendix A).

Exceedances of the TTS thresholds for fleeing receivers are <250 m for all hearing groups except the PW (seals) and the VHF group (porpoises), which has risk ranges to 1300 m and 11000 m respectively for exceedance of the TTS threshold.

Exceedances of AUD INJ thresholds for fleeing receivers are <10 m for all hearing groups except the VHF group (porpoises), which has risk range to 150 m for exceedance of the AUD INJ threshold.

Table 6-1 Threshold exceedance ranges for the bathymetric survey in the Irish Sea with no SBP or UHRS equipment.

Condition		LF	HF	VHF	PW	OW	Fishes
Behavioural disturbance range	90th percentile range [m]	>20,000	>20,000	>20,000	>20,000	>20,000	13000
TTS,1 seconds' exposure	90th percentile range [m]	<10	<10	130	<10	<10	<10
AUD INJ,1 seconds' exposure	90th percentile range [m]	<10	<10	<10	<10	<10	<10
TTS, sound exposure, fleeing receiver	90th percentile range [m]	150	180	11000	1300	250	<10
AUD INJ, sound exposure, fleeing receiver	90th percentile range [m]	<10	<10	150	<10	<10	<10

6.2.2 Bathymetric Survey – Baldoyle Bay, no SBP or UHRS

The behavioural disturbance ranges are up to 1200 m.

Exceedances of the TTS thresholds for fleeing receivers are <240 m for all hearing groups except the VHF group (porpoises), which has risk ranges to 1100 m for exceedance of the TTS threshold.

Exceedances of AUD INJ thresholds for fleeing receivers are <50 m for all hearing groups.

Table 6-2 Threshold exceedance ranges for the bathymetric survey in Baldoyle Bay with no SBP or UHRS equipment.

Condition		LF	HF	VHF	PW	OW	Fishes
Behavioural disturbance range	90th percentile range [m]	1200	1200	1200	1200	1200	1200
TTS,1 seconds' exposure	90th percentile range [m]	<10	<10	80	<10	<10	<10
AUD INJ,1 seconds' exposure	90th percentile range [m]	<10	<10	<10	<10	<10	<10
TTS, sound exposure, fleeing receiver	90th percentile range [m]	40	60	1100	240	60	<10
AUD INJ, sound exposure, fleeing receiver	90th percentile range [m]	<10	<10	50	<10	<10	<10

6.2.3 Geophysical Survey – Baldoyle Bay, incl. SBP & UHRS

The behavioural disturbance ranges are up to 1300 m.

Exceedances of the TTS thresholds for fleeing receivers are <400 m for all hearing groups except the VHF group (porpoises), which has risk ranges to 1100 m for exceedance of the TTS threshold.

Exceedances of AUD INJ thresholds for fleeing receivers are <10 m for all hearing groups except the VHF group (porpoises), which has risk range to 270 m for exceedance of the AUD INJ threshold.

Table 6-3 Threshold exceedance ranges for the geophysical survey in Baldoyle Bay with SBP and UHRS equipment active.

Condition		LF	HF	VHF	PW	OW	Fishes
Behavioural disturbance range	90th percentile range [m]	1200	1300	1300	1200	1200	1200
TTS,1 seconds' exposure	90th percentile range [m]	<10	10	400	10	<10	<10
AUD INJ,1 seconds' exposure	90th percentile range [m]	<10	<10	20	<10	<10	<10
TTS, sound exposure, fleeing receiver	90th percentile range [m]	120	190	1100	400	100	<10
AUD INJ, sound exposure, fleeing receiver	90th percentile range [m]	<10	<10	270	<10	<10	<10

6.2.4 Geotechnical Survey – Baldoyle Bay

The behavioural disturbance ranges are up to 1200 m.

Exceedances of the TTS thresholds for fleeing receivers are <240 m for all hearing groups except the VHF group (porpoises), which has risk ranges to 600 m for exceedance of the TTS threshold.

Exceedances of AUD INJ thresholds for fleeing receivers are <10 m for all hearing groups.

Table 6-4 Threshold exceedance ranges for the geotechnical survey in Baldoyle Bay.

Condition		LF	HF	VHF	PW	OW	Fishes
Behavioural disturbance range	90th percentile range [m]	1200	1200	1200	1200	1200	1200
TTS,1 seconds' exposure	90th percentile range [m]	<10	<10	10	<10	<10	<10
AUD INJ,1 seconds' exposure	90th percentile range [m]	<10	<10	<10	<10	<10	<10
TTS, sound exposure, fleeing receiver	90th percentile range [m]	160	24	600	240	40	<10
AUD INJ, sound exposure, fleeing receiver	90th percentile range [m]	<10	<10	<10	<10	<10	<10

6.2.5 Geotechnical Survey – Irish Sea, Small Vessel

The behavioural disturbance ranges are >20,000 m.

Exceedances of the TTS thresholds for fleeing receivers are 11,000 m for the VHF group, 6,000 m for the PW group, 5,000 m for the LF group and <240 m for the remaining groups.

Exceedances of AUD INJ thresholds for fleeing receivers are <10 m for all hearing groups.

Table 6-5 Threshold exceedance ranges for the geotechnical survey in the Irish Sea using the small vessel (<25 m).

Condition		LF	HF	VHF	PW	OW	Fishes
Behavioural disturbance range	90th percentile range [m]	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
TTS,1 seconds' exposure	90th percentile range [m]	<10	<10	10	<10	<10	<10

AUD INJ,1 seconds' exposure	90th percentile range [m]	<10	<10	<10	<10	<10	<10
TTS, sound exposure, fleeing receiver	90th percentile range [m]	5000	120	11000	6000	240	<10
AUD INJ, sound exposure, fleeing receiver	90th percentile range [m]	<10	<10	<10	<10	<10	<10

6.2.6 Geotechnical Survey – Irish Sea, Large Vessel

The behavioural disturbance ranges are >20,000 m.

Exceedances of the TTS thresholds for fleeing receivers are 13,000 m for the VHF group, 10,000 m for the PW group, 13,000 m for the LF group, 600 m for the OW group and <270 m for the remaining groups.

Exceedances of AUD INJ thresholds for fleeing receivers are <10 m for all hearing groups.

Table 6-6 Threshold exceedance ranges for the geotechnical survey in the Irish Sea using the large vessel (<85 m).

Condition		LF	HF	VHF	PW	OW	Fishes
Behavioural disturbance range	90th percentile range [m]	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
TTS,1 seconds' exposure	90th percentile range [m]	10	<10	10	<10	<10	<10
AUD INJ,1 seconds' exposure	90th percentile range [m]	<10	<10	<10	<10	<10	<10
TTS, sound exposure, fleeing receiver	90th percentile range [m]	13000	270	13000	10000	600	<10
AUD INJ, sound exposure, fleeing receiver	90th percentile range [m]	<10	<10	<10	<10	<10	<10

6.3 Summary of Results and Discussion

6.3.1 Geophysical and Bathymetric Surveys

6.3.1.1 Irish Sea

The behavioural disturbance thresholds are generally exceeded to beyond 20 km. Depending on the presence of other vessels in the area and the habituation of the animals, the actual ranges to disturbance are likely to be significantly smaller.

Risk ranges to exceedance of the TTS thresholds are up to 11 km for the VHF group (porpoises) and 1.3 km for the PW group (seals), with the USBL being the sound source driving this range.

Part of the reason for these ranges is the 24-hour potential active survey durations, meaning that even modest received levels can build up over time to exceed the TTS threshold.

Risk of exceedance of the AUD INJ threshold extends to 150 m for the VHF group and <10 m for the remaining hearing groups.

6.3.1.2 Baldoyle Bay

The behavioural disturbance thresholds are generally exceeded within in-water line-of-sight.

Risk ranges to exceedance of the TTS thresholds are up to 1100 m for the VHF group (porpoises) and 400 m for the PW group (seals).

Risk of exceedance of the AUD INJ threshold extends to 270 for the VHF group and <10 m for the remaining hearing groups.

6.3.2 Geotechnical Surveys

6.3.2.1 Irish Sea

The behavioural disturbance thresholds are generally exceeded to beyond 20 km. Depending on the presence of other vessels in the area and the habituation of the animals the actual ranges to disturbance are likely to be significantly smaller.

Risk ranges to exceedance of the TTS thresholds are up to 13 km for the VHF group (porpoises) and LF group (Baleen whales) and 10 km for the PW group (seals), with the vessel noise driving this range. Depending on the actual activity pattern (vessel speed, use of thrusters) this range will likely reduce

Part of the reason for these ranges is the 24-hour potential active survey durations, meaning that even modest received levels can build up over time to exceed the TTS thresholds.

Risk of exceedance of the AUD INJ threshold extends to <10 m for all hearing groups.

6.3.2.2 Baldoyle Bay

The behavioural disturbance thresholds are generally exceeded within in-water line-of-sight.

Risk ranges to exceedance of the TTS thresholds are up to 600 m for the VHF group (porpoises) and <240 m for the remaining hearing groups, with the sonic drilling noise driving this range.

Risk of exceedance of the AUD INJ threshold extends to <10 m for all hearing groups.

7 CONCLUSIONS

This study has taken a conservative approach in modelling representative worst-case source levels, environmental variables and propagation losses to estimate reasonable worst-case ranges of risk of exceedance to acoustic thresholds for injury (AUD INJ), temporary hearing impairment (TTS) and possible behavioural disturbance. The maximal range for risk of injury was found to be 270 m for any realistic combination of the sources presented, with risk of injury for surveys in the Irish Sea limited to 150 m from the vessel during geophysical and bathymetric surveys.

