C2 - Restricted

CP1146 CARRICKMINES TO POOLBEG PROJECT

Subsea Noise Technical Report

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Glossary

Term	Meaning
Decibel (dB)	A relative scale most commonly used for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10 \cdot \log_{10}$(“actual”/”reference”), where (“actual”/”reference”) is a power ratio. The standard reference for underwater sound pressure is 1 micro-Pascal (μPa), while 20 micro-Pascals is the standard for airborne sound. The dB symbol is often followed by a second symbol identifying the specific reference value (i.e. re 1 μPa).
Grazing angle	A glancing angle of incidence (the angle between a ray incident on a surface and the line perpendicular to the surface).
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear and thus, a permanent reduction of hearing acuity.
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.
Sound Exposure Level (SEL)	The cumulative sound energy in an event, formally: “ten times the base-ten logarithm of the integral of the squared pressures divided by the reference pressure squared”. Equal to the often seen “L_E” or “dB SEL” quantity. Defined in: ISO 18405:2017, 3.2.1.5
Sound Pressure level (SPL)	The average sound energy over a specified period of time, formally: “ten times the base-ten logarithm of the arithmetic mean of the squared pressures divided by the squared reference pressure”. Equal to the deprecated “RMS level”, “dB_{rms}” and to L_{eq} if the period is equal to the whole duration of an event. Defined in ISO 18405:2017, 3.2.1.1
Peak Level, Peak Pressure Level (L_P)	The maximal sound pressure level of an event, formally: “ten times the base-ten logarithm of the maximal squared pressure divided by the reference pressure squared” or “twenty times the base-ten logarithm of the peak sound pressure divided by the reference pressure, where the peak sound pressure is the maximal deviation from ambient pressure”. Defined in ISO 18405:2017, 3.2.2.1
Source Level (SL)	Taken here to mean the level (SEL/SPL/L_P) at 1 meter range. If not otherwise stated, it is assumed the source is omnidirectional (equal level in all directions). For sources larger than 1 m in radius, the Source Level is back-calculated to 1 m.
Decidecade	Used to refer to a step in frequency, similar to “one-third-octave”, defined as a ratio of $10^{0.1} \approx 1.259$ (one third octave is 21/3 ≈ 1.260). Used interchangeably with “3rd octave”.
Noise	Sound that is irrelevant, unwanted or harmful to the organism(s) in question. Noise is often detrimental, but not necessarily so.
Kurtosis	A statistical measure of “peakedness” of a distribution (of e.g. pressure values in a sound pulse). Defined in ISO 5479:1997

Acronyms

Term	Meaning
ADD	Acoustic Deterrent Device
ADCP	Acoustic Doppler Current Profiler
LF	Low Frequency (Cetaceans)
HF	High Frequency (Cetaceans)
VHF	Very High Frequency (Cetaceans)
MF	Mid Frequency (Cetaceans) – **DEPRECATED** only for reference to NOAA/NMFS 2018 groups
OW/OCW	Otariid pinnipeds/Other Carnivores in water (refers to the same weighting and animal groups)
PW/PCW	Phocid pinnipeds
NMFS	National Marine Fisheries Service
RMS	Root Mean Square
SEL	Sound Exposure Level, [dB]
SPL	Sound Pressure Level, [dB]
L_P	Peak Pressure Level, [dB]
SL	Source Level [dB]
TTS	Temporary Threshold Shift
PTS	Permanent Threshold Shift
SSS	Side Scan Sonar – Towed sonar device typically positioned 10-15 m above the sediment. Its main purpose is to characterise the sediment surface texture.
MBES	Multibeam Echosounder – Uses multiple narrow beams to measure the depth across a swath below the vessel.
SBP	Sub-Bottom Profiler – Any device/system that uses acoustics to record echoes from within the sediment. Examples include seismic arrays, sparkers, boomers, chirpers, pingers and associated recorder array.
USBL	Ultra Short Baseline Array – Small array of at least 4 hydrophones and a pinger to measure positions of equipment under water.
UHRS	Ultra High-Resolution Seismic survey – Usually a sparker driven sub-bottom characterisation system.
c.	Circa, i.e., approximately
CPT	Cone Penetration Testing – insertion/pushing of rod with standardised, cone-shaped front into sediment to measure various characteristics of the sediment.

Units

Unit	Description
dB	Decibel (Sound)
Hz	Hertz (Frequency)
kHz	Kilohertz (Frequency)
kJ	Kilojoule (Energy)
km	Kilometre (Distance)
km^2	Kilometre squared (Area)
m	Metre
ms	Millisecond (10^{-3} seconds) (Time)
ms^{-1} or m/s	Metres per second (Velocity or speed)
kn	Knots (speed), 1 kn = 0.514 m/s, 1 m/s = 1.944 kn
µPa	Micro Pascal
Pa	Pascal (Pressure: newton/m^2)
psu	Practical Salinity Units (parts per thousand of equivalent salt in seawater, weight-based)
kg/m^3	Specific density (of water, sediment or air)
Z	Acoustic impedance [$kg/(m^2 \cdot s)$ or $(Pa \cdot s)/m^3$]

Units will generally be enclosed in square brackets e.g.: “[m/s]”

1 INTRODUCTION

The CP1146 Carrickmines to Poolbeg project is a proposed new underground electricity cable from the Carrickmines 220 kV substation to the Poolbeg 220 kV substation and includes a section of marine cable. The marine section is located between Blackrock Park and Shelley Banks car-park on the Poolbeg peninsula, Co. Dublin

This Subsea Noise Technical Report presents the results of a desktop study considering the potential effects of underwater noise on the marine environment from the proposed geophysical and geotechnical surveys in Dublin Bay (hereafter referred to as “SI Works”) for the CP1146 Carrickmines to Poolbeg project. The other surveys to be undertaken as part of the SI Works, have not been modelled as they will either not result in underwater noise or will not have any appreciable effect on receptors, e.g. the metocean device (ADCP) operates at frequencies well above the hearing ranges of sensitive receptors.

The aim of the SI Works is to acquire data to a high quality and specification for the site. The SI Works covers an area of 2101 Ha within Dublin Bay between the south side of the Poolbeg peninsula and Dun Laoghaire West Pier. The sediment within the survey area is mostly silty to sandy and water properties in the area are relatively stable given the lack of major river outflows and a modest tidal range. Geophysical and geotechnical surveys such as those proposed for the SI Works use equipment that generate loud and potentially injurious noise to marine life.

Sound is readily transmitted in the underwater environment and there is potential for the sound emissions from anthropogenic sources to adversely affect marine life such as marine mammals or fish. At close ranges from a noise source with high noise levels, permanent or temporary hearing damage 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 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 SI Works on the surrounding marine environment based on the Southall et al. 2019 and Popper et al. 2014 frameworks for assessing impact from noise on marine mammals and fish.

Consequently, the primary purpose of the underwater noise assessment is to predict the likely range of onset for potential physiological and behavioural effects due to increased anthropogenic noise as a result of the SI Works.

1.1 Statement of Authority

[redacted] is a Senior Project Scientist with RPS. He holds a master’s degree in biology, biosonar and marine mammal hearing from University of Southern Denmark. [redacted] has over 11 years’ experience as a marine biologist and over 9 years’ experience with underwater noise modelling and marine noise impact assessments. [redacted] has co-developed commercially available underwater noise modelling software, as well developed multiple source models for e.g. impact piling, seismic airgun arrays and sonars.

[redacted] is an 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 Technical Director in the Environmental Services Business Unit in RPS. He has over 24 years’ experience. He holds an honours degree in Civil Engineering (B.E.) from NUI, Galway, a postgraduate diploma in Environmental Sustainability from NUI, Galway, and a Master’s in Business Studies from the Irish Management Institute/ UCC.[redacted] is also a Chartered Engineer and Project Management Professional with the Project Management Institute (PMI-PMP). He has managed the delivery of numerous environmental projects including marine and terrestrial projects that have required environmental impact assessment, appropriate assessment, and Annex IV species reports.

2 ASSESSMENT 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*).

  * 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). 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[1] of 40 (Martin, et al., 2020). See examples in Appendix A, Impulsiveness.

  This latter criterion 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 Southall et al. 2019 and the Popper et al. 2014 framework limits are based on the narrower definition of impulsive as given in “Impulsive sounds” above.

There is scope for some sounds to be classified as both impulsive and non-impulsive, depending on the criteria applied. 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[2] rising 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.

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 (here kurtosis <40 is used) (Appendix A, Impulsiveness). This range is established using raytracing, but as the effect varies with exact depth and range of source and receiver, the transition range to non-impulsive used for exposure modelling is doubled from the modelled range where kurtosis goes below 40.

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).

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

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

2.2 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 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[3].
- **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).
- **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).
- **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 Permanent Threshold Shift (PTS). 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 (PTS) 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.

2.2.1 Irish Guidance Interpretation

We note that the DAHG “Guidance to Manage the Risk to Marine Mammals from Man-made Sound Sources in Irish Waters” 2014 (Department of Arts, Heritage and the Gealtacht, 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[4]. However, the guidance goes on to specify the use of thresholds from a 2007 publication (Brandon L. Southall, 2007) which has since been superseded (by (Southall, et al., 2019)) and no longer represents best available science, nor reflects best practice internationally. Thus, the following excerpt from the guidance is relevant:

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[3] 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.

[4] 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

"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, but the guidance clearly states intent, we have applied the latest guidance, reflecting the current best available method for assessing impact from noise on marine mammals.

2.3 Thresholds for Marine mammals

The zone of injury in this study is classified as the distance over which a fleeing marine mammal can suffer PTS leading to non-reversible auditory injury. Injury thresholds are based on a dual criteria approach using both un-weighted L_P (maximal instantaneous SPL) and marine mammal hearing weighted SEL. The hearing weighting function is 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*).
- **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. This group is only represented in the NOAA guidelines.

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 SI Works survey area, but all hearing groups are presented in this report for completeness.

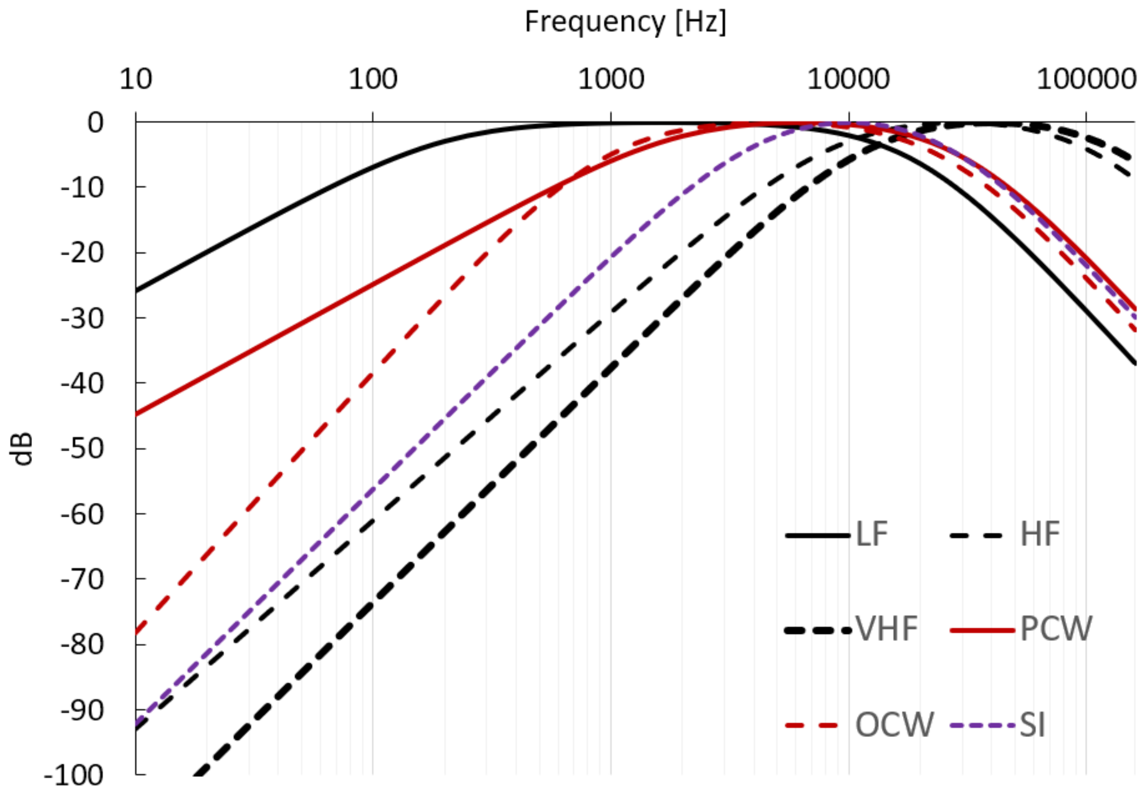

Figure 2-1: Auditory weighting functions for seals, whales and sirenians (NMFS, 2018; Southall et al. 2019)

Both the criteria for impulsive and non-impulsive sound are relevant for this study given the nature of the sound sources used during the SI Works. The relevant PTS and TTS criteria proposed by Southall *et al*. (2019) are summarised in Table 2-1.

Table 2-1: PTS and TTS onset acoustic thresholds (Southall *et al., 2019*; Tables 6 and 7)

Hearing Group	Parameter	Impulsive [dB]		Non-impulsive [dB]	
		PTS	TTS	PTS	TTS
Low frequency (LF) cetaceans	L_P, (unweighted)	219	213	-	-
	SEL, (LF weighted)	183	168	199	179
High frequency (HF) cetaceans	L_P, (unweighted)	230	224	-	-
	SEL, (MF weighted)	185	170	198	178
Very high frequency (VHF) cetaceans	L_P, (unweighted)	202	196	-	-
	SEL, (HF weighted)	155	140	173	153
Phocid carnivores in water (PCW)	L_P, (unweighted)	218	212	-	-
	SEL, (PW weighted)	185	170	201	181
Other marine carnivores in water (OCW)	L_P, (unweighted)	232	226	-	-
	SEL, (OW weighted)	203	188	219	199
Sirenians (SI) (NOAA only)	L_P, (unweighted)	226	220	-	-
	SEL, (OW weighted)	190	175	206	186

These updated marine mammal injury criteria were published in March 2019 (Southall, et al., 2019). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document NMFS (2018) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in Table 2-2.

The naming convention used in this report is based upon those set out in Southall *et al*. (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall *et al*. (2019).

Table 2-2: Comparison of Hearing Group Names between NMFS (2018) and Southall *et al.* (2019)

NMFS (2018) hearing group name	Southall *et al*. (2019) hearing group name
Low-frequency cetaceans (LF)	LF
Mid-frequency cetaceans (MF)	HF
High-frequency cetaceans (HF)	VHF
Phocid pinnipeds in water (PW)	PCW
Otariid pinnipeds in water (OW)	OCW
Sirenians (SI)	Not included

2.4 Disturbance to Marine Mammals

Disturbance thresholds for marine mammals are summarised in Table 2-3. Note that the non-impulsive threshold can often be lower than ambient noise for coastal waters with some human activity, meaning that ranges determined using this limit will tend to be higher than actual ranges. However, the levels are unweighted and ranges to threshold will be dominated by low-frequency sound, which for most hearing groups is outside their hearing range. For hearing groups with low thresholds this can mean that their range to TTS/PTS is *larger* than the range to the behavioural threshold, e.g., the PTS threshold for impulsive sound for the VHS group is 155 dB SEL, while the behavioural threshold is 160 dB SPL. For a typical scenario, for 1 second’s exposure (SEL equals SPL for 1-second durations) that means the range to the behavioural threshold will be approximately twice the range to the PTS threshold (a difference of 5 dB). This is just one of the reasons why this behavioural threshold should be interpreted with caution.