Additional details depending on survey type and locations in the section below.

7.1 Geophysical and Bathymetric Surveys

All risk of injury is below 10 m for all hearing groups except the VHF hearing group (porpoises), which have risk of auditory injury to a maximal range of 270 m from the use of SBPs or UHRS equipment in Baldoyle Bay or to 150 m in the Irish Sea (no SBP or UHRS equipment).

Risk ranges for TTS are up to 11 km for the VHF hearing group (porpoises). This is mainly the result of activities being assumed to continue for 6-24 hours (meaning long duration of sound exposure accumulation [see section 5.2]) and the assumption that the activities from this study are the main contributors to the sound exposure – at ranges of a few kilometres from the source, any other larger vessel nearer an animal will be the primary contributor to its sound exposure, not these surveys.

Ranges to exceedance of the behavioural disturbance thresholds are generally limited by the underwater line-of-sight (Baldoyle Bay) or greater than 20 km for the Irish sea. These ranges assume a quiet sea, so with other vessels active in the area the realised exceedance from these activities will be limited to a range where these surveys are the loudest received levels to an animal. The range at which this occurs depends on the relative source levels and is shorter for other loud sources (merchant vessel, fast ferries).

7.2 Geotechnical Surveys

All risk of injury is below 10 m for all hearing groups.

Risk ranges for TTS are 10-13 km for several hearing groups (LF, VHF & PW). This is mainly the result of activities being assumed to continue for 6-24 hours (meaning long duration of sound exposure accumulation [see section 5.2]) and the assumption that the activities from this study are the main contributors to the sound exposure – at ranges of a few kilometres from the source, any other larger vessel nearer an animal will be the primary contributor to its sound exposure, not these surveys.

Ranges to exceedance of the behavioural disturbance thresholds are generally limited by the underwater line-of-sight (Baldoyle Bay) or greater than 20 km for the Irish sea. These ranges assume a quiet sea, so with other vessels active in the area the realised exceedance from these activities will be limited to a range where these surveys are the loudest received levels to an animal. The range at which this occurs depends on the relative source levels and is shorter for other loud sources (merchant vessel, fast ferries).

8 REFERENCES

Ainslie Michael A. Principles of Sonar Performance Modeling [Book]. - Heidelberg : Springer, 2010.

ANSI S1.13-2005 Measurement of Sound Pressure Levels in Air. - [s.l.] : American National Standards Institute, 2005.

ANSI S12.7-1986 Method for Measurement of Impulsive Noise. - [s.l.] : American National Standards Institute, 1986.

ANSI S3.20-1995 Bioacoustical Terminology. - [s.l.] : American National Standards Institute, 1995.

Audoly C and Rizzuto E Ship Underwater Radiated Noise Patterns [Journal]. - [s.l.] : Technical Report, AQUO European Collaborative Project, Deliverable D2.1., 2015.

Benhemma-Le Gall A Graham IM, Merchant ND and Thompson PM Broad-Scale Responses of Harbor Porpoises to Pile-Driving and Vessel Activities During Offshore Windfarm Construction [Journal]. - [s.l.] : Frontiers in Marine Science, 2021. - 664724 : Vol. 8.

BOOTH C.G., HARWOOD, J., PLUNKETT, R, MENDES, S, & WALKER, R. Using the Interim PCoD framework to assess the potential impacts of offshore wind developments in Eastern English Waters on harbour porpoises in the North Sea [Report]. - [s.l.] : Natural England, 2017.

Brandon L. Southall Ann E. Bowles, William T. Ellison, James J. Finneran, Roger L. Gentry,Charles R. Greene Jr., David Kastak, Darlene R. Ketten, James H. Miller, Paul E. Nachtigall,W. John Richardson, Jeanette A. Thomas, & Peter L. Tyack Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations [Report]. - [s.l.] : Aquatic Mammals, 2007.

Bureau of Ocean Energy Management Appendix A: Description of Equipment. - [s.l.] : Bureau of Ocean Energy Management.

Center for Marine Acoustics Sound Source List. A desriction of sounds commonly produced during ocean exploration activity. [Report]. - [s.l.] : Bureau of Ocean Energy Management, 2023.

Chion C, Lagrois D and Dupras J A Meta-Analysis to Understand the Variability in Reported Source Levels of Noise Radiated by Ships From Opportunistic Studies [Journal]. - [s.l.] : Frontiers in Marine Science, 2019.

Danish Centre for Environment and Energy Thresholds for behavioural responses to noise in marine mammals [Report]. - Aarhus : Aarhus Universitet, 2021.

Department of Arts, Heritage and the Gaeltacht Guidance to Manage the Risk to Marine Mammals from Man-made Sound in Irish Waters [Report]. - [s.l.] : Department of Arts, heritage and the Gaeltacht, 2014.

Erbe Christina and McPherson Craig Underwater noise from geotechnical drilling and standard penetration testing [Journal] // Journal of the Acoustical Society of America. - 2017.

F Papi [et al.] Satellite tracking experiments on the navigational ability and migratory behaviour of the loggerhead turtle caretta caretta. [Journal]. - [s.l.] : Marine Biology, 1997. - 129:215-220.

Graham IM Merchant ND, Farcas A, Barton TR, Cheney B, Bono S, Thompson PM. Harbour porpoise responses to pile-driving diminish over time [Journal]. - [s.l.] : Royal Society Open Science, 2019. - 190335 : Vol. 6.

Heitmeyer Stephen C. Wales and Richard M. An ensemble source spectra model for merchant ship-radiated noise [Journal]. - Washington : Naval Research Laboratory, 2001.

INFOMAR Sea surface alkalinity across the Irish shelf from underway temperature and salinity data collected during the INFOMAR project [Report]. - Galway : NUI Galway, 2012.

L-F Huang [et al.] Underwater noise characteristics of offshore exploratory drilling and its impact on marine mammals. [Journal]. - [s.l.] : Frontiers in Marine Science, 2023.

Liefvendahl M, Feymark A and RE Bensow Methodology for noise source modelling and its application to Baltic Sea shipping - Deliverable D4.1 of the BONUS SHEBA project [Journal]. - [s.l.] : Chalmers University of Technology, 2015.

MacGillivray A. and Jong C. de A Reference Spectrum Model for Estimating Source Levels of Marine Shipping based on Automated Identification System Data [Journal]. - [s.l.] : JMSE, 2021.

Martin S. Bruce and Klaus Lucke David R. Barclay Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals [Journal]. - [s.l.] : Journal of the Acoustical Society of America, 2020. - 4 : Vol. 147.

MSFD Technical Subgroup on Underwater Noise Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications [Report]. - [s.l.] : European commision, 2014.

Nedwell .R. [et al.] A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise [Report]. - [s.l.] : subacoustech, 2007.

Nedwell Dr. J.R. [et al.] Fish and Marine Mammal Audiograms: A summary of available information [Report]. - 2004.

NIOSH Criteria for a Recommended Standard: Occupational Noise Exposure. - [s.l.] : National Institute for Occupational Safety and Health, 1998.

NMFS 2024 Update to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 3.0) [Report]. - Silver Spring : National Marine Fisheries Service, 2024.

Popper A. N. [et al.] Sound Exposure Guidelines for Fishes and Sea Turtles [Report]. - [s.l.] : Springer, 2014.

Rogers P. H. Onboard Prediction of Propagation Loss in Shallow Water [Report]. - Washington DC : Naval Research Laboratory, 1981.

SA Eckert Swim speed and movement patterns of gravid leatherback sea turtles(Dermochelys coriacea) at St Croix, US Virgin Islands [Journal]. - [s.l.] : Croix, US Virgin Islands, 2002. - 205:3689-3697.

Sarnoci´nska J Teilmann J, Balle JD, van Beest FM, Delefosse M and Tougaard J Harbor Porpoise (Phocoena phocoena) Reaction to a 3D Seismic Airgun Survey in the North Sea [Journal]. - [s.l.] : Frontiers in Marine Science, 2020. - 824 : Vol. 6.

Simard Yvan, RoyCédric Nathalie and Giard Gervaise Samuel Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence Seaway [Journal]. - [s.l.] : journal of the Acoustical Society of America, 2016. - 2002 : Vol. 140.

Sinclair R.R. [et al.] Review and recommendations on assessment of noise disturbance for marine mammals [Report]. - Bangor : Natural Resources Wales, 2023.

Southall Brandon L. [et al.] Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects [Journal]. - [s.l.] : Aquatic Mammals, 2019. - 2 : Vol. 45.

Weston D. E. Intensity-Range Relations in Oceanographic Acoustics [Report]. - Teddington : Admiralty Research Laboratory, 1971.

Wittekind Dietrich Kurt A Simple Model for the Underwater Noise Source Level of Ships [Journal]. - Schwentinental : DW-ShipConsult GmbH, 2014.

Worcester T. Effects of Seismic Energy on Fish; A Literature Review [Report]. - Dartmouth, Canada : Department of Fisheries and Oceans, Bedford Institute of Oceanography, 2006.

WSDOT Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual, CH 7 [Report]. - [s.l.] : Washington State Department of Transport, 2020.

Appendix A – Acoustic Concepts and Terminology

Sound travels through water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1 μPa, one micro-pascal, whereas airborne sound is usually referenced to a pressure of 20 μPa. To convert from a sound pressure level referenced to 20 μPa to one referenced to 1 μPa, a factor of 20 log (20/1) i.e. 26 dB has to be added to the former quantity. Thus, a sound pressure of 60 dB re 20 μPa is the same as 86 dB re 1 μPa, although care also needs to be taken when converting from in air sound to in water sound levels due to the different sound speeds and densities of the two mediums resulting in a conversion factor of approximately 62 dB for comparing intensities (watt/m²), see Table 8-1 , below.

Table 8-1 Comparing sound quantities between air and water.

	Constant intensity		Constant pressure	
Properties	**Air**	**Water**	**Air**	**Water**
Soundspeed (C) [m/s]	340	1500	340	1500
Density (ρ) [kg/m³]	1.293	1026	1.293	1026
Acoustic impedance (Z=C·ρ) [kg/(m²·s) or (Pa·s)/m³]	440	1539000	440	1539000
Sound intensity (I=p²/Z) [Watt/m²]	1	1	22.7469	0.0065
Sound pressure (p=(I*Z)^{½}) [Pa]	21	1241	100	100
Particle velocity (I/p) [m/s]	0.04769	0.00081	0.22747	0.00006
dB re 1 μPa²	146.4	**181.9**	160.0	**160.0**
dB re 20 μPa²	**120.4**	155.9	**134.0**	134.0
Difference dB re 1 μPa² & dB re 20 μPa²	**61.5**		**26.0**	

All underwater sound pressure levels in this report are described in dB re 1 μPa². In water, the sound source strength is defined by its sound pressure level in dB re 1 μPa², referenced back to a representative distance of 1m from an assumed (infinitesimally small) point source. This allows calculation of sound levels in the far-field. For large, distributed sources, the actual sound pressure level in the near-field will be lower than predicted.

There are several descriptors used to characterise a sound wave. The difference between the lowest pressure deviation (rarefaction) and the highest pressure deviation (compression) from ambient is the peak to peak (or pk-pk) sound pressure ($L_{pk\text{-}pk}$ for the level in dB), Note that $L_{pk\text{-}pk}$ can be hard to measure consistently, as the maximal duration between the lowest and highest pressure deviation is not standardised. The difference between the highest deviation (either positive or negative) and the ambient pressure is called the peak pressure (L_{pk} for the level in dB). Lastly, the average sound pressure is used as a description of the average amplitude of the variations in pressure over a specific time window (SPL for the level in dB). SPL is equal to the L_{eq} when the time window for the SPL is equal to the time window for the total duration of an event. The cumulative sound energy from pressure is the integrated squared pressure over a given period (SEL for the level in dB). These descriptions are shown graphically in Figure 8-1 and reflect the units as given in ISO 18405:2017, “Underwater Acoustics – Terminology”.

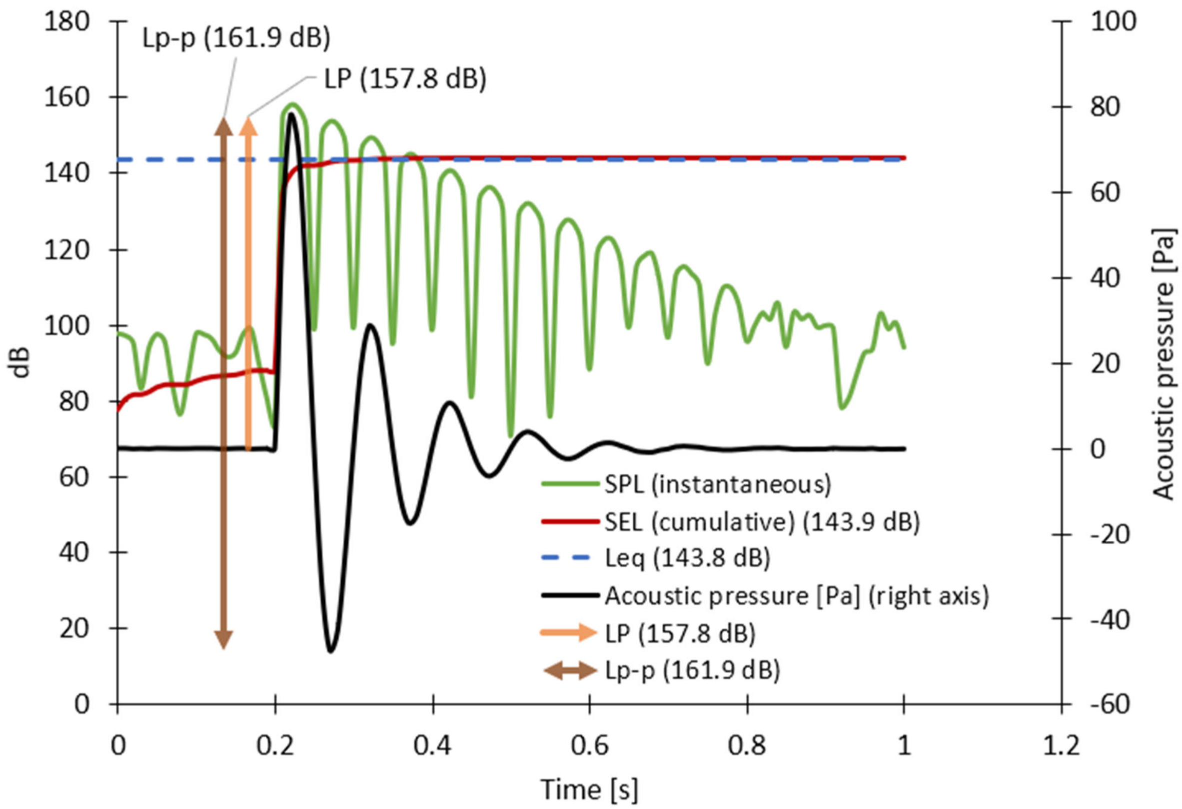


Figure 8-1: Graphical representation of acoustic wave descriptors.

The sound pressure level (SPL[10]) is defined as follows (ISO 18405:2017, 3.2.1.1):

$$SPL = 10 \cdot Log_{10}\left(\frac{\overline{p^2}}{1 \cdot 10^{-12} Pa}\right) \qquad (1)$$

Here $\overline{p^2}$ is the arithmetic mean of the squared pressure values. Note that L_{pk} is simply the instantaneous SPL (ISO 18405:2017, 3.2.2.1).

The peak sound pressure level, L_{pk}, is the instantaneous decibel level of the maximal deviation from ambient pressure and is defined in (ISO 18405:2017, 3.2.2.1) and can be calculated as:

$$L_{pk} = 10 \cdot Log_{10}\left(\frac{max(p^2)}{1 \cdot 10^{-12} Pa}\right)$$

Another useful measure of sound used in underwater acoustics is the Exposure Level, or SEL. This descriptor is used as a measure of the total sound energy of a single event or a number of events (e.g.

[10] Equivalent to the commonly seen “RMS-level”.

over the course of a day). This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis. Historically, use was primarily made of SPL and L_{pk} metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events over e.g. a 24-hour period to be taken into account. The SEL is defined as follows (ISO 18405:2017, 3.2.1.5):

$$SEL = 10 \cdot Log_{10}\left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right) \quad (2)$$

To convert from SEL to SPL the following relation can be used:

$$SEL = \mathrm{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \quad (3)$$

Converting from a single event to multiple events for SEL:

$$SEL_{n\ events} = SEL_{single\ event} + 10 \cdot Log_{10}(n) \quad (4)$$

The frequency, or pitch, of the sound is the rate at which these oscillations occur and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dB(A). However, the hearing faculties of marine mammals and fish are not the same as humans, with marine mammals hearing over a wider range of frequencies, fish over a typically smaller range of frequencies and both with different sensitivities. It is therefore important to understand how an animal's hearing varies over the entire frequency range to assess the effects of sound on marine life. Consequently, use can be made of frequency weighting scales to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 8-2. Note that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown. It is also worth noting that some fish are sensitive to particle velocity rather than pressure, although paucity of data relating to particle velocity levels for anthropogenic sound sources means that it is often not possible to quantify this effect. Marine reptiles (mostly sea turtles) have relatively poor hearing underwater, lacking a good acoustic coupling mechanism from the sea water to the inner ear.

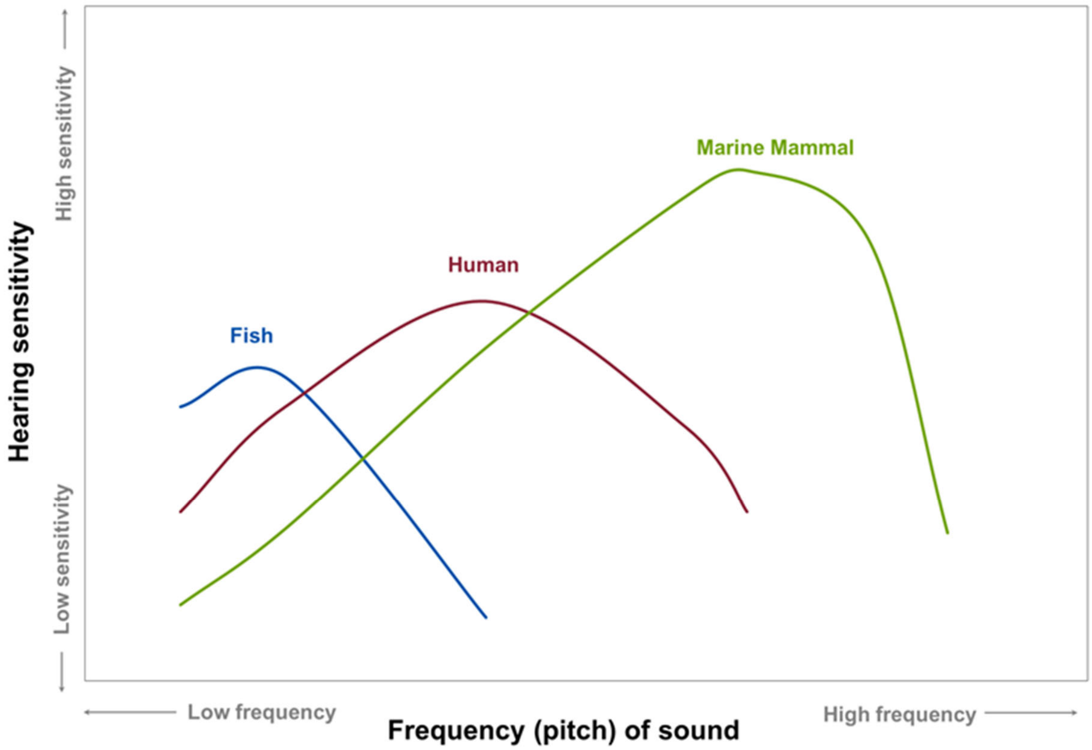


Figure 8-2: Comparison between hearing thresholds of different marine animals and humans.