Table 2-3: Disturbance Criteria for Marine Mammals Used in this Study based on Level B harassment of NMFS (National Marine Fisheries Service, 2005)

Effect	Non-Impulsive Threshold	Impulsive Threshold
Disturbance (all marine mammals)	120 dB SPL	160 dB $SEL_{\text{single impulse}}$ or 1-second SEL

2.5 Injury and Disturbance to Fishes

The injury criteria used in this noise assessment are given in Table 2-4 and Table 2-5 for impulsive noises and continuous noise respectively. L_P and SEL criteria presented in the tables are unweighted. 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 (“PTS” 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 PTS 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_P 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_P, the 10th percentile level for behavioural response was 158 dB L_P.

Given the large variations in the data from the two sources above, we have rounded the value to 160 dB L_P as the behavioural threshold for fishes for impulsive sound, and 150 dB SPL for non-impulsive sound.

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 PTS/TTS for impulsive sound & 222/204 PTS/TTS for non-impulsive sound). These lower thresholds also cover “Eggs and Larvae.

Table 2-4: 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 (PTS) [dB]	TTS [dB]	Behavioural [dB]
Fish: no swim bladder (particle motion detection) Example: Sharks.	SEL	219[1]	216[1]	186[1]	150[3]
	L_P	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_P	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_P	207[1]	**207[1]**	**193[2]**	**160[2]**
Sea turtles	SEL	210[1]	(*Near*) High* (*Mid*) Low (*Far*) Low	-	-
	L_P	207[1]		-	-
Eggs and larvae	SEL	210[1]	(*Near*) Moderate (*Mid*) Low (*Far*) Low	-	-
	L_P	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 PTS, TTS, and behaviour are given in Table 2-5. Note that for the behaviour threshold we have used the impulsive threshold as basis for the continuous noise threshold, in absence of better evidence.

Table 2-5: 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	Recoverable injury (PTS) [dB]	TTS [dB]	Behavioural [dB]
All fishes	SEL	(*Near*) Low (*Mid*) Low (*Far*) Low	222†	204†	150 [SPL]*

*Based on the impulsive criteria.

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

3 THE SITE ENVIRONMENT

3.1 SI Works Area of Interest

The SI Works Area of Interest (AoI) and nearby surroundings are characterised by shallow water (c. 14 m at the deepest extents), generally silty to sandy sediment and stable water properties (Figure 3-1).

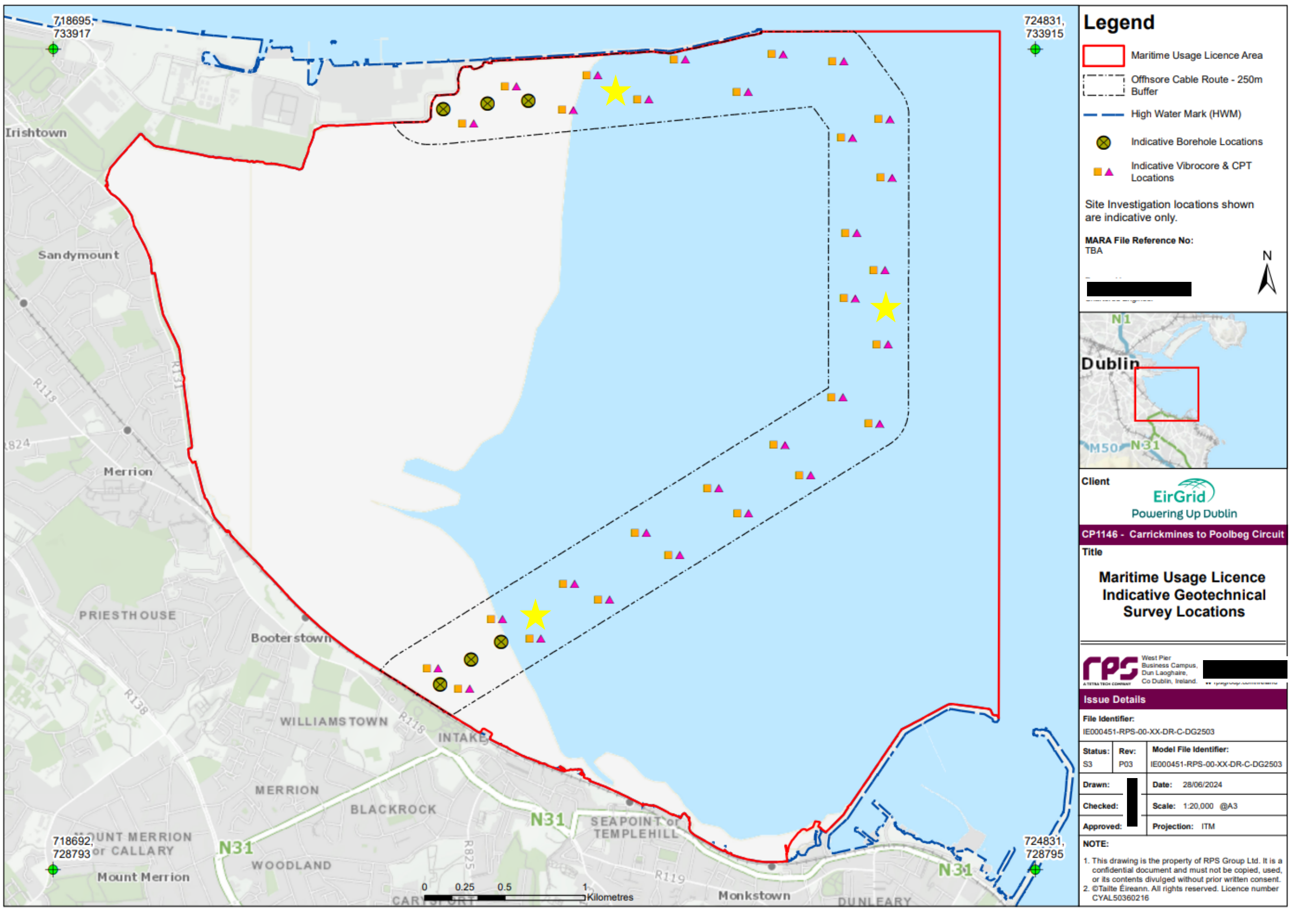

Figure 3-1: Maximal extent of surveys (red line). Indicative cable route (dot-dash line) with indicative locations for boreholes and geotechnical sampling locations. Additionally (yellow stars) are 3 indicative locations for ADCP deployments.

The maximal area to be surveyed is 2101 Ha of depths up to 14 meters (at mean high water springs “MHWS”).

The survey speed is expected to be 4 knots (2.1 m/s), limited by the survey equipment. The survey transects plan is yet to be determined so reasonable worst-case locations throughout the survey area have been used as basis for the modelling rather than a specific survey plan.

3.2 Water Properties

Water properties were determined from historical data for the area. Where a range of values are expected or observed, the value resulting in the lowest transmission loss was chosen for a more conservative assessment (more noise at range). Thus, this also covers seasonal variation.

- Temperature: 18°C – maximal summer temperature given by seatemperature.net for the past seven years for bay Dublin.

- Salinity: 34.5 psu – Measurements in relation to Ringsend Wastewater Treatment Plant Upgrade Project[5]
- Soundspeed profile: Assumed uniform given high mixing as a result of tidal flows and generally shallow water and absence of river outflows.

3.3 Sediment Properties

Sediment properties are based on sediments given in Table 3-1.

Sediment types are informed by the “Folk 7-class Classification” from EMODnet Geology[6] (European Commision, 2024). A sediment model (Ainslie, 2010) was used to derive the acoustic properties of the sediment from the grain size. (Table 3-1).

Table 3-1: Sediment Properties for the two survey areas.

Site	Sediment type (ISO 14688-1:2017)	Density [kg/m³]	Soundspeed [m/s]	Grain size [mm] (nominal)
Outer/deeper part of the Survey area	Medium Silt	1551	1544	0.011
Inner/shallower part of the Survey area	Sand	2123	1801	0.35

[5] “Ringsend WwTP - EIAR modelling services” Figure 5.39 available online (2024/07/11)

[6] https://drive.emodnet-geology.eu/geoserver/gtk/wms

4 SOURCE NOISE LEVELS

Underwater noise sources are usually quantified in dB scale with values generally referenced to 1 µPa pressure amplitude 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 for comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source, this imagined point at 1 m from the acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from an imagined acoustic centre point. Therefore, the stated sound pressure level at 1 m does not occur for large sources. 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 (SL).

4.1 Source Models

The noise sources and activities investigated during this assessment are summarised in Table 4-1.

Note that:

1. The ping rate, and therefore the SPL and SEL of the sound source varies with the local depth.

2. Due to differences in sediment, the angle at which the sediment will tend to reflect sound back into the water column changes. As we use this information to derive practical source levels for highly directional sources, this will change with sediment type (further information below and in Appendix A & Figure 8-7).

3. To account for the shallow depth, and therefore assumed short duration of pulses from Multibeam Echo-Sounder (MBES), Side Scan Sonar (SSS) and pinger/chirper, we have assessed the weighted kurtosis in order to determine impulsiveness (Section 2.1).

Sonars and echosounders generally use tone pulses of either constant frequency or as a frequency sweep. These pulses are typically windowed to limit “spectral leakage[7]”. We assume use of a Von Hann window (sometimes “Hanning”) which gives effective attenuation of frequencies outside the intended frequencies. This means that while a sonar with a centre frequency of 200 kHz is well above the hearing range of any marine mammal, there will be energy at 100 kHz c. 50 dB lower than the source level at 200 kHz. This is accounted for in the assessment. Note that this might contrast with some guidelines, such as the “JNCC guidelines mitigation during geophysical surveys” (JNCC, 2017), which state that “*Multi-beam surveys in shallower waters (<200m) are not subject to these requirements* [mitigation for protection of European Protected Species]”. However, given the fact there is substantial energy outside the nominal frequency range of any echo sounder (see example in Figure 4-1), we have included this energy spread here.

[7] Acoustic phenomenon where a sharp change in pressure produces sound in a wide frequency range (similar to an ideal impulse) outside the intended frequencies.

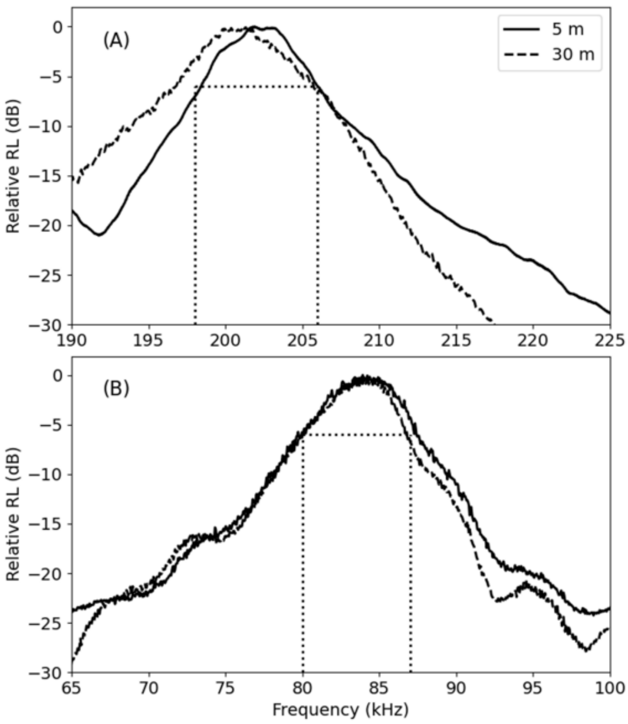

Figure 4. The relative received levels (RLs, in decibels (dB)) of the signals of the acoustic frequency bandwidth of the dual-frequency echosounder used in this study, as observed at two different depths. The dotted lines indicate the −6 dB acoustic bandwidths of 198–206 (**A**) and 80–87 kHz (**B**). The peak frequencies of the two channels were found to be 201.5 (**A**) and 84 kHz (**B**).

Figure 4-1. Example of recorded levels from an echosounder showing significant energy outside the nominal frequencies, necessitating assessment at those frequencies too (Burnham, et al., 2022).

Highly directional sources with narrow beams (sonars and echosounders) will tend to ensonify only a narrow cone of water at any given time. For multibeam echosounders or side scan sonars, the beam(s) sweeps though the water, side to side, to get wider sediment coverage. For this type of sonar, we have converted the source to an omnidirectional source with the same acoustic energy as the original but represented as omnidirectional. This simplifies the calculation process, but yields identical results, and means that we account for the probabilistic nature of an animal being “ensonified” by the source.

For beams only directed vertically down or up, such as sub-bottom profilers or ADCPs, we incorporate the directivity of the beam as well as the ability of the sediment to reflect the sound emitted. This means that we can account for the fact that primarily, a narrow cone directly below/above the source is ensonified with high sound levels and also that a significant attenuation occurs in the sediment where sound enters at steep angles. In practice, we use the angle with the highest level after accounting for directivity combined with sediment loss to a range of 100 m.

Table 4-1: Summary of Sound Sources and Activities Included in the Subsea Noise Assessment

Equipment	Source level [SPL] (as used in model)	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
Survey vessel, Geophysical	161 dB SPL	10-16,000 Hz	Based on <20 m generic survey vessel.	Non-impulsive
Survey vessel, Geotechnical	168 dB SPL	10 – 25,000 Hz	Based on <30 m tug with dynamic positioning system	Non-impulsive
MBES	187 dB SPL (Spherical equivalent level)	200,000-800,000 Hz	Based on Reason SeaBat T50 & R2 Sonic 2024.	Impulsive

Equipment	Source level [SPL] (as used in model)	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
SSS	166 dB SPL (Spherical equivalent level)	100,000-1,000,000 Hz	Generic SSS from 400-1,000 kHz.	Impulsive
USBL	190 dB SPL	18,000-31,500 Hz	Active with non-hull mounted SSS* & during vibro-core operations, 2 Hz ping rate, ping length 10 ms.	Impulsive
SBP-parametric (P-SBP)	204 dB SPL	80,000-150,000 Hz (Primary) 2,000-22,000 Hz (Secondary)	Source level adjusted for sediment effects and beam widths. Based on Innomar Standard, worst-case for shallow water.	Impulsive
SBP-chirper/pinger (C-SBP)	181 dB SPL	2,000-12,000 Hz	Generic shallow water SBP of chirper/pinger type. Source level adjusted for sediment effects and beam widths.	Impulsive
SBP-sparker/UHRS (S-SBP)	184 dB SPL	600 – 6,300 Hz	Based on GeoSource 400. Firing rate of 1 Hz assumed	Impulsive
ADCP (**Not modelled given high frequency**)	114 dB SPL	500,000-1,260,000 Hz	Based on suitable ADCP for depths <100 m (e.g. Nortek AWAC, Teledyne Reason Sentinel, Workhorse or Monitor) Source level adjusted for sediment effects and beam widths.	Impulsive
Drilling/ rotary coring (Boreholes, no USBL)	145 dB SPL	10-500,000 Hz	Based on published levels (Erbe, et al., 2017; Fisheries and Marine Service, 1975; MR, et al., 2010; L-F, et al., 2023)	Non-impulsive
Vibro-coring & CPT	187 dB SPL	50 – 16,000 Hz	Based on levels from previous work & (Reiser, et al., 2010)	Non-impulsive

*If the SSS and SBP are hull-mounted, there is no need for a positioning device (USBL) and this noise source should be removed from consideration.

The ADCP has not been modelled due to its lowest frequency being significantly above the upper frequency limit of hearing of any marine animal. Furthermore, the extremely high frequencies will attenuate rapidly with range, meaning that on top of the spreading loss there will be an additional c. 140 dB/km loss from absorption[8].

In addition to the activities outlined above, there may also be grab sampling. However, this activity has not been modelled given the low noise levels associated with the activity.

[8] See e.g., APPENDIX A, Figure 8-12 or http://resource.npl.co.uk/acoustics/techguides/seaabsorption/ for further information.

All other surveys undertaken in the intertidal area, e.g. environmental walkover surveys, intertidal sampling, etc. have not been included in this assessment as they will not result in underwater noise.

4.1.1 Equipment

This section presents details on each sound source individually. Combined sources, with expected combination of active equipment, are presented in Section 4.1.2.

4.1.1.1 Survey Vessel, Geophysical

A small survey vessel of up to 20 m in length, travelling at 4 knots (equipment limited), has been assessed in this report as this represents the anticipated vessel parameters for the geophysical and geotechnical surveys. Broadband level of the vessel is 161 dB SPL with decidecade band levels given in Figure 4-2 (maximal band level is 150 dB SPL at the 25 Hz band). Smaller vessels will have lower emitted levels and are therefore covered by this assessment.

This vessel is also used as a proxy for a suitable platform for support vessels, representing generic machinery noise.

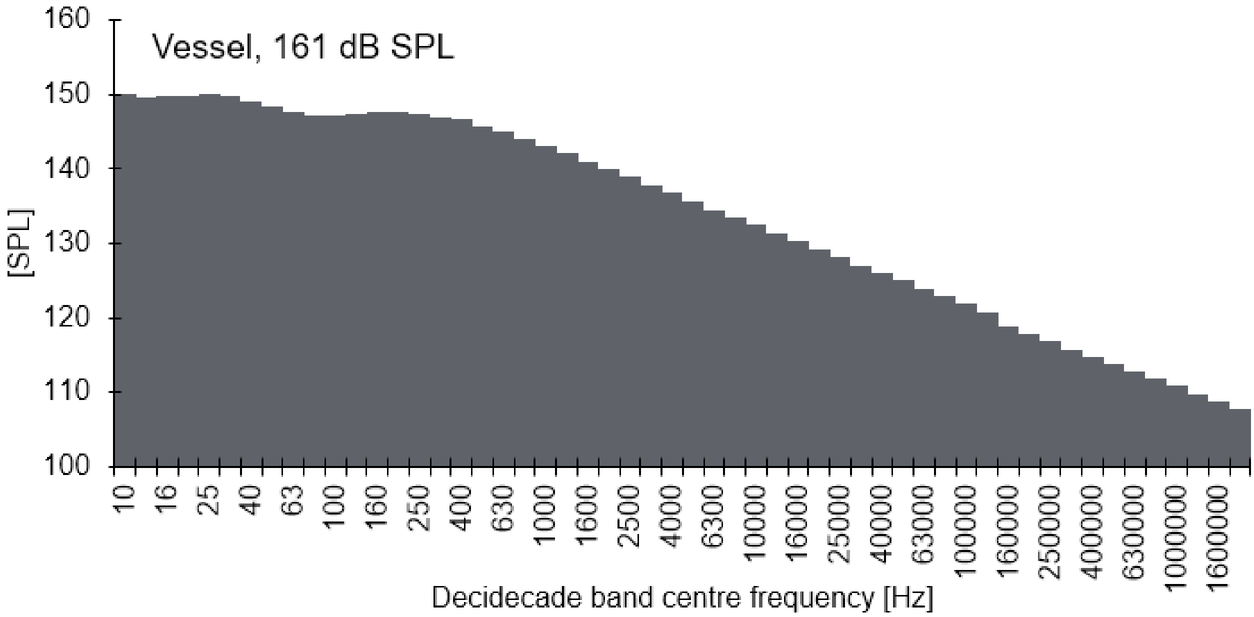

Figure 4-2. Vessel source band levels. Broadband level: 161 dB SPL. Based on generic survey craft at 4 kn.

4.1.1.2 Survey Vessel, Geotechnical

A small survey vessel of up to 30 m in length, travelling at 4 knots transiting to SI locations (equipment limited), has been assessed in this report as this represents the anticipated vessel parameters for carrying out the geotechnical survey. Broadband level of the vessel is 168 dB SPL with decidecade band levels given in Figure 4-2 (maximal band level is 157 dB SPL at the 400 Hz band). Smaller vessels will have lower emitted levels and are therefore covered by this assessment.

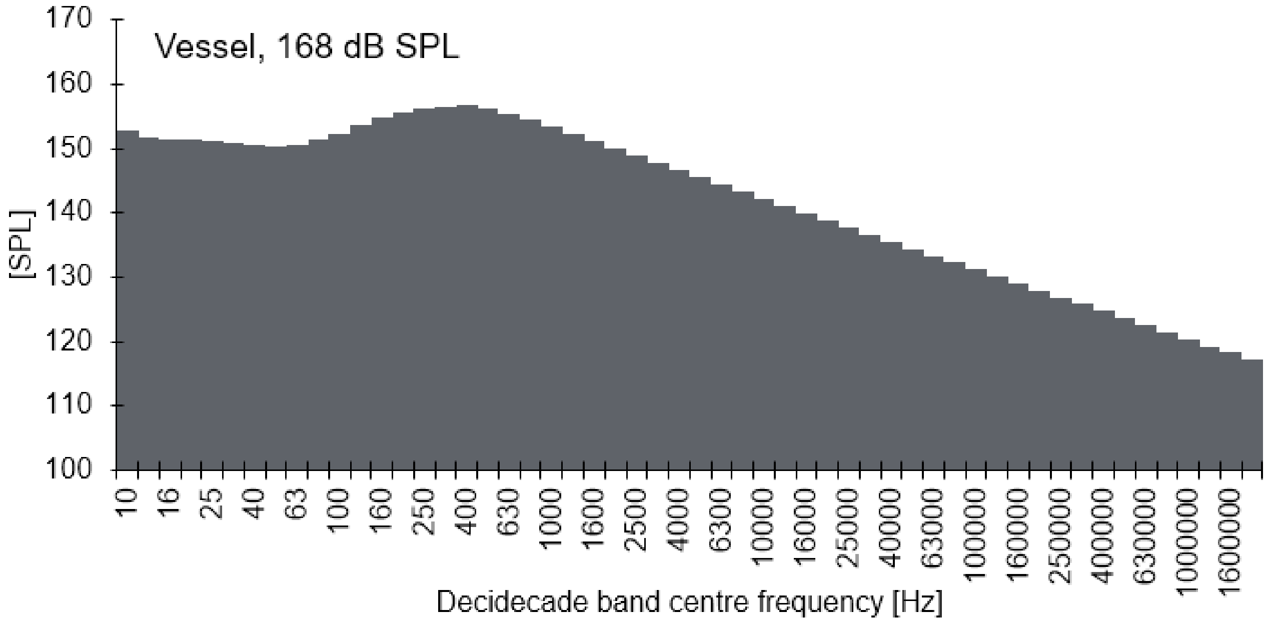

Figure 4-3. Vessel source band levels. Broadband level: 168 dB SPL. Based on generic tug with DP system at 4 kn.

4.1.1.3 Multibeam Echosounder (MBES)

The “Reason SeaBat T50-P”, “R2 Sonic 2024”, or similar shallow water model, is a likely MBES for this survey. Nominal frequencies from 200 kHz to 800 kHz have been modelled. The equivalent spherical level is 187 dB SPL (maximally 179 dB SPL in each band). Band levels are presented in Figure 4-4.

Given the shallow water (<14 m depth), it is likely that shorter pulses will be used as they offer sufficient energy for a clear returning echo. This will increase kurtosis (“impulsiveness”) for realistic ping rates for the depth. Therefore, the MBES is modelled as an impulsive noise source.

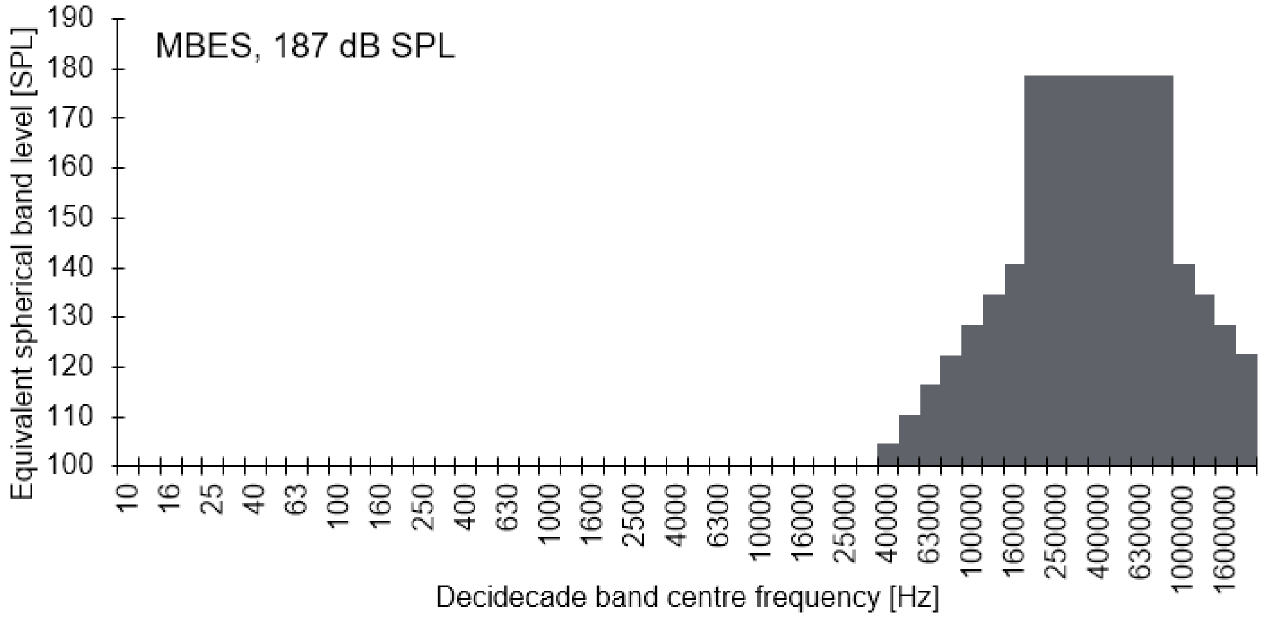

Figure 4-4. MBES source band levels as equivalent spherical/omnidirectional levels.

4.1.1.4 Side Scan Sonar (SSS)

No specific model of side scan sonar (SSS) has been determined for the survey, except for specification of nominal frequencies of 100 – 1,000 kHz. To address this uncertainty, a generic SSS model has been generated from seven commonly used SSS systems (from EdgeTech, C_MAX and Klein Systems). We have used the 90th percentile level as the representative level. The equivalent spherical broadband level is 166 dB SPL (Figure 4-5).

Given the shallow water (<14 m depth), it is likely that shorter pulses will be used as they offer sufficient energy for a clear returning echo. This will increase kurtosis ("impulsiveness") for realistic ping rates for the depth. Therefore, the SSS is modelled as an impulsive noise source.

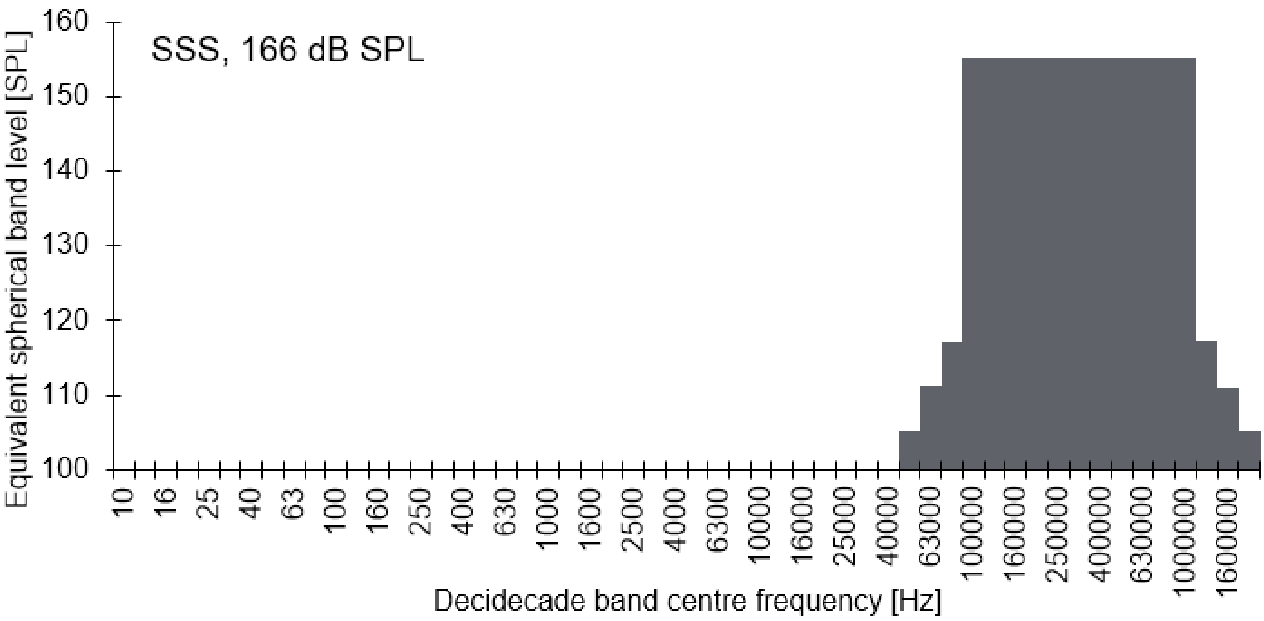

Figure 4-5. SSS source band levels as equivalent spherical/omnidirectional levels.

4.1.1.5 Ultra Short Base-Line positioning system (USBL)

If the SSS or SBP is deployed as a towfish (towed behind the vessel), its accurate positions will need to be known. A USBL positioning system is a common solution. This is also the case for the deployed Vibro-corer units. Here, a generic USBL is used, with a 10 ms pulse length and 2 Hz ping rate, consistent with popular models (Edgetech BATS, IxBlue GAPS, Sonardyne Ranger). A max SPL [L_P] of 210 dB have been modelled, giving an SPL of 190 dB (Figure 4-6).

The relatively short pulses and slow repetition of pulse gives a weighted kurtosis over the limit value (40), therefore, the USBL is modelled as an impulsive noise source.

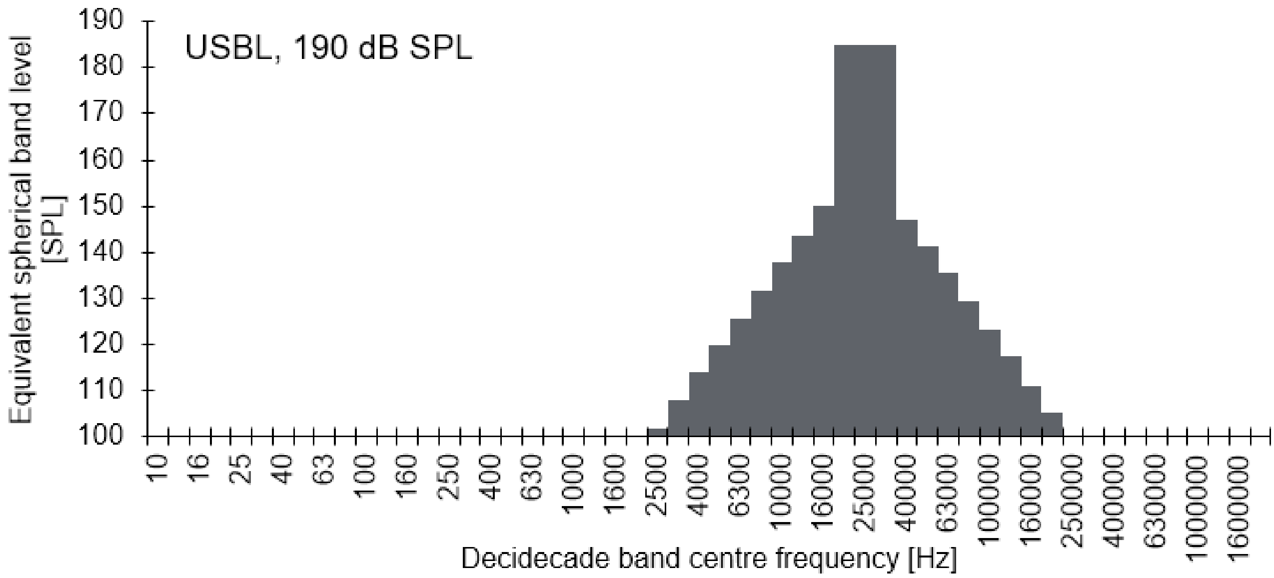

Figure 4-6. USBL source band levels.