Impulsiveness

The impulsiveness of a source can be estimated from the kurtosis of the weighted signal (as suggested by Matin et al. in “Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals”, Journal of the Acoustical Society of America, 2020)

The consequence of this is that the same equipment can be both impulsive and non-impulsive, depending o marine mammal presence and the local environment.

Below is an example of a hull mounted echo sounder at 15 m depth and at 250 m depth.

In shallow water the ping rate can be high as reflections from the sediment return quickly, but the single pulse duration is usually shorter as less energy in the signal is required due to the short range the pulse must travel. This leads to high repetition rate (decreases kurtosis) and shorter pulses (increases kurtosis). Figure 8-3 shows an example where this leads to a non-impulsive source, to be compared to the thresholds for non-impulsive noise.

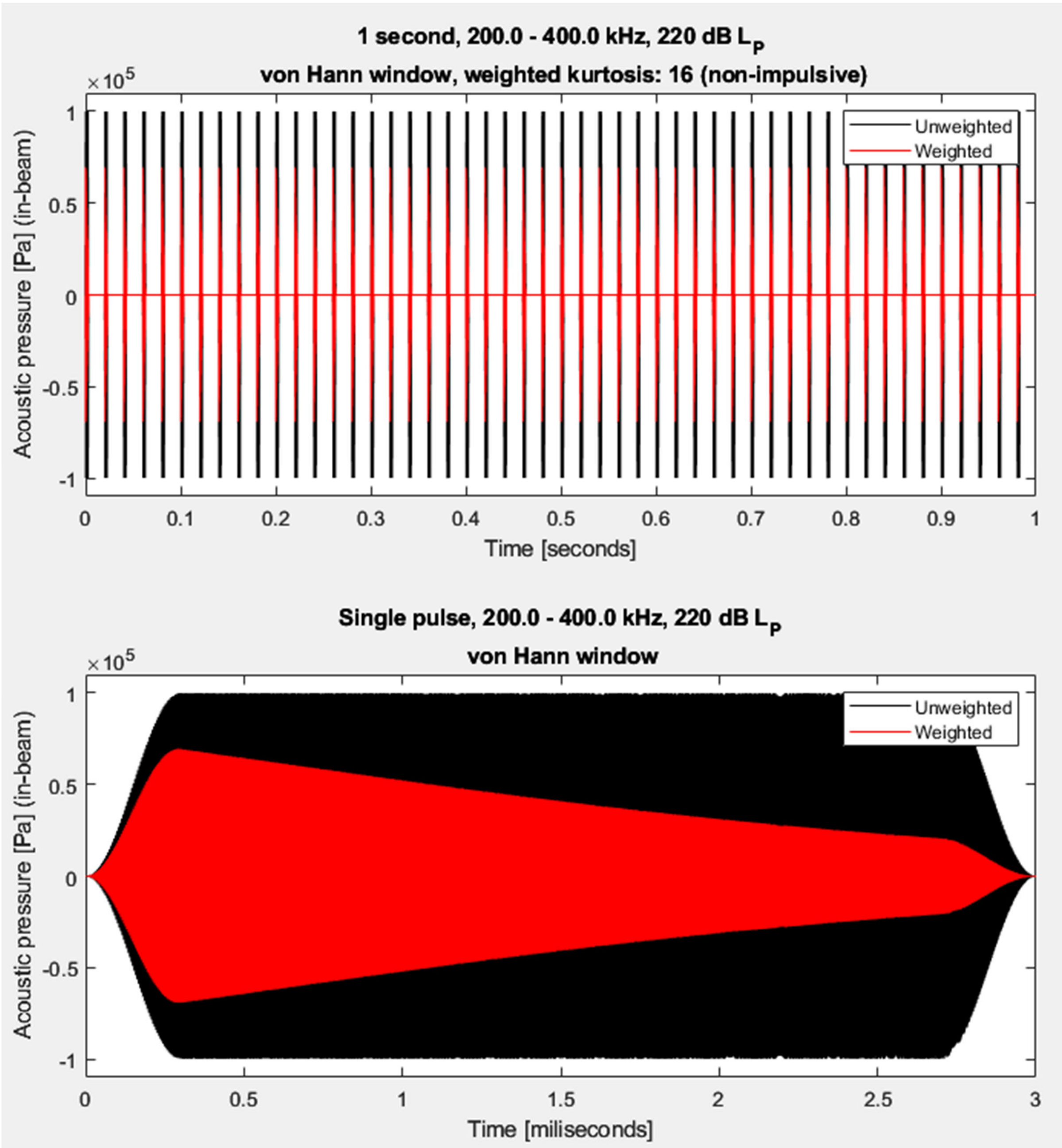


Figure 8-3. Example of a multibeam echosounder at 15 m depth (achieving 50 ping/sec) with a 3 ms ping duration. VHF-weighted kurtosis of 16 – non-impulsive.

In deeper water, the ping rate will usually be slower as echoes take longer to return to the sediment and the pulses will be longer to increase the energy in the pulses and make their echoes easier to detect. This leads to low repetition rate (increases kurtosis) and longer pulses (decreases kurtosis). Figure 8-4 shows an example where this combination resulted in an impulsive source, to be compared to the thresholds for impulsive noise.

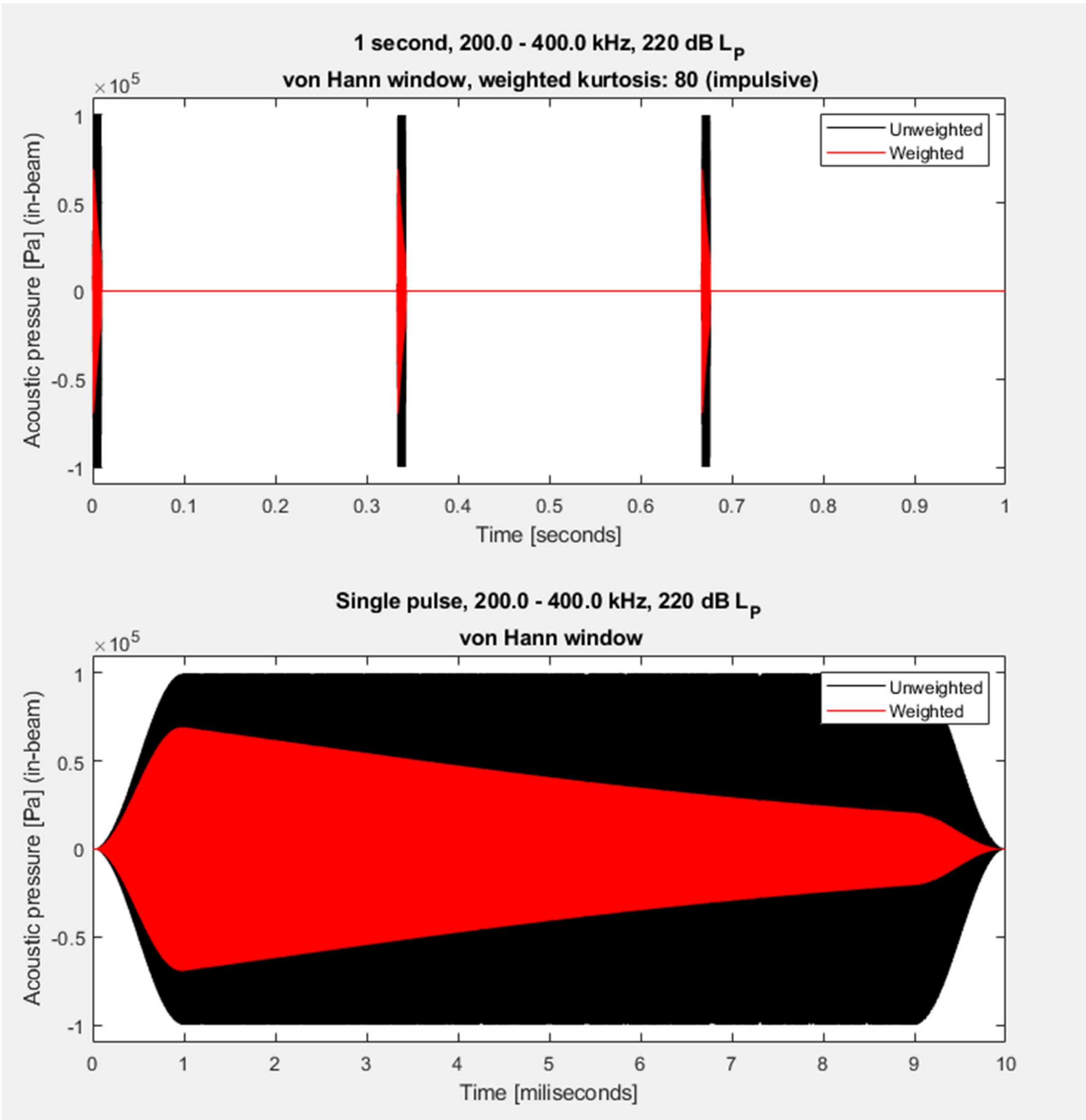


Figure 8-4. Example of a multibeam echosounder at 250 m depth (achieving 3 ping/sec) with a 10 ms ping duration. VHF-weighted kurtosis of 80 – impulsive.

With range, due to multiple reflections and scattering, the kurtosis will decrease with increased range, for shallow water this decrease will be quicker than for deeper water, compare Figure 8-5 & Figure 8-6, where a kurtosis <40 is reached at c. 200 m in 20 m depth, but at over 1000 m at 200 m depth.

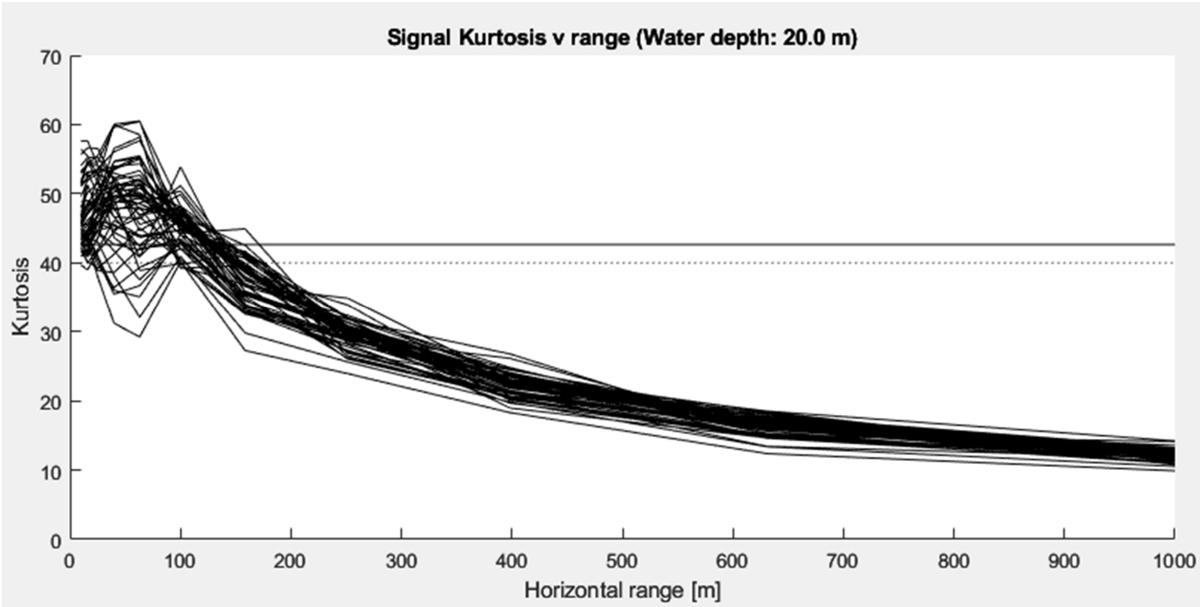


Figure 8-5. Example of USBL signal kurtosis decreasing with range at 20 m depth. Multiple lines are various combinations of source and receiver depths.

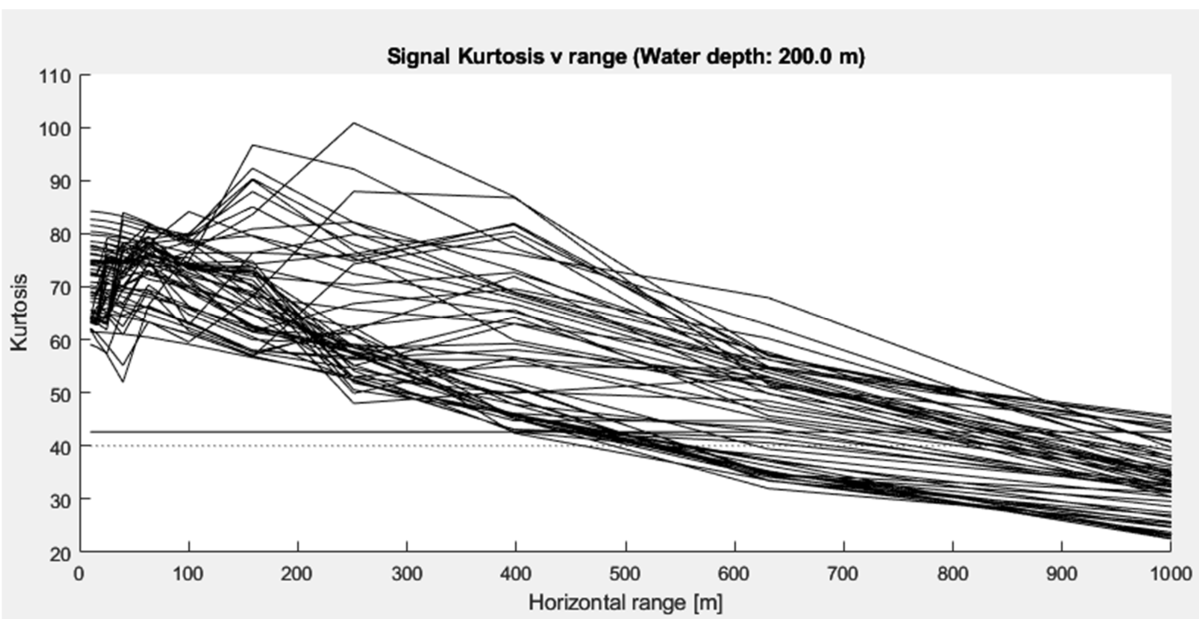


Figure 8-6. Example of USBL signal kurtosis decreasing with range at 200 m depth. Multiple lines are various combinations of source and receiver depths.

Review of Sound Propagation Concepts

Increasing the distance from the sound source usually results in the level of sound getting lower, due primarily to the spreading of the sound energy with distance, analogous to the way in which the ripples in a pond spread after a stone has been thrown in.

The way that the sound spreads will depend upon several factors such as water column depth, pressure, temperature gradients, salinity, as well as water surface and seabed conditions. Thus, even for a given locality, there are temporal variations to the way that sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source, with no boundaries) or a cylindrical pattern (much further from the source, bounded by the surface and the sediment), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases.

In acoustically shallow waters[11] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh and Lysanov 2003, Kinsler et al., 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound is reflected many times by the surface and sediment.

At the sea surface, the majority of sound is reflected back into the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, scattering of sound at the surface of the sea is an important factor with respect to the propagation of sound from a source. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound wave energy will be reflected back into the sea. However, for rough waters, much of the sound energy is scattered (Eckart, 1953; Fortuin, 1970; Marsh, Schulkin, and Kneale, 1961; Urick and Hoover, 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or fish or due to suspended solids in the water such as particulates and marine life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex. Generally, the scattering effect at a particular frequency depends on the physical size of the roughness in relation to the wavelength of the frequency of interest.

As surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the source sound and in acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the water surface smoothness/wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. Depending upon variations in the aforementioned factors, significant scattering could occur at sea state 3 or more for higher frequencies (e.g. 15 kHz or more). It should be noted that variations in propagation due to scattering will vary temporally (primarily due to different sea-states/wind speeds at different times) and that more sheltered areas (which are more likely to experience calmer waters) could experience surface scattering to a lesser extent, and less frequently, than less sheltered areas which are likely to encounter rougher waters. However, over shorter ranges (e.g. within 10-20 times

[11] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and seabed (Etter, 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the sound speed gradient, water depth, sediment type, frequency of the sound and distance between the source and receiver.

the water depth) the sound will experience fewer reflections and so the effect of scattering should not be significant. Consequently, over the likely distances over which injury will occur, this effect is unlikely to significantly affect the injury ranges presented in this report, and not including this effect will overestimate the impact.

When sound waves encounter the seabed, the amount of sound reflected will depend on the geoacoustic properties of the seabed (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle (see Figure 8-7[12]) and frequency of the sound (Cole, 1965; Hamilton, 1970; Mackenzie, 1960; McKinney and Anderson, 1964; Etter, 2013; Lurton, 2002; Urick, 1983). Thus, seabeds comprising primarily of mud or other acoustically soft sediment will reflect less sound than acoustically harder seabeds such as rock or sand. This effect also depends on the profile of the seabed (e.g. the depth of the sediment layers and how the geoacoustic properties vary with depth below the sea floor). The sediment interaction is less pronounced at higher frequencies (a few kHz and above) where interaction is primarily with the top few cm of the sediment (related to the wavelength). A scattering effect (similar to that which occurs at the surface) also occurs at the seabed (Essen, 1994; Greaves and Stephen, 2003; McKinney and Anderson, 1964; Kuo, 1992), particularly on rough substrates (e.g. pebbles and larger).