4.1.1.6 Sub-bottom Profilers (SBP)

4.1.1.6.1 Parametric SBP (P-SBP)

The survey might use a parametric sub-bottom profiler (SBP) such as the “Innomar standard”. These SBPs 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, leading to a much smaller sound impact (Appendix A, Figure 8-8). We account for these differences in beam pattern by including the sediment reflection loss at high incidence angles (see Appendix A, Figure 8-7) to reduce the effective source level accordingly.

The source level for the P-SBP is split into two regions according to the nominal frequencies, accounting for some spectral leakage (Figure 4-7) and assuming the full range of frequencies is used during the survey (a conservative assumption). The total, broad band level for the parametric SBP is 204 dB SPL, with the secondary frequencies being 144 dB SPL.

Given the shallow water (<14 m depth), it is likely that shorter pulses will be used as they offer sufficient energy for a clear returning echo. This will increase kurtosis (“impulsiveness”) for realistic ping rates for the depth. Therefore, the P-SBP is modelled as an impulsive noise source.

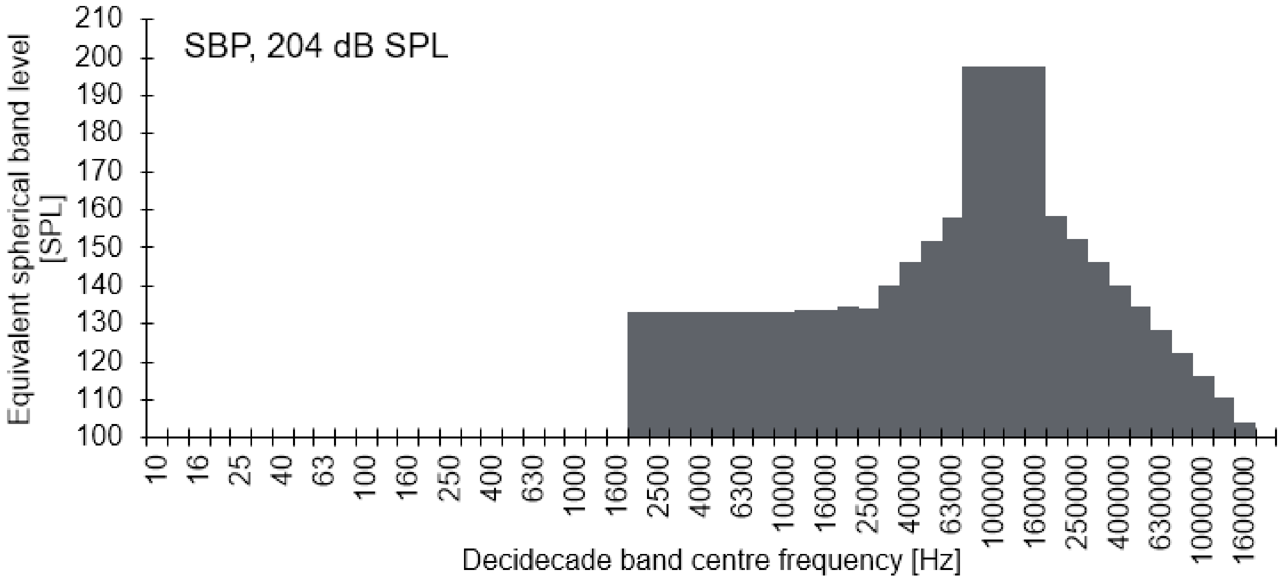

Figure 4-7. Parametric SBP source band levels as equivalent spherical/omnidirectional levels. Primary frequencies 85 kHz – 150 kHz, secondary frequencies 2 kHz – 22 kHz.

4.1.1.6.2 Chirper/Pinger SBP (C-SBP)

A chirper or pinger type SBP might be used for the survey. As no specific model has been specified, we have used a generic model based on common SBPs of this type. These have wide beams and therefore a comparatively higher noise impact, relative to their in-beam source levels. A single SBP source has been generated to represent both these sources as they are acoustically similar. Total broadband level for this SBP is 181 dB SPL with band levels given in Figure 4-8.

Given the shallow water (<14 m depth), it is likely that shorter pulses will be used as they offer sufficient energy for a clear returning echo. This will increase kurtosis (“impulsiveness”) for realistic ping rates for the depth. Therefore, the C-SBP is modelled as an impulsive noise source.

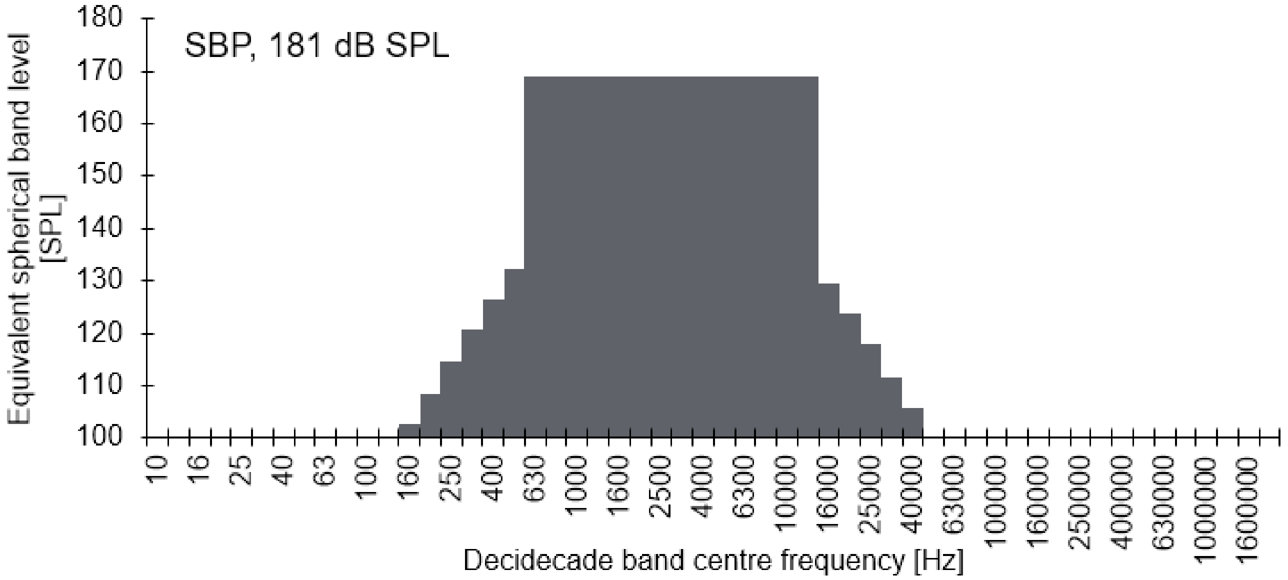

Figure 4-8. Chirper/Pinger type SBP band levels.

4.1.1.6.3 Sparker SBP (S-SBP)

A sparker type SBP (sometimes "UHRS") might be used during the survey. As no specific model has been specified, we have used a generic model based on common SBPs of this type and an energy per firing of 400 J and 1 firing per second. The total broadband level for this SBP is 184 dB SPL, with band levels given in Figure 4-8. Levels at frequencies below 100 Hz are taken from a spectral analysis of the timeseries in Figure 4-10.

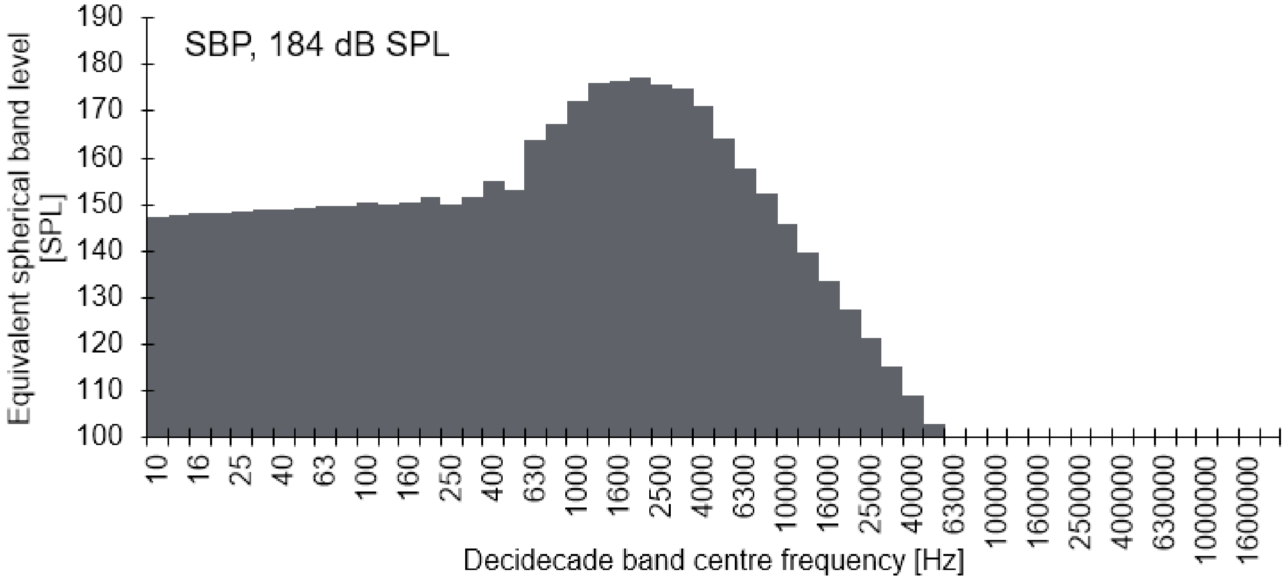

Figure 4-9. Chirper/Pinger type SBP band levels.

The very short impulses and slow repetition mean that this source is modelled as an impulsive noise source.

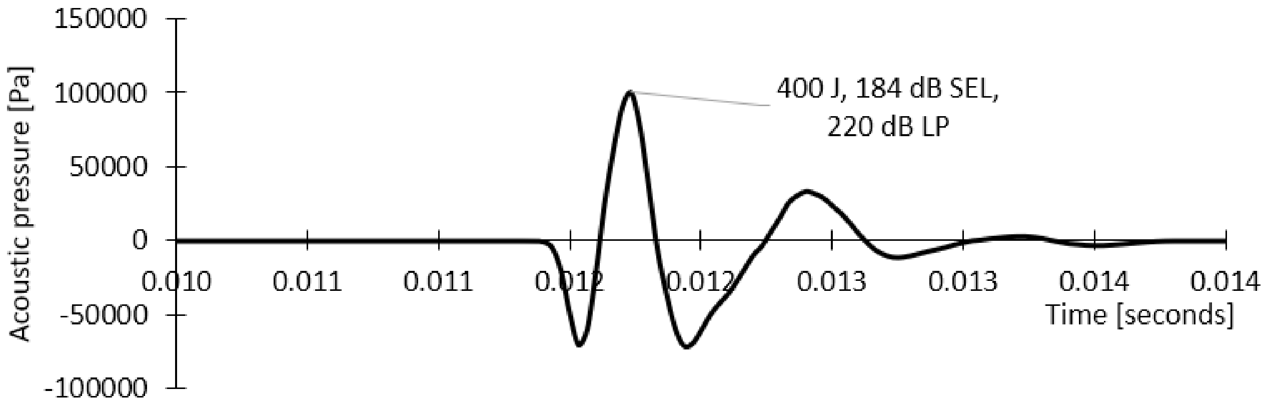

Figure 4-10. Example of an impulse from a sparker type SBP.

4.1.1.7 Boreholes Drilling

Boreholes are planned in the shallow parts of the SI Works area, with a drill of c. 0.1 m diameter. Recordings from similar equipment has informed the source levels used here (Erbe, et al., 2017; Fisheries and Marine Service, 1975; MR, et al., 2010; L-F, et al., 2023) Figure 4-11. This activity is a non-impulsive sound source with a broadband level of 145 dB SPL.

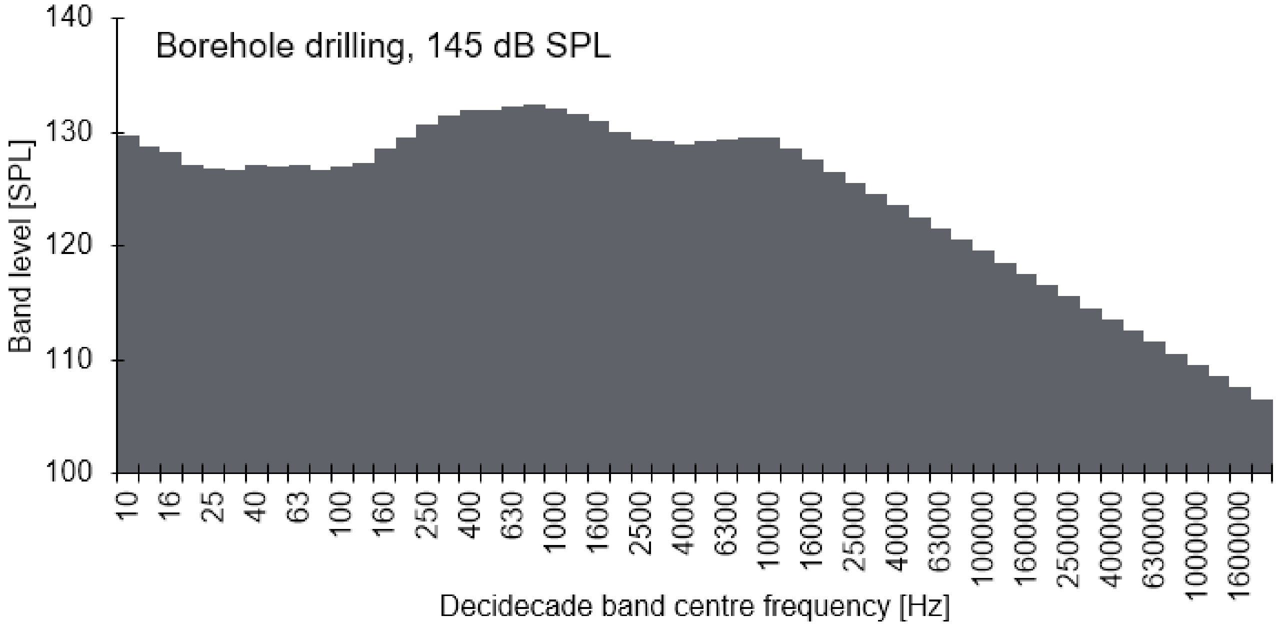

Figure 4-11. Band levels for drilling, Levels above 25 kHz are extrapolated based on trend in bands at lower frequencies.

4.1.1.8 Vibro-coring & CPT

For extraction of physical samples and sediment testing, vibro-coring and Cone Penetration Testing (CPT) will be carried out. Band levels are shown in Figure 4-11. The “Vibro-coring & CPT” activity is a non-impulsive sound source with a broadband level of 187 dB SPL.

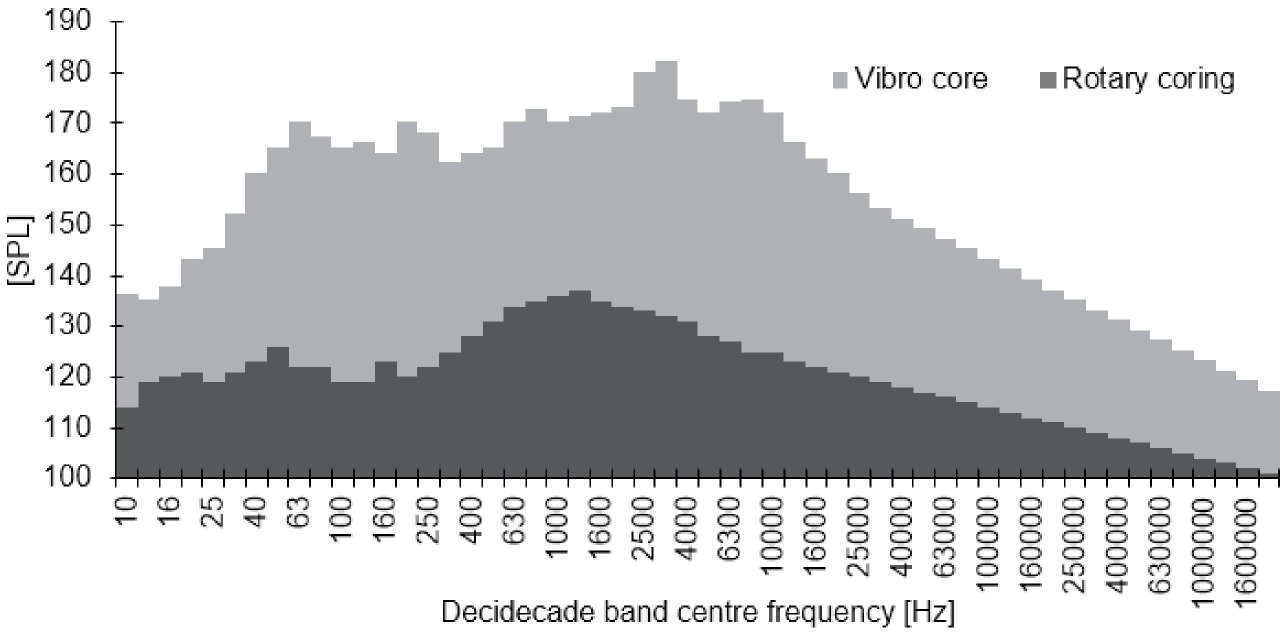

Figure 4-12. Band levels vibro-coring and CPT. Levels above 25 kHz are extrapolated based on trend in bands at lower frequencies.

4.1.2 Combined Sources

The relevant equipment for each survey type has been grouped into six scenarios that represent the most combinations for the survey equipment proposed to be used in the SI works.

MBES and SSS are active for all combined sources of the geophysical survey.

The “Vessel” noise source is active for all sources of both geophysical and geotechnical surveys.

4.1.2.1 Geophysical Survey (Parametric SBP & USBL Active)

This scenario assumes the geophysical survey is using a parametric SBP and that a towfish is deployed requiring an active USBL. Total broadband level of 204 dB SPL.

Active equipment:

- Vessel
- MBES
- SSS
- USBL
- Parametric SBP

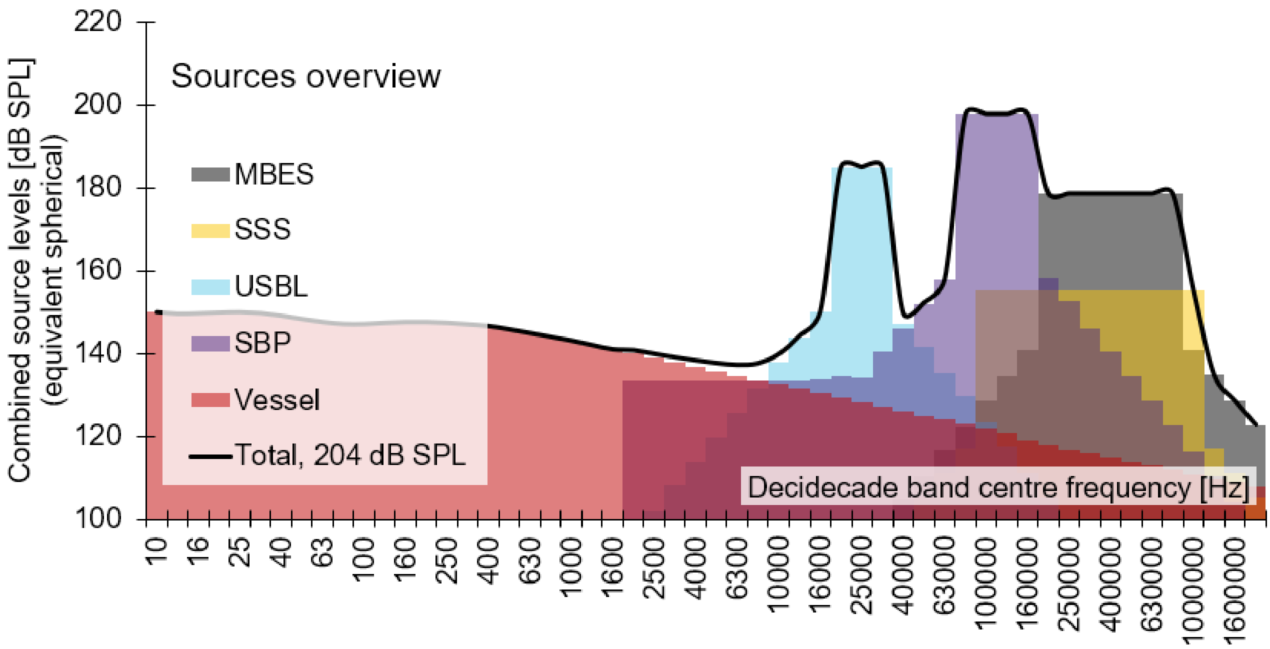

Figure 4-13. Source band level during geophysical survey (parametric SBP & USBL active).

4.1.2.2 Geophysical Survey (Parametric SBP & USBL Not Active)

This scenario assumes the geophysical survey is using a parametric SBP and that there is no need for a USBL (hull mounted SBP and SSS with known positions). Total broadband level of 204 dB SPL.

Active equipment:

- Vessel
- MBES
- SSS
- Parametric SBP

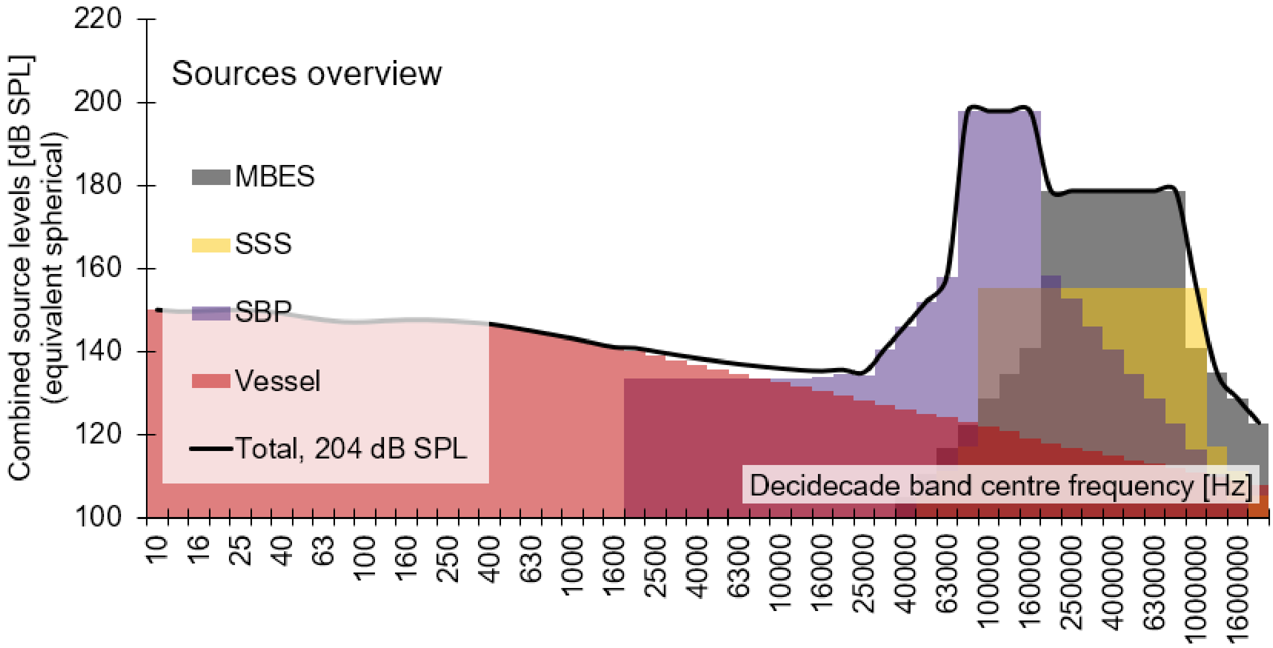

Figure 4-14. Source band level during geophysical survey (parametric SBP & USBL not active).

4.1.2.3 Geophysical Survey (Chirper/Pinger SBP & USBL Active)

This scenario assumes the geophysical survey is using a chirper or pinger type SBP and that a towfish is deployed requiring an active USBL. Total broadband level of 191 dB SPL.

Active equipment:

- Vessel
- MBES
- SSS
- USBL
- Chirper/pinger SBP

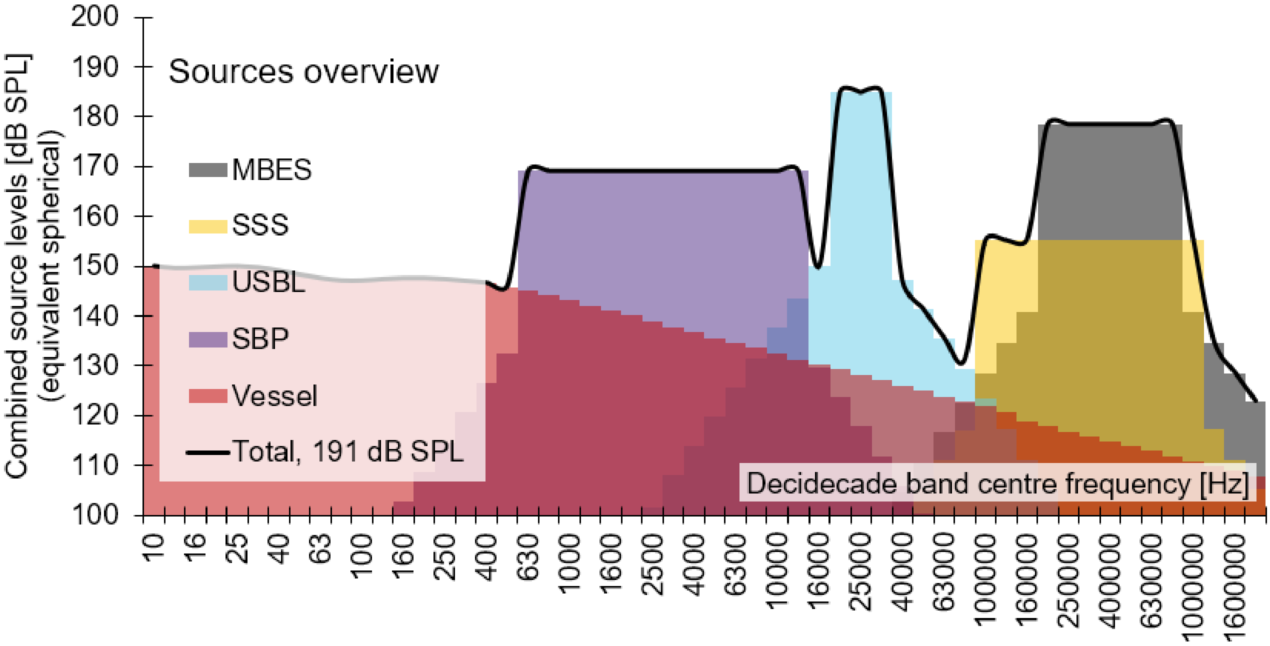

Figure 4-15. Source band level during geophysical survey (chirper/pinger SBP & USBL active).

4.1.2.4 Geophysical Survey (Chirper/Pinger SBP & USBL Not Active)

This scenario assumes the geophysical survey is using a chirper or pinger type SBP and that there is no need for a USBL (hull mounted SBP and SSS, with known positions). Total broadband level of 183 dB SPL.

Active equipment:

- Vessel
- MBES
- SSS
- Chirper/pinger SBP

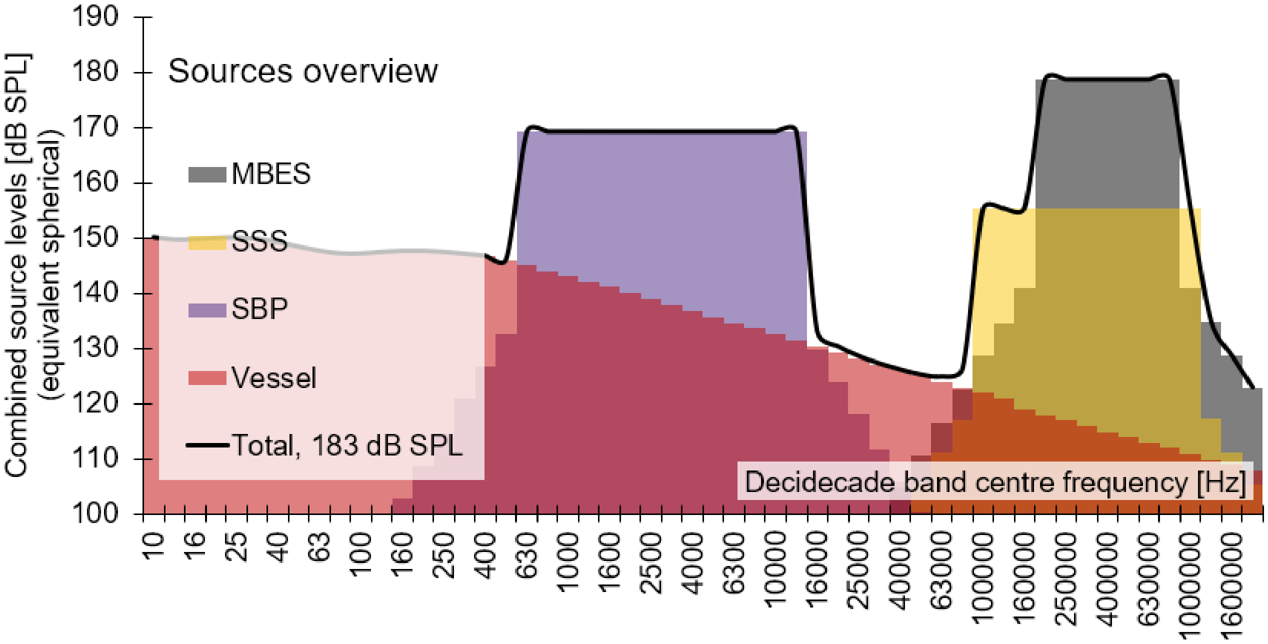

Figure 4-16. Source band level during geophysical survey (chirper/pinger SBP & USBL not active).

4.1.2.5 Geophysical Survey (Sparker SBP & USBL Active)

This scenario assumes the geophysical survey is using a sparker type SBP and that a towfish is deployed requiring an active USBL. Total broadband level of 191 dB SPL.