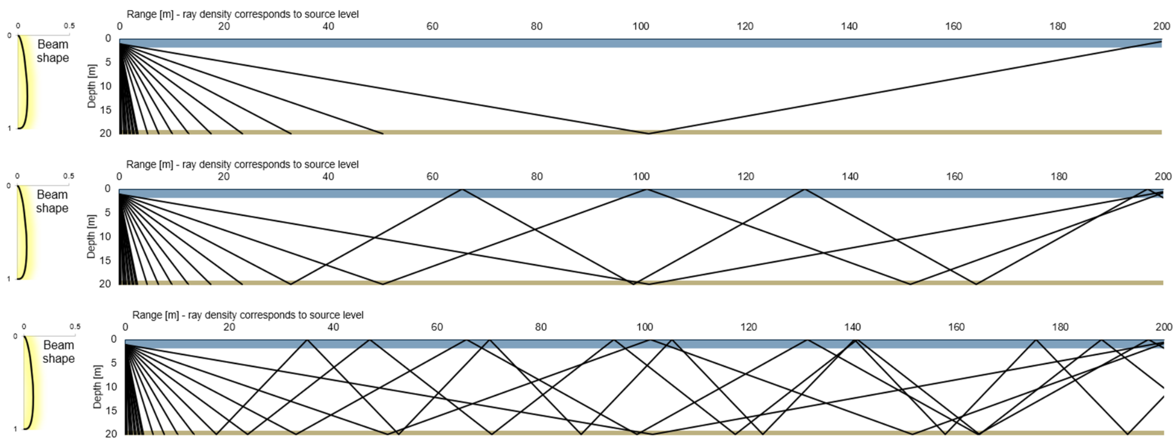


Figure 8-7: Schematic of the effect of sediment on sources with narrow beams. Sediments range from fine silt (top panel), sand (middle panel), and gravel (lower panel).

These sediment effects mean that the directivity of equipment such as sub-bottom profilers have a profound effect on the effective source level – the apparent source level to a far-away receiver.

[12] The density of “rays” indicate difference in effective propagation angle from the source, with acoustically harder sediments (gravel) having better reflection at steeper angles leading to more “rays” being effectively propagated (no significant bottom attenuation) in the waveguide. Beam shape indicated in left chart, with the black line showing the same received level.

A parametric SBP such as the "Innomar Medium" or "Standard" sub-bottom profiler use two higher frequencies ("primary frequencies") to generate an interference pattern at lower frequencies ("secondary frequencies"). This means that the secondary beam can be made extraordinarily narrow, e.g. 5 degrees at -10 dB (Figure 8-8), versus c. 50 degrees for a chirper/pinger type, leading to a much smaller sound impact – even when a parametric sub-bottom profiler has higher sound output within the main beam. We account for these differences in beam pattern by including the sediment reflection loss at high incidence angles (Figure 8-7) to reduce the effective source level accordingly.

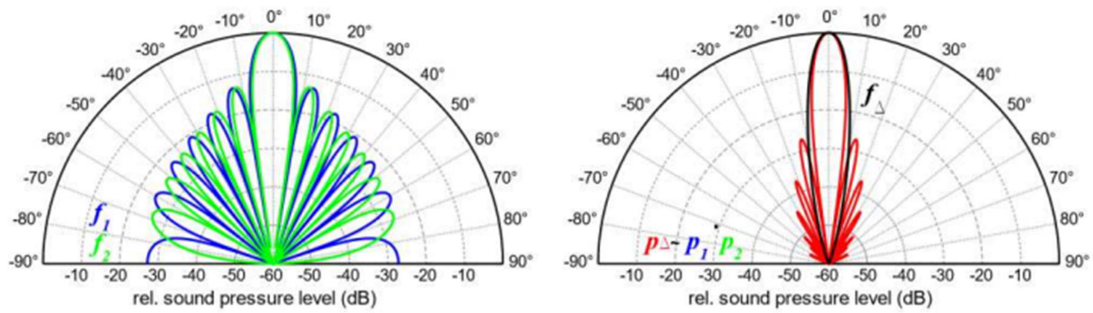


Figure 8-8. Example of a beam pattern on an Innomar SES 2000. Primary frequencies left (f1 & f2), the interference pattern between the primary frequencies means that the beam pattern for the secondary frequency (right plot) is very narrow (Source: Innomar technical note TN-01).

Another phenomenon is the waveguide effect which means that shallow water columns do not allow the propagation of low frequency sound (Urick, 1983; Etter, 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties. Any sound below this frequency will not propagate far due to energy losses through multiple reflections. The cut-off frequency as a function of water depth is shown in Figure 8-9 for a range of seabed types. Thus, for a water depth of 10m (i.e. shallow waters typical of coastal areas and estuaries) the cut-off frequency would be approximately 70Hz for sand, 115Hz for silt, 155Hz for clay and 10Hz for bedrock.

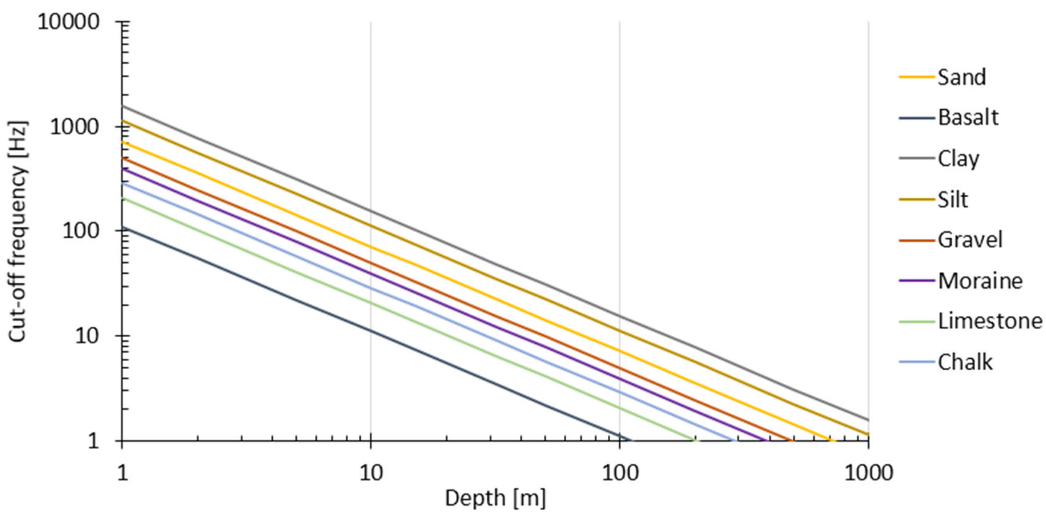


Figure 8-9: Lower cut-off frequency as a function of depth for a range of seabed types.

Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for high-frequency sound. Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel but, for example, a 25m thick layer would not act as a duct for frequencies below 1.5 kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

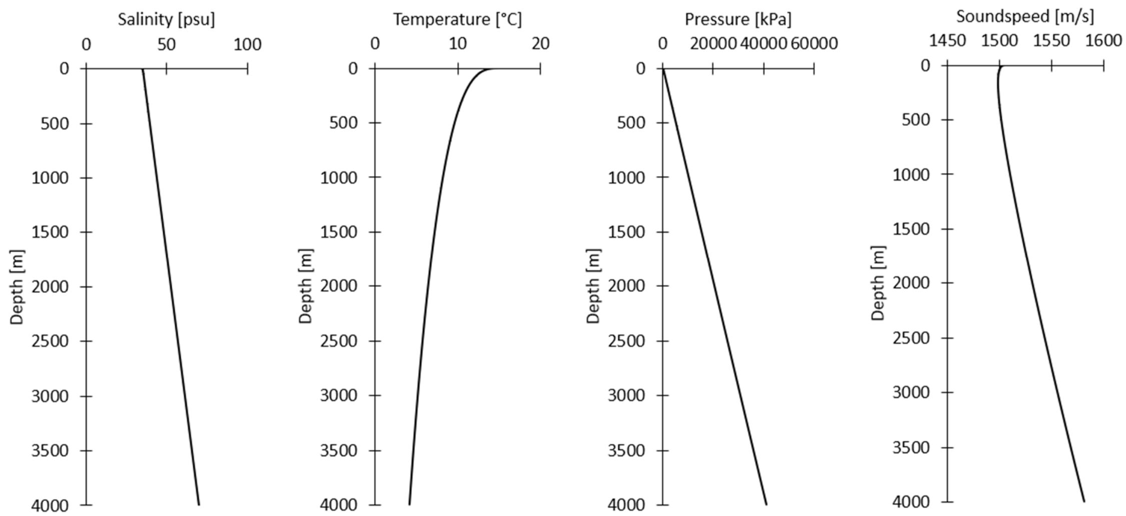


Figure 8-10: Soundspeed profile as a function of salinity, temperature and pressure.

Wind can make a significant difference to the soundspeed in the uppermost layers as the introductions of bubbles decreases the soundspeed and refracts (bends) the sound towards the surface, where the increased roughness and bubbles from the wind will cause increased transmission loss.

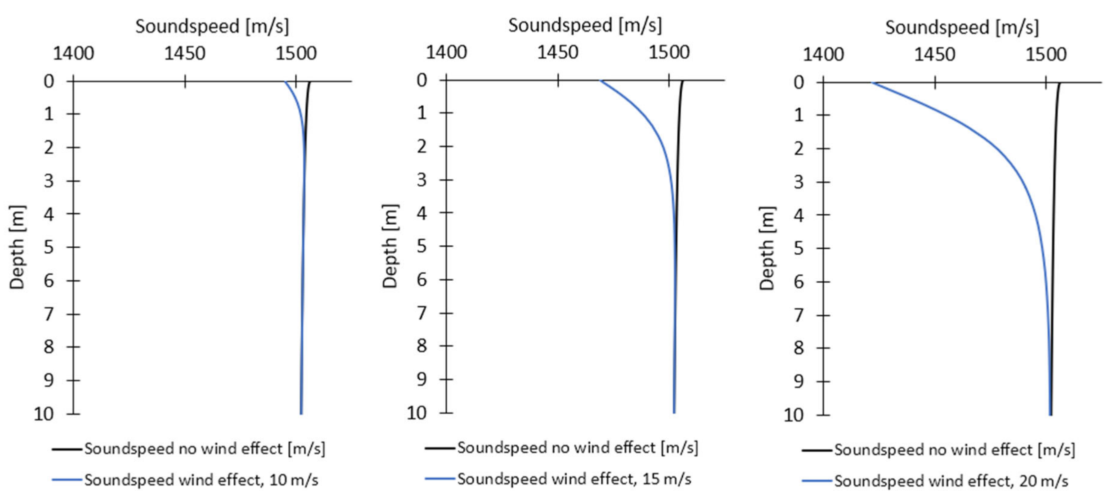


Figure 8-11: Effect of wind (at 10 m height) on upper portion of soundspeed profile.