Active equipment:

- Vessel
- MBES
- SSS
- USBL
- Sparker

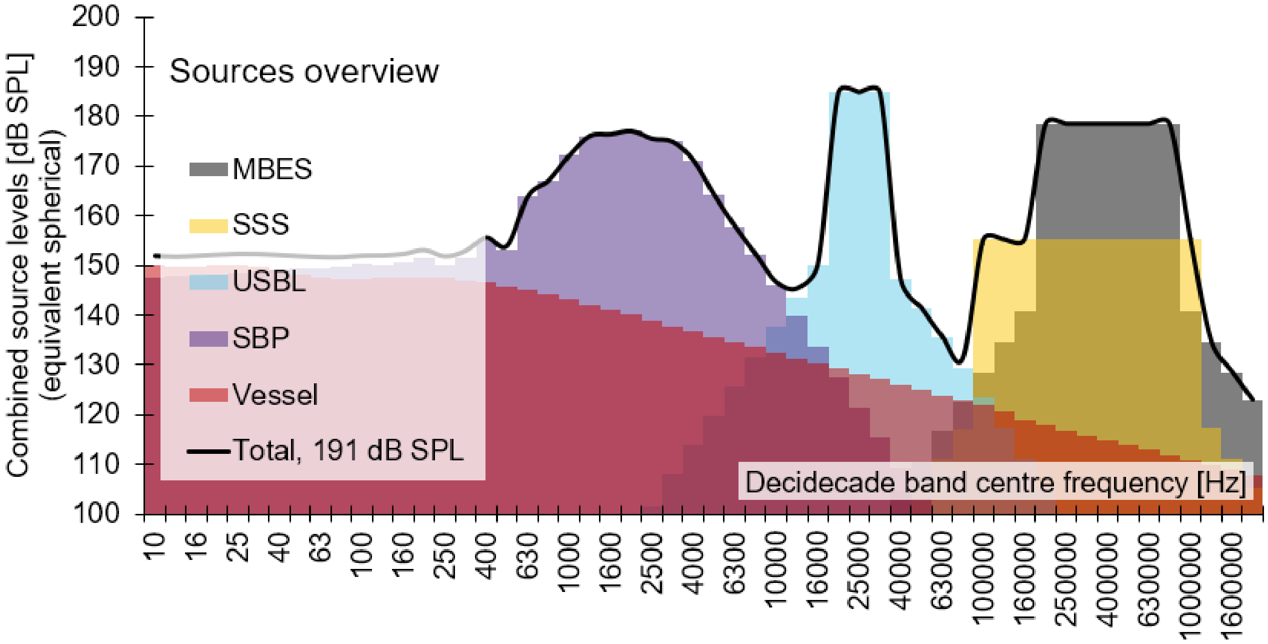

Figure 4-17. Source band level during geophysical survey (sparker SBP & USBL active).

4.1.2.6 Geophysical Survey (Sparker SBP & USBL not Active)

This scenario assumes the geophysical survey is using a sparker type SBP and that there is no need for a USBL (hull mounted SBP and SSS, with known positions). Total broadband level of 185 dB SPL.

Active equipment:

- Vessel
- MBES
- SSS
- Sparker

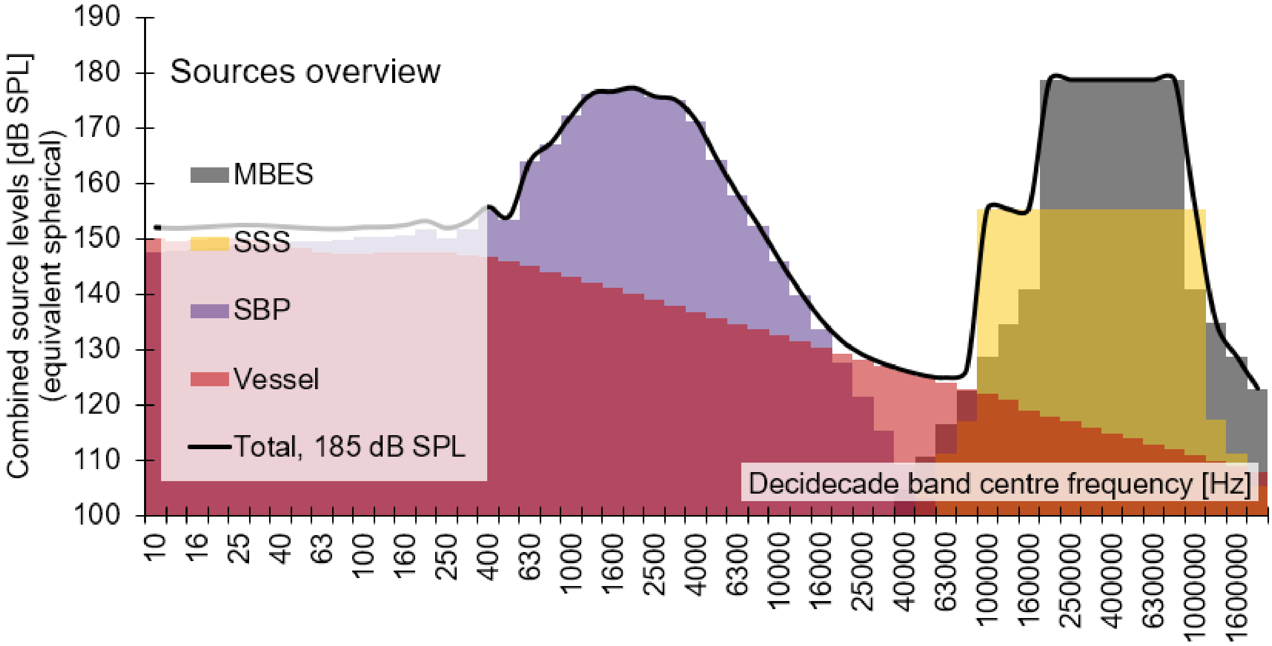

Figure 4-18. Source band level during geophysical survey (sparker SBP & USBL not active).

4.1.2.7 Soft Start Source (Geophysical)

During soft starts, it is assumed that any SBP and USBL will not be active but the MBES and/or the SSS will be active. Total broadband level of 179 dB SPL.

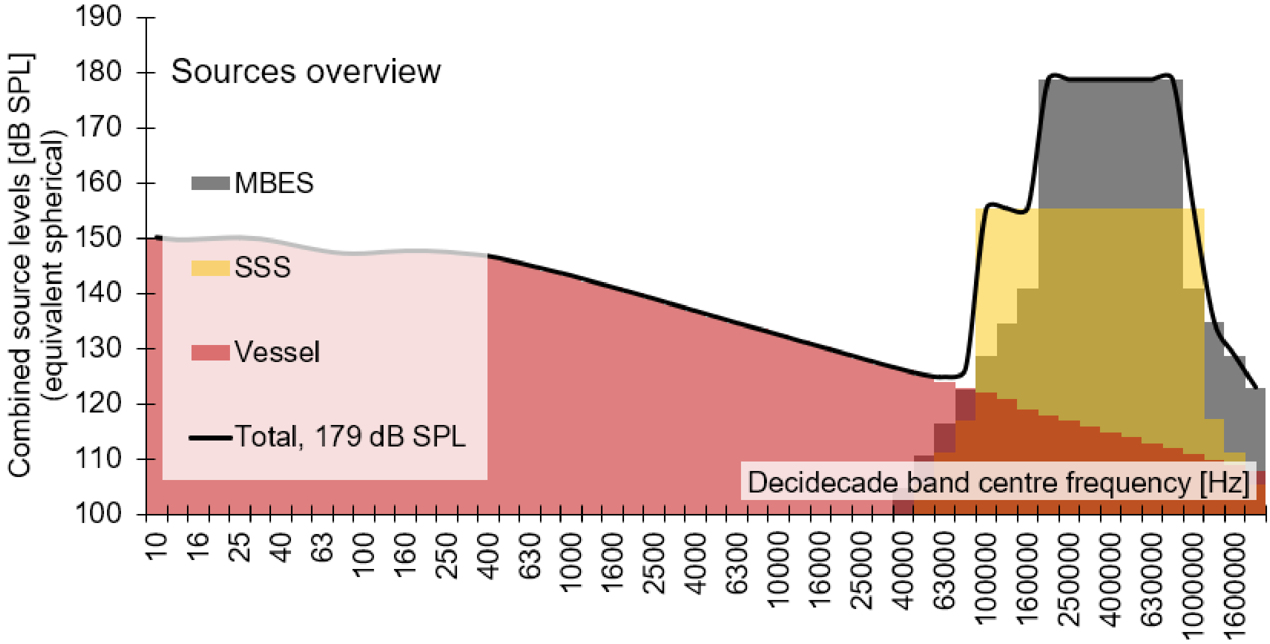

Figure 4-19. Source band level during geophysical survey soft start.

4.1.2.8 Geotechnical Survey (Drilling, boreholes)

Equipment related to drilling boreholes are active. Additionally, the "Vessel" source is active to account for support vessels and general machinery. Total broadband level of 162 dB SPL.

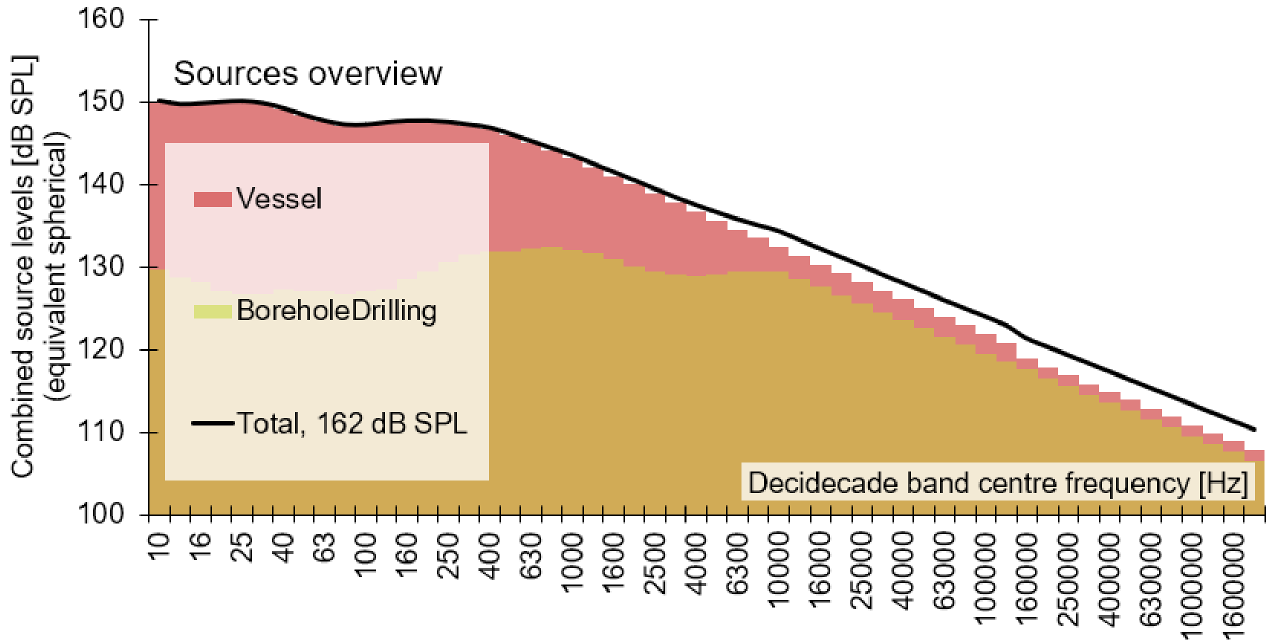

Figure 4-20. Source band level during geotechnical survey – borehole drilling.

4.1.2.9 Geotechnical Survey (Vibro-coring & CPT)

Vibro-coring, CPT, vessel (geotechnical) and USBL are active. Total broadband level of 192 dB SPL.

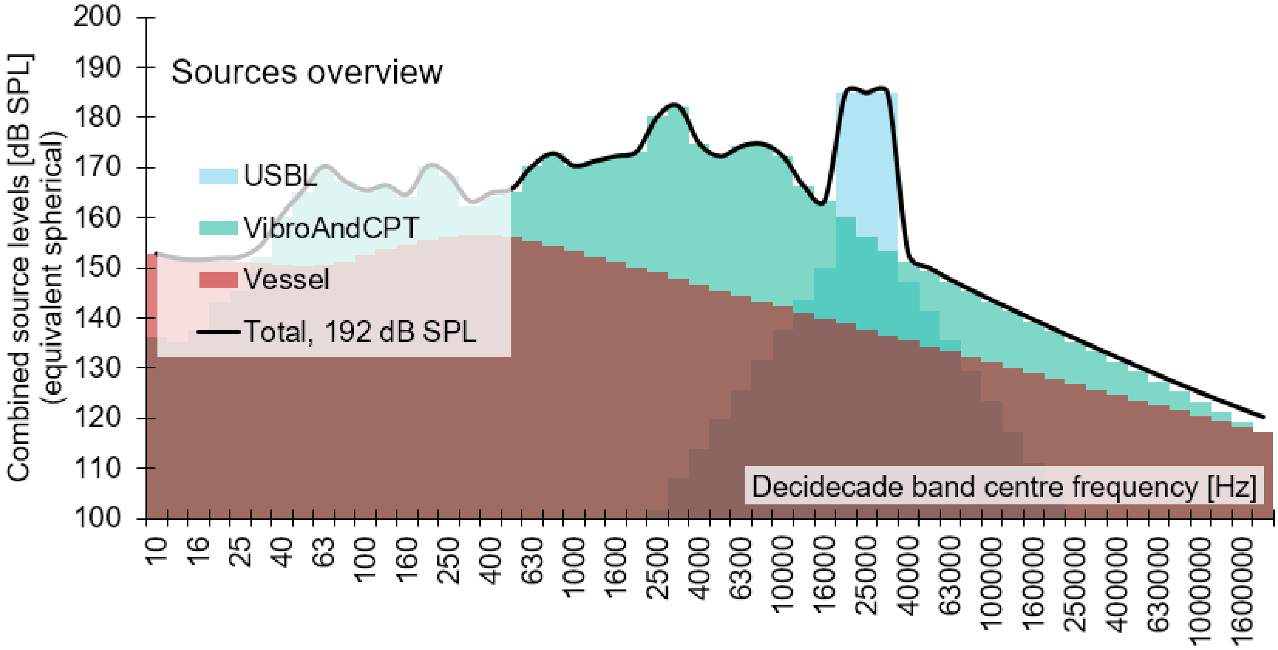

Figure 4-21. Source band level during geotechnical survey – vibro-coring and CPT.

4.1.2.10 Soft Start Source (Geotechnical – Vibro-coring & CPT)

As the geotechnical survey plans to use a USBL, it is likely that some form of soft start will need to be considered. Here, the vessel itself (with no active USBL) will perform this function. Total broadband level of 168 dB SPL.