Sound energy can also be absorbed due to interactions at the molecular level converting the acoustic energy into heat. This is another frequency dependent effect with higher frequencies experiencing much higher losses than lower frequencies. This is shown in Figure 8-12 where the variation of the absorption (sometimes called volume attenuation) is shown for various salinities and temperatures. As the effect is proportional to the wavelength, colder water, with slower soundspeed/period and being slightly more viscous, will have more absorption. Higher salinity slightly decreases absorption at low frequencies (mostly due to increase in soundspeed and wavelength/period), but much higher absorption at higher frequencies where interaction with pressure sensitive molecules of magnesium sulphite and boric acid increase the conversion acoustic energy to heat.

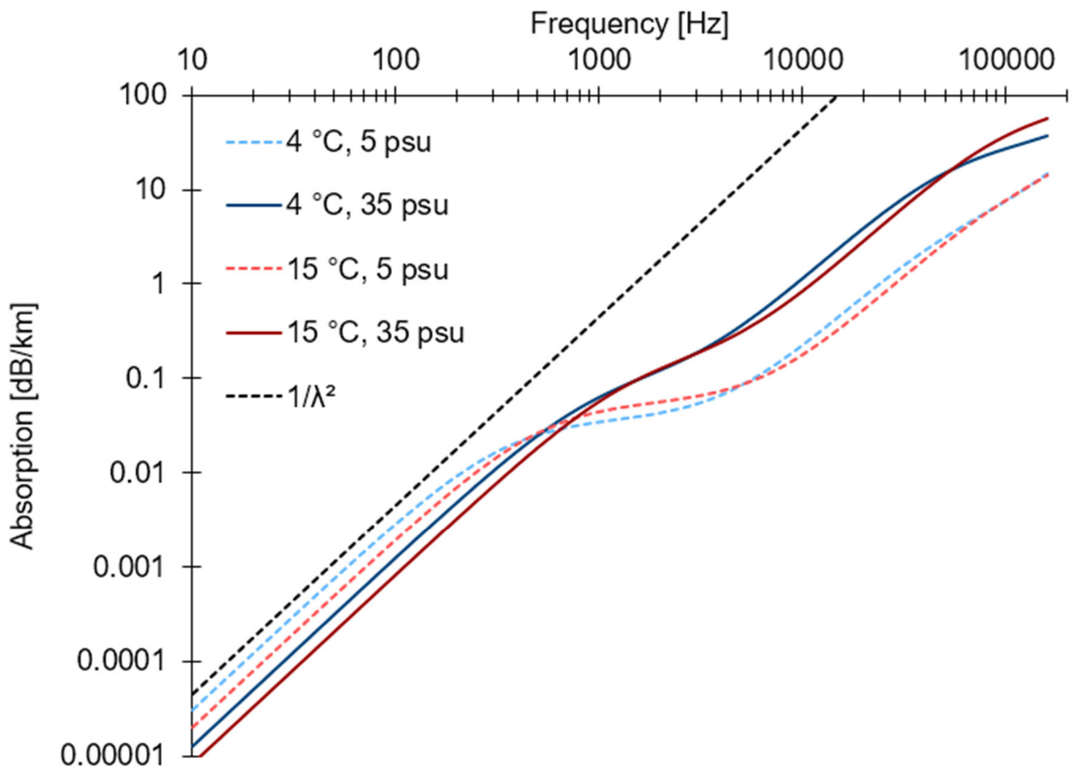


Figure 8-12: Absorption loss coefficient (dB/km) for various salinities and temperature.

Appendix B – Weston Propagation Model Validation

The Weston 1971-1976 sound propagation model was first published in 1971 as “Intensity-Range Relations in Oceanographic Acoustics” by D. E. Weston in the Journal of Sound and Vibration, with an update in 1976 as “Propagation in Water With Uniform Sound Velocity but Variable-Depth Lossy Bottom” by D.E. Weston in the Journal of Sound and Vibration.

The model presents a pragmatic approach to sound propagation modelling by splitting propagation into four distinct regions dependent on the given range, water depth and wavelength, and has be made range-dependent for both depth, soundspeed and sediment properties.

This appendix presents a few testcases with known solutions compared to this implementation of the Weston propagation model.

Comparison to normal modes, ray-tracing and parabolic equation models

Source:

Sertlek H. Ö. & Ainslie M. A (2003), “Propagation loss model comparisons on selected scenarios from the Weston memorial workshop”. 1st International Conference and Exhibition on Underwater Acoustics.

Case 1

Depth 100 m, max range 40 km.

This is a simple semi-deep waveguide which might be considered representative for parts of the continental shelf.

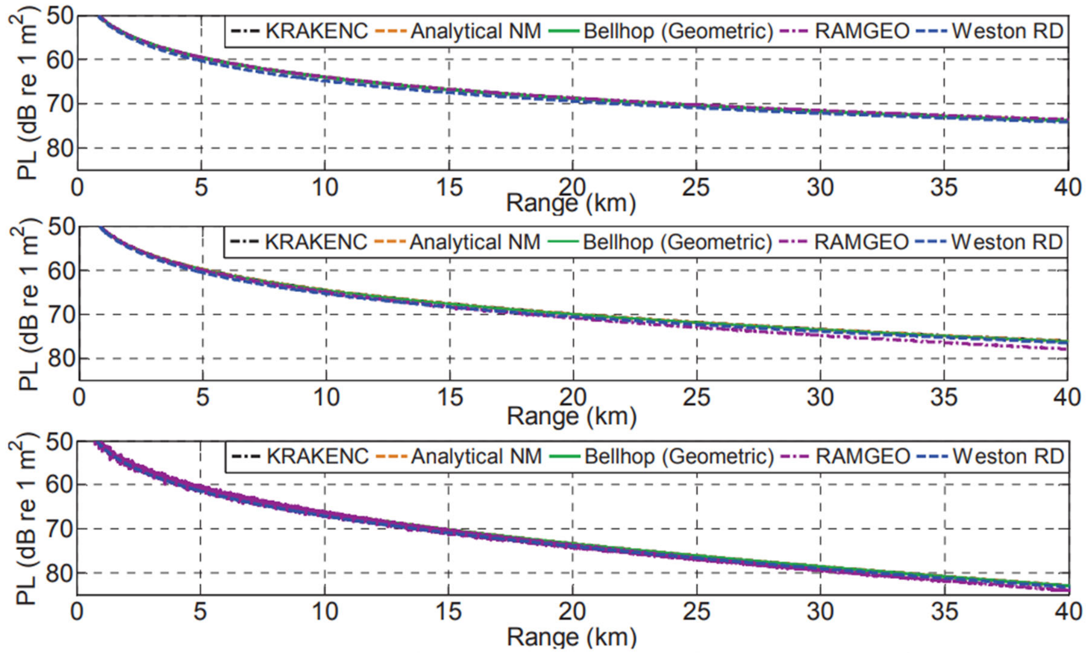


Figure 5. Depth-averaged (over receiver depth)PL vs range for Case 1 (f=250 Hz (top), f=1 kHz (middle), f=3.5 kHz (bottom)). Source depth = 30 m.

Case 2

Depth 100 m to 5 km then sloping up to 30 m at 7 km. Remaining at 30 m depth to 40 km range.

The step up at 5 km range tests the models' ability to calculate the effect of slowly changing depths in an upslope environment. Note that for 250 Hz (top panel in figure below) the Weston model underestimates the loss after c. 20 km, leading to a higher received level. The ray-tracer (Bellhop) shows the same result. This is expected as the Weston model relies on approximations made from ray-theory to specify the transitions between propagation regions.

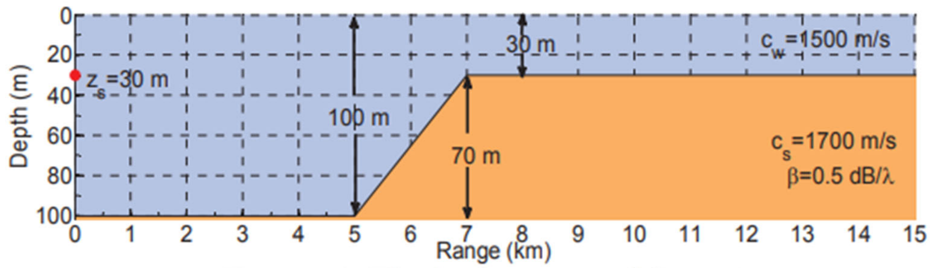


Figure 6. The bathymetry of Case 4

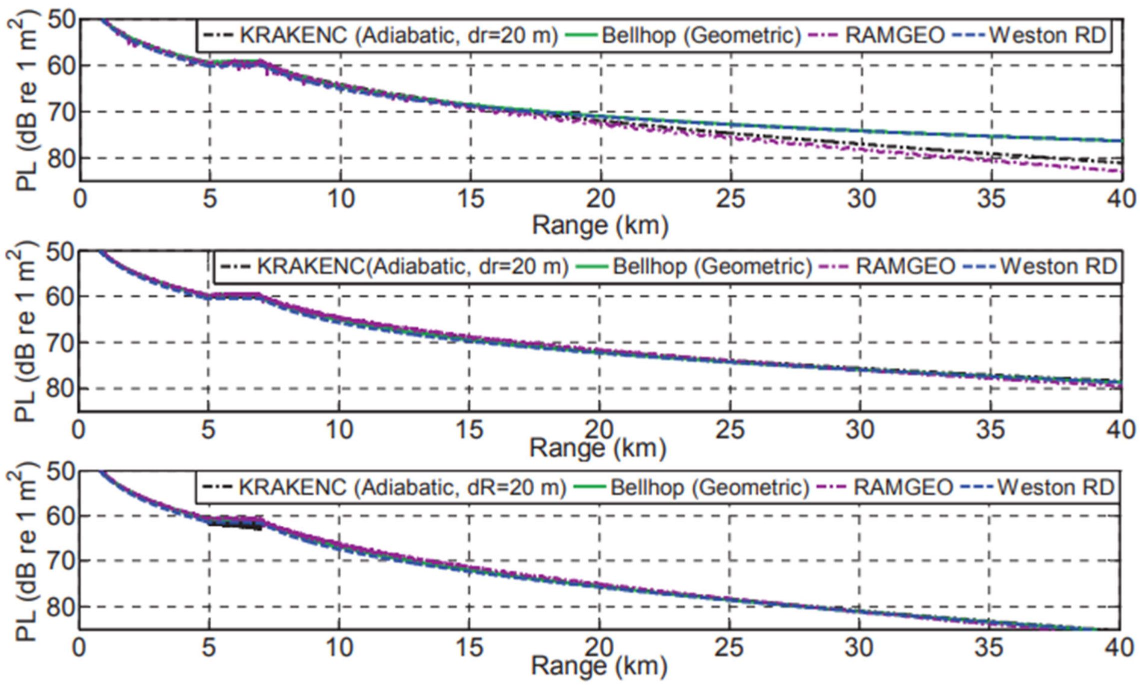


Figure 7. Depth-averaged (over receiver depth)PL vs range for Case 4 (f=250 Hz (top), f=1 kHz (middle), f=3.5 kHz (bottom)). Source depth = 30 m.

Case 3

Depth 100 m to 5 km, then sloping up to 30 m at 7 km. Remaining at 30 m depth to 7 km, then sloping down to 100 m depth at 10 km.

The “bump” scenario represents a shallow bank between two deeper sections. It tests the models’ ability to transition between different regions of propagation. There is excellent agreement between the Weston model and the numerical models.

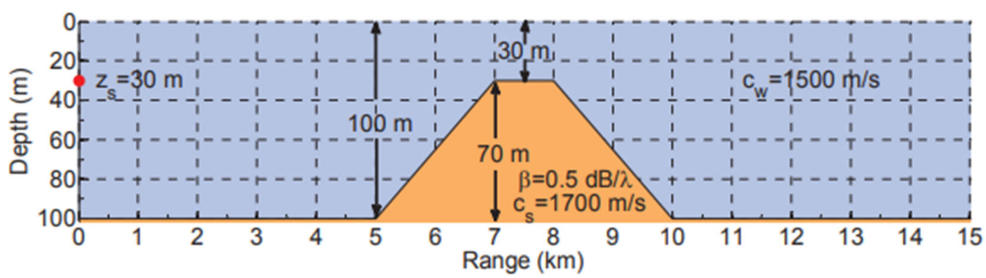


Figure 8. The bathymetry of Case 9

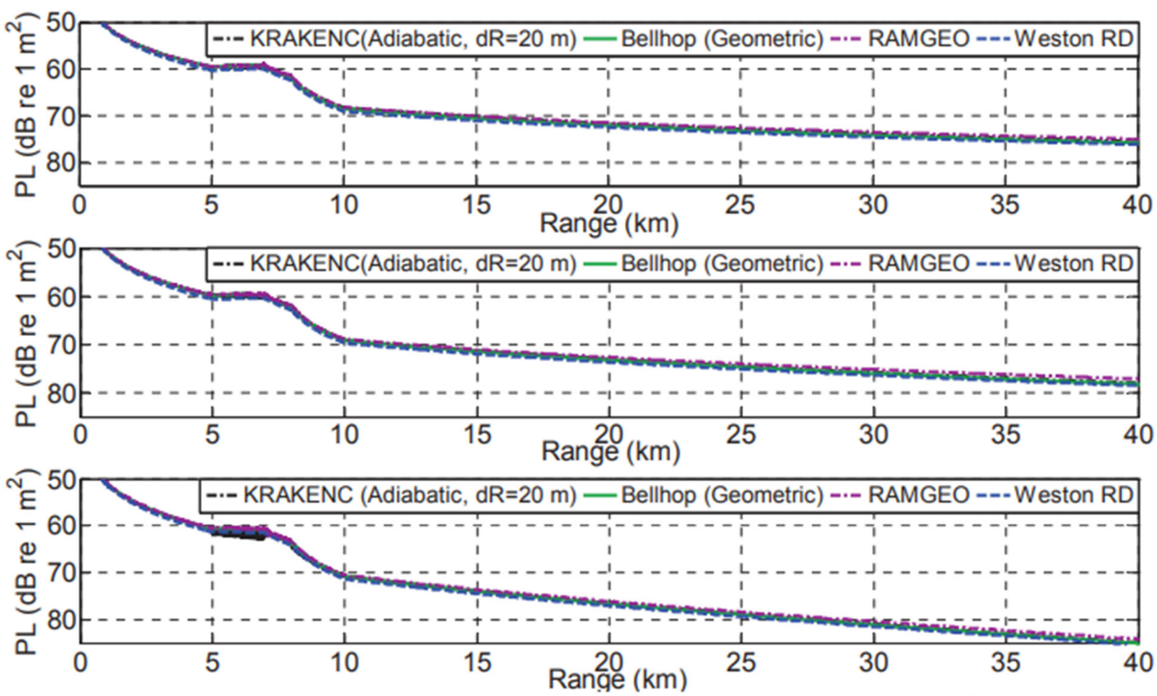


Figure 9. Depth-averaged (over receiver depth) PL vs range for Case9 (f=250 Hz (top), f=1 kHz (middle), f=3.5 kHz (bottom)). Source depth = 30 m.

Broadband comparison with various commercial models

Source:

Bas Binnerts, Christ de Jong, Ilkka Karasalo, Martin Östberg, Thomas Folegot, Dominique Clorennec, Michael A. Ainslie, Graham Warner, Lian Wang (2109), "Model Benchmarking Results For Ship Noise In Shallow Water", JOMOPANS.

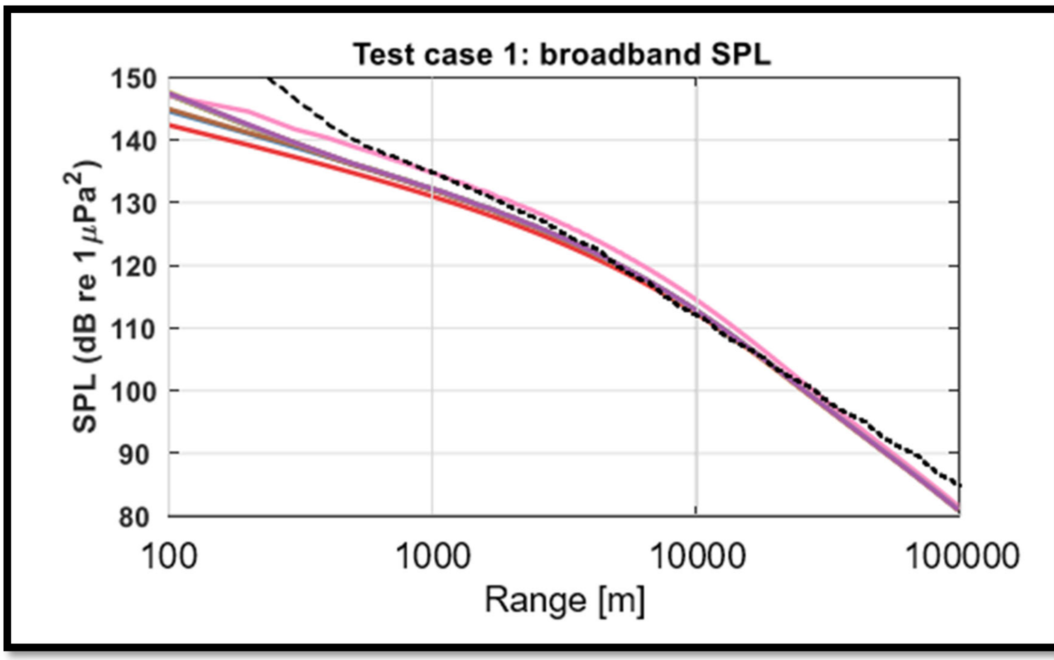
Two cases are investigated, both with a vessel source model used as the source and from 10 Hz to 20 kHz.

Case 1

50 m depth to 100 km range.

Broadband levels versus range

The Weston model matches the general losses well at ranges over c. 500 m.



Case 2

100 m depth to 5 km, then upslope to 30 m depth at 7 km. Remaining at 30 m depth to 50 km range.

Broadband levels versus range

The Weston model matches the general losses well at ranges over c. 500 m.