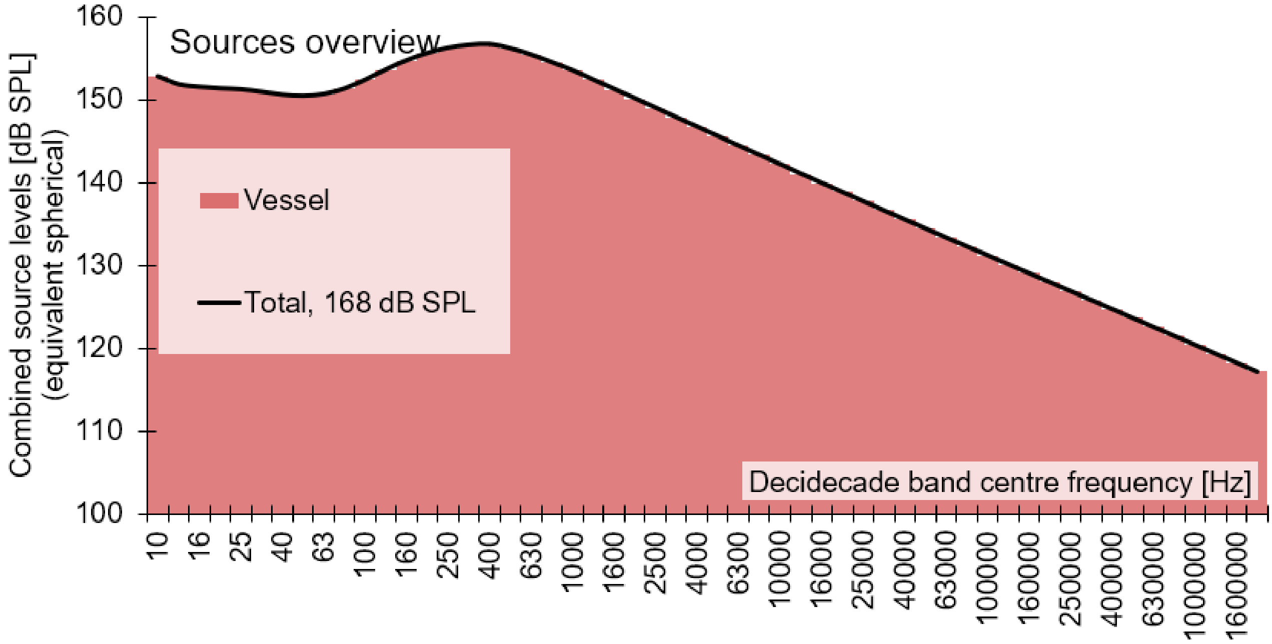

Figure 4-22. Source band level during geotechnical (vibro-core & CPT) survey soft start.

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 $10 \cdot \log_{10}$(range) or $20 \cdot \log_{10}$(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))[9].

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 “Roger’s” model (Rogers, 1981), which is suitable to depths of c. 200 m and generally softer 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.

5.1 Modelling Assumptions

The main assumptions made for the modelling are:

1. A soft start where no SBP and no USBL is active, but MBES and/or SSS is active (section 4.1.2.7) is a feasible and practical option for the survey operator. This gives the VHF group a c. 9-18 dB reduction in received level for the duration of the soft start, depending on exact equipment configuration.
2. Animals fleeing the area will not return within a 24-hour period.
3. Animals flee for up to 2 hours, after which they will be up to 10.8 km and 3.6 km away for marine mammals and fish, respectively.
4. Modelling assumes high tide; this is a worst-case assumption.
5. Results assume a transition from impulsive (kurtosis >40) to non-impulsive (kurtosis <40) at a 500 m distance from the source. This means that all ranges greater than 500 m are assessed against the non-impulsive thresholds. This assumption is also applicable for the assessment of behavioural disturbance.

5.2 Exposure Calculations (dB SEL)

To compare modelled levels with the two impact assessment frameworks (Southall et al. 2019 & 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. The conversion is relatively easy:

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

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

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

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

[9] This model is compared to measurements in the paper (Rogers, 1981) describing it and is capable of accurate modelling in acoustically simpler scenarios. Simpler meaning shallow in relation to the wavelengths and with no significant sound speed gradient in the water column.

And SPL from SEL:

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

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 a PTS 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, we used a swim speed of 1.5 m/s for marine mammals, and 0.5 m/s for fishes, including sharks.

For very long fleeing durations, the ambient sound itself can exceed the thresholds, e.g., an ambient sound level of 117.5 dB, weighted for the VHF group, will exceed the non-impulsive TTS threshold of 153 dB SEL after 2 hours' exposure[10]. For this assessment, we consider fleeing durations of 2 hours (7200 seconds, allowing 10800 m of fleeing), meaning that weighted levels of 117.5 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)

[10] 117.5 dB SPL + 10*$\log_{10}$(3600 seconds) = 153.1 dB SEL, TTS non-impulsive threshold for the VHF group is 153 dB SEL.

6 RESULTS AND ASSESSMENT

Results are presented here as the geographical “risk range” to an auditory threshold (TTS/PTS/Behavioural), as given in Sections 2.3 and 2.5. A given risk range specifies the expected range, within which, a receiver would exceed the relevant threshold. Risk ranges are given for the 90th percentile value.

Several result types are presented for each activity to inform this assessment and to provide flexibility in mitigation:

1. **“1 second exposure risk range”:**
   This is the range of acute risk of impact from the activity (a one second exposure) and is presented to indicate instantaneous risk and for comparison with other studies. This assumes a stationary animal (during the 1-second exposure) with all equipment operating at full power and does not include a soft start.

2. **“Minimal starting range for a fleeing animal with no soft start”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s (0.5 m/s for fish, including sharks).

3. **“Minimal starting range for a fleeing animal with a 20 min soft start with no SBP and no USBL active”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s (0.5 m/s for fish, including sharks).

4. **“Behavioural response range”:**
   The range at which the behavioural limit for the marine mammals (160/120 dB SPL impulsive/non-impulsive) or the fishes (including sharks) (150 dB SPL) is exceeded. No hearing group weightings are applied when assessing against this threshold.

6.1 Assumptions and Notes on Results

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

- Results are rounded to the nearest 2 significant digits. This can lead to some curious appearing overlaps in risk ranges.
- Results for behavioural disturbance mainly rely on the non-impulsive threshold of 120 dB SPL (for marine mammals), as the impulsive noise transitions to non-impulsive at c. 500 m. This means that there are large ranges of disturbance, but should be considered in relation to, for example, the radiated noise from common vessels, which will also exceed this threshold to ranges of 500-5000 m (assuming 160-175 dB SPL source level).
- The soft start has little effect on the TTS ranges for the VHF group when the USBL is active. This is due to the relatively low threshold for TTS for the VHF group (153 dB SEL) and the logarithmic nature of transmission losses. A constant reduction of received level with a multiplication of range – a 3-6 dB reduction per doubling of distance, such as from 2 km to 4 km (until ranges become large enough for absorption to become significant) – means that fleeing is not very effective at reducing received level.
- Animals are modelled as fleeing in straight lines. Where sites are very confined, the maximal risk ranges will be restricted by line-of-sight ranges (and cut short where they meet land).
- Modelling assumed a maximal fleeing time of 7200 seconds (2 hours). This allows for 10.8 km of fleeing for marine mammals (3.6 km for fish).
- Modelling is limited to a range of 15 km from the source.
- No modelling of risk ranges for *mortality* for fishes are presented as risk ranges to PTS (recoverable injury) are all smaller than 30 m.

- No results are presented for assessment against the L_P thresholds as, for all scenarios, the risk ranges to the TTS thresholds were <30 m for fish (TTS: 193 dB L_P) and <20 m for marine mammals (VHF TTS: 196 dB L_P).
- Results are *only* given in relation to the behavioural thresholds (SPL) and TTS/PTS thresholds for sound exposure level (SEL).
- The hearing group "Fish" includes sharks and are for unweighted received levels assessed against the lowest thresholds for fishes as found in guidance (Popper, et al., 2014).

6.2 Results – Tabulated

For all geophysical survey results, the vessel, SSS and MBES sources are active. Only the type of SBP and presence of a USBL is changing between the scenarios modelled.

6.2.1 Geophysical Survey (Parametric SBP & USBL Active)

This scenario assumes that the geophysical survey is using a parametric SBP and that a towfish is deployed, requiring an active USBL (Section 4.1.2.1).

Risk ranges for exceeding PTS is below 50 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 500 m with no soft start.

A soft start of 20 minutes will allow sufficient time for the VHF group to swim away to reduce the PTS exceedance risk range to 50 m.

The soft start itself has a PTS risk range of 50 m for the VHF group. Therefore, extension of the soft start duration will not decrease the PTS risk range further.

Table 6-1: Risk ranges for exceeding the behavioural threshold for all hearing groups during Geophysical survey (Parametric SBP & USBL active).

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	4000	4000	4000	4000	4000	380

Table 6-2: Risk ranges for exceeding the TTS threshold for all hearing groups during Geophysical survey (Parametric SBP & USBL active).

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	40	770	<10	<10	<10
Fleeing receiver, no soft start	80	310	2700	140	<10	130
Fleeing receiver, 20 min soft start	<10	<10	1500	<10	<10	<10

*See Comments, Section 6.1 on results limitations.

Table 6-3. Risk ranges for exceeding the PTS threshold for all hearing groups during Geophysical survey (Parametric SBP & USBL active).

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	240	<10	<10	<10
Fleeing receiver, no soft start	<10	50	500	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	50	<10	<10	<10

6.2.2 Geophysical Survey (Parametric SBP & USBL Not Active)

This scenario assumes that the geophysical survey is using a parametric SBP and that there is no need for a USBL as the SBP and SSS are hull-mounted with known positions (Section 4.1.2.2).

Risk ranges for exceeding PTS is below 40 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 470 m with no soft start.

A soft start of 20 minutes will allow sufficient time for the VHF group to swim away to reduce the PTS exceedance risk range to 50 m.

The soft start itself has a PTS risk range of 50 m for the VHF group. Therefore, extension of the soft start duration will not decrease the PTS risk range further.

Table 6-4: Risk ranges for exceeding the behavioural threshold for all hearing groups during Geophysical survey (Parametric SBP & USBL not active).

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	1100	1100	1100	1100	1100	330

Table 6-5: Risk ranges for exceeding the TTS threshold for all hearing groups during Geophysical survey (Parametric SBP & USBL not active).

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	40	500	<10	<10	<10
Fleeing receiver, no soft start	<10	230	640	30	<10	120
Fleeing receiver, 20 min soft start	<10	<10	160	<10	<10	<10

Table 6-6. Risk ranges for exceeding the PTS threshold for all hearing groups during Geophysical survey (Parametric SBP & USBL not active).

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	210	<10	<10	<10
Fleeing receiver, no soft start	<10	40	470	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	50	<10	<10	<10

6.2.3 Geophysical Survey (Chirper/Pinger SBP & USBL Active)

This scenario assumes that the geophysical survey is using a chirper or pinger type SBP and that a towfish is deployed requiring an active USBL (Section 4.1.2.3).

Risk ranges for exceeding PTS is below 10 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 490 m with no soft start.

A soft start of 20 minutes will allow sufficient time for the VHF group to swim away to reduce the PTS exceedance risk range to 50 m.

The soft start itself has a PTS risk range of 50 m for the VHF group. Therefore, extension of the soft start duration will not decrease the PTS risk range further.

Table 6-7: Risk ranges for exceeding the behavioural threshold for all hearing groups during Geophysical survey (Chirper/pinger SBP & USBL active).

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	5700	5700	5700	5700	5700	270

Table 6-8: Risk ranges for exceeding the TTS threshold for all hearing groups during Geophysical survey (Chirper/pinger SBP & USBL active).

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	10	750	<10	<10	<10
Fleeing receiver, no soft start	140	250	2800	160	<10	30
Fleeing receiver, 20 min soft start	<10	<10	1600	<10	<10	<10

Table 6-9. Risk ranges for exceeding the PTS threshold for all hearing groups during Geophysical survey (Chirper/pinger SBP & USBL active).

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	110	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	490	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	50	<10	<10	<10

6.2.4 Geophysical Survey (Chirper/Pinger SBP & USBL Not Active)

This scenario that assumes that the geophysical survey is using a chirper or pinger type SBP and that there is no need for a USBL as the SBP and SSS are hull mounted with known positions (Section 4.1.2.4).

Risk ranges for exceeding PTS is below 10 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 120 m with no soft start.

A soft start of 20 minutes will allow sufficient time for the VHF group to swim away to reduce the PTS exceedance risk range to 50 m.

The soft start itself has a PTS risk range of 50 m for the VHF group. Therefore, extension of the soft start duration will not decrease the PTS risk range further.

Table 6-10: Risk ranges for exceeding the behavioural threshold for all hearing groups during Geophysical survey (Chirper/pinger SBP & USBL not active).

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	5200	5200	5200	5200	5200	90

Table 6-11: Risk ranges for exceeding the TTS threshold for all hearing groups during Geophysical survey (Chirper/pinger SBP & USBL not active).

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	70	<10	<10	<10
Fleeing receiver, no soft start	70	<10	490	30	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	170	<10	<10	<10

Table 6-12. Risk ranges for exceeding the PTS threshold for all hearing groups during Geophysical survey (Chirper/pinger SBP & USBL not active).

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	10	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	120	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	50	<10	<10	<10

6.2.5 Geophysical Survey (Sparker SBP & USBL Active)

This scenario assumes the geophysical survey is using a Sparker type SBP and that a towfish is deployed requiring an active USBL (Section 4.1.2.5).

Risk ranges for exceeding PTS is below 10 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 490 m with no soft start.

A soft start of 20 minutes will allow sufficient time for the VHF group to swim away to reduce the PTS exceedance risk range to 50 m.

The soft start itself has a PTS risk range of 50 m for the VHF group. Therefore, extension of the soft start duration will not decrease the PTS risk range further.

Table 6-13: Risk ranges for exceeding the peak pressure level impulsive threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL active).

Risk ranges (L_P thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
TTS	10	<10	20.1	10	<10	30.1
PTS	10	<10	20.1	10	<10	10

Table 6-14: Risk ranges for exceeding the behavioural threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL active).

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	8000	8000	8000	8000	8000	290

Table 6-15: Risk ranges for exceeding the TTS threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL active).

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	10	750	<10	<10	<10
Fleeing receiver, no soft start	220	250	2700	180	<10	30
Fleeing receiver, 20 min soft start	<10	<10	1500	<10	<10	<10

Table 6-16. Risk ranges for exceeding the PTS threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL active).

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	110	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	490	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	50	<10	<10	<10

6.2.6 Geophysical Survey (Sparker SBP & USBL Not Active)

This scenario assumes the geophysical survey is using a Sparker type SBP and that there is no need for a USBL as the SBP and SSS are hull mounted with known positions (Section 4.1.2.6).

Risk ranges for exceeding PTS is below 10 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 50 m with no soft start.

A soft start of 20 minutes will not reduce this range for the VHF group.

The soft start itself has a PTS risk range of 50 m for the VHF group. Therefore, extension of the soft start duration will not decrease the PTS risk range further.

Table 6-17: Risk ranges for exceeding the peak pressure level impulsive threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL not active).

Risk ranges (L_P thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
TTS	10	<10	20.1	10	<10	30.1
PTS	10	<10	20.1	10	<10	10

Table 6-18: Risk ranges for exceeding the behavioural threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL not active).

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	7900	7900	7900	7900	7900	120

Table 6-19: Risk ranges for exceeding the TTS threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL not active).

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	50	<10	<10	<10
Fleeing receiver, no soft start	160	<10	330	60	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	160	<10	<10	<10

Table 6-20. Risk ranges for exceeding the PTS threshold for all hearing groups during Geophysical survey (Sparker SBP & USBL not active).

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	<10	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	50	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	50	<10	<10	<10

6.2.7 Geotechnical Survey (Drilling, boreholes)

This scenario assumes the drilling and vessel source is active (Section 6.2.7).

No soft start has been modelled for this activity; this is based on:

1. Risk ranges for exceeding PTS are below 10 meters for all groups.
2. The sampling platform (vessel or barge) will itself emit similar noise to the sampling activity and will serve as a type of soft start exceeding normal soft start durations.
3. The geotechnical equipment itself cannot easily be operated at reduced noise output.

Table 6-21: Risk ranges for exceeding the behavioural threshold for all hearing groups during drilling.

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	<20	<20	<20	<20	<20	<10

Table 6-22: Risk ranges for exceeding the TTS threshold for all hearing groups during drilling.

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	<10	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	<10	<10	<10	<10

Table 6-23. Risk ranges for exceeding the PTS threshold for all hearing groups during drilling.

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	<10	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	<10	<10	<10	<10

6.2.8 Geotechnical Survey (Vibro-coring & CPT)

This scenario assumes the vessel, vibro-corer, CPT and USBL sources are active (Section 4.1.2.9).

Risk ranges for exceeding PTS is below 10 m for all groups except the VHF group, which risks exceeding the PTS threshold to a range of 490 m with no soft start.

A soft start of 20 minutes will allow sufficient time for the VHF group to swim away to reduce the PTS exceedance risk range to less than 10 m.

Table 6-24: Risk ranges for exceeding the behavioural threshold for all hearing groups during Vibro-coring and CPT.

Behavioural Threshold exceedance Risk ranges (SPL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
Non-impulsive	5700	5700	5700	5700	5700	270

Table 6-25: Risk ranges for exceeding the TTS threshold for all hearing groups during Vibro-coring and CPT.

TTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	10	750	<10	<10	<10
Fleeing receiver, no soft start	130	250	2700	160	<10	20
Fleeing receiver, 20 min soft start	<10	<10	1500	<10	<10	<10

Table 6-26. Risk ranges for exceeding the PTS threshold for all hearing groups during Vibro-coring and CPT.

PTS Threshold Exceedance Risk ranges (SEL thresholds)	LF [m]	HF [m]	VHF [m]	PCW [m]	OCW [m]	Fish [m]
One second	<10	<10	110	<10	<10	<10
Fleeing receiver, no soft start	<10	<10	490	<10	<10	<10
Fleeing receiver, 20 min soft start	<10	<10	<10	<10	<10	<10

6.3 Results Summary

6.3.1 Geophysical Survey

PTS – hearing injury

Apart from the VHF hearing group, all risk ranges to PTS exceedance for fleeing receivers is below 50 m with no soft start.

For the VHF hearing group, the risk range for PTS exceedance for fleeing receivers is up to 500 m with no soft start and below 50 m with a 20-minute soft start.

TTS – temporary hearing impairment

Apart from the VHF hearing group, all risk ranges to TTS exceedance for fleeing receivers is below 310 m with no soft start and below 10 m with a 20-minute soft start.

For the VHF hearing group, the risk range for TTS exceedance for fleeing receivers is up to 2800 m with no soft start and below 1600 m with a 20-minute soft start.

Behavioural disturbance

Ranges for behavioural disturbance for all hearing groups except Fish is up to 8 km (driven by the sparker type SBP). For Fish the range for behavioural disturbance is much less at up to 380 m (driven by the parametric SBP & USBL).

6.3.2 Geotechnical Survey

Drilling, Boreholes

The drilling of boreholes has virtually no risk of exceeding PTS or TTS thresholds for any hearing group, with all risk ranges to PTS and TTS exceedance below 10 m.

Behavioural threshold is also not exceeded beyond 20 m.

Vibro-coring & CPT with USBL

PTS – hearing injury

The VHF group has a PTS exceedance risk for moving receivers to 490 m with no soft start, reducing to under 10 m with a 20-minute soft start.

All remaining hearing groups have PTS risk exceedance ranges for moving receivers below 10 m, even with no soft start.

TTS – temporary hearing impairment

The VHF group has a TTS exceedance risk for moving receivers to 2700 m with no soft start, reducing to 1500 m with a 20-minute soft start.

All remaining hearing groups have risk ranges for PTS exceedance for moving receivers at or below 260 m, with no soft start, reducing to below 10 m with a 20-minute soft start.

Behavioural disturbance

Ranges for behavioural disturbance for all hearing groups except Fish is up to 5700 m (driven by the USBL). For Fish the range for behavioural disturbance is much less at up to 270 m (driven by the USBL).

7 CONCLUSIONS

This assessment concludes that the risk of inducing hearing injury (PTS – Permanent Threshold Shift) following noise from the SI Works is below 50 m with no soft start for all hearing groups except the VHF group . The VHF group (harbour porpoise) has an injury risk up to 500m from the active noise sources with no soft start. Applying a 20-minute soft start reduces the injury risk to below 50 m.

There is risk of inducing temporary hearing effects (TTS – Temporary Threshold Shift). This extends to c. 3000 m for the VHF group (harbour porpoise) and below c. 300 m for remaining marine mammals and fishes. Introducing a 20-minute soft start, where only some equipment is active, will reduce the risk of TTS for the VHF group to within 1600 m, and to below 10 m for the remaining marine mammals and fishes.

Behavioural disturbance ranges of up to 8,000 m have been modelled for the geophysical survey for marine mammals while the Sparker type SBP is active. For the geotechnical survey, the use of a USBL means that behavioural disturbance ranges up to 5,700 m. The low noise levels of the borehole drilling means that the behavioural disturbance limit is within 20 m.

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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_{P-P} for the level in dB), Note that L_{P-P} 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_P 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”.

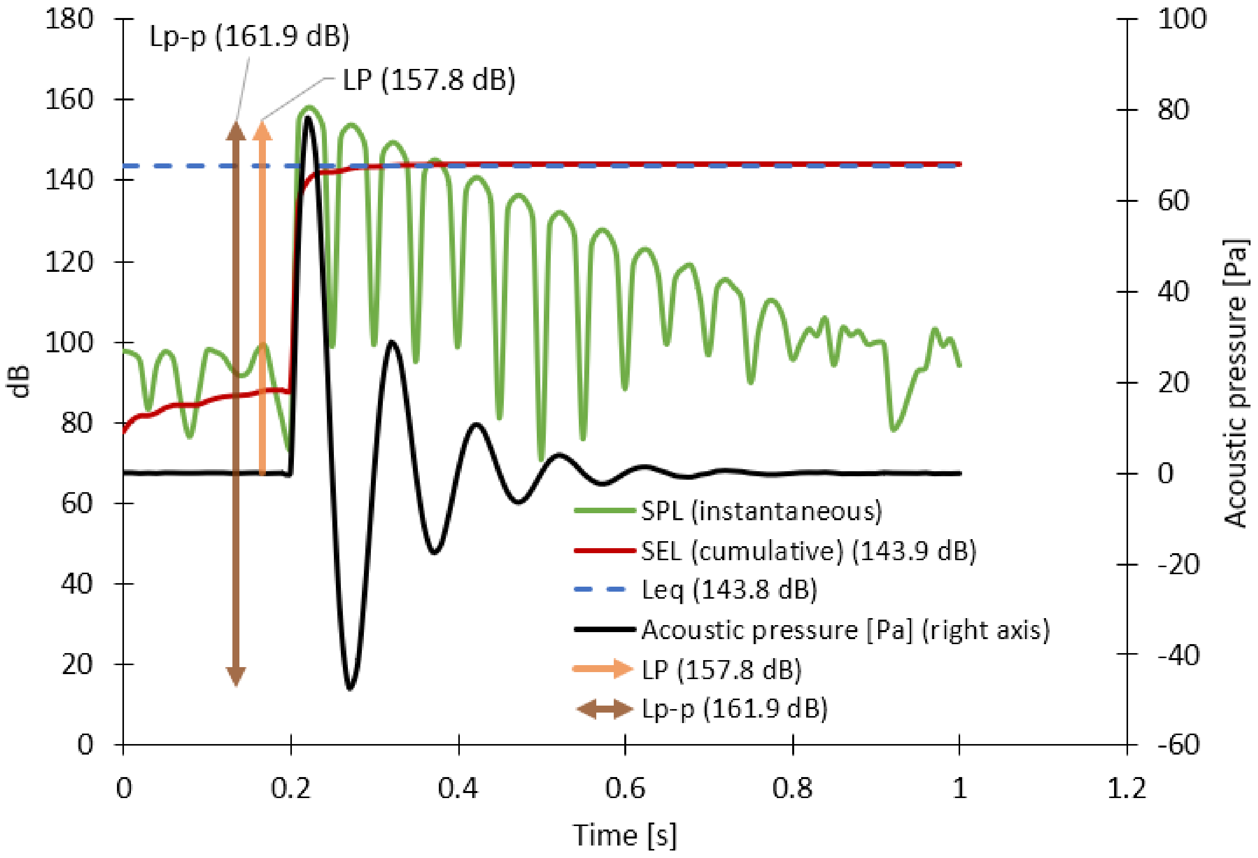

Figure 8-1: Graphical representation of acoustic wave descriptors ("LE" = SEL).

The sound pressure level (SPL[11]) is defined as follows (ISO 18405:2017, 3.2.1.1):

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

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

The peak sound pressure level, L_P, 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:

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

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. 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_P 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):

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

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

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

[11] Equivalent to the commonly seen "RMS-level".

Converting from a single event to multiple events for SEL:

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

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.

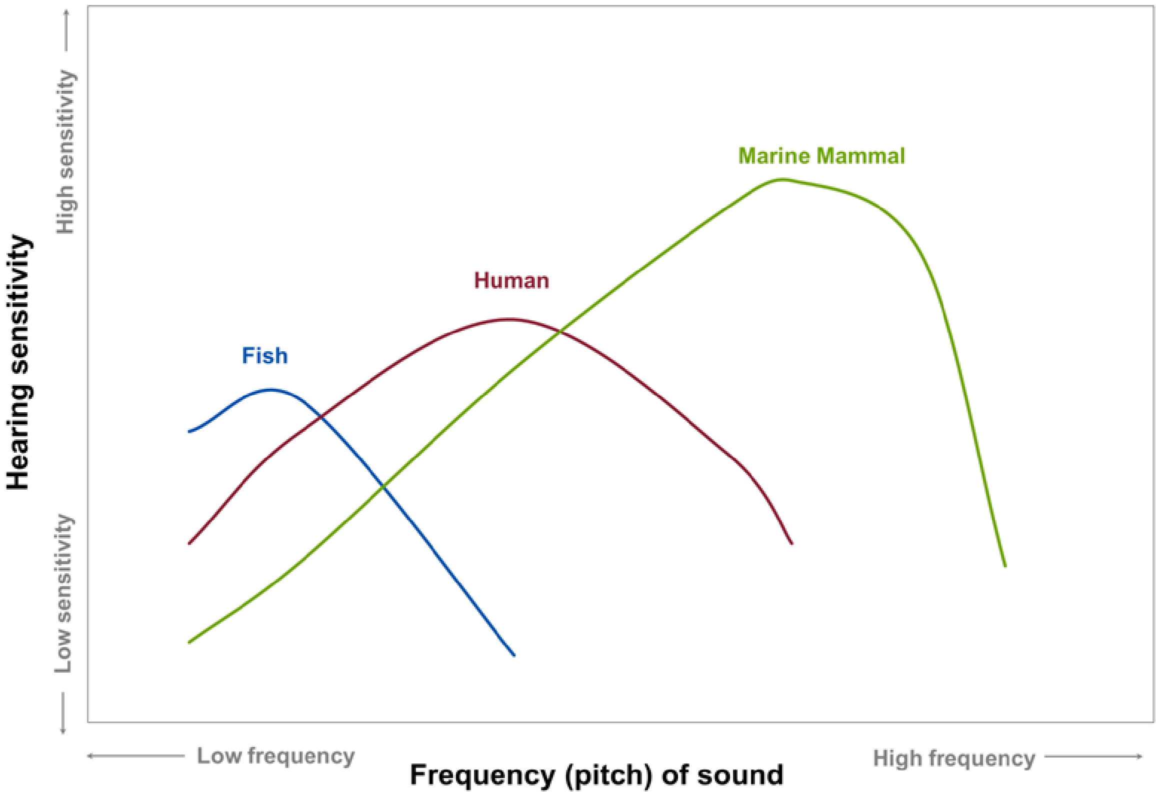

Figure 8-2: Comparison between hearing thresholds of different marine animals and humans.

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.

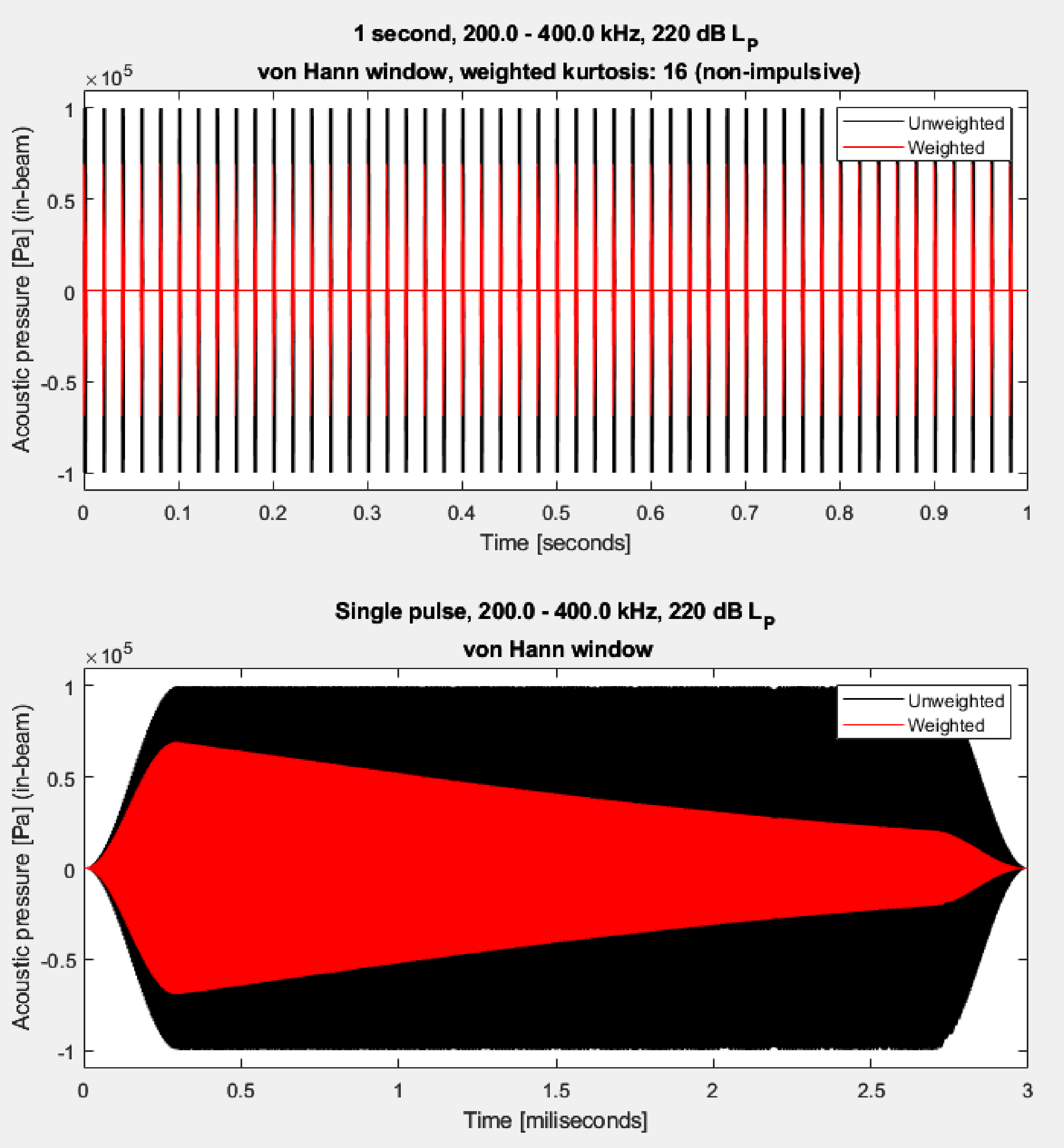

Figure 8-3. Example of a multibeam echosounder at 15 m depth (achieving 50 ping/sec) with a 3 ms ping duration. VHF-weighted kurtosis of 16 – non-impulsive.

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.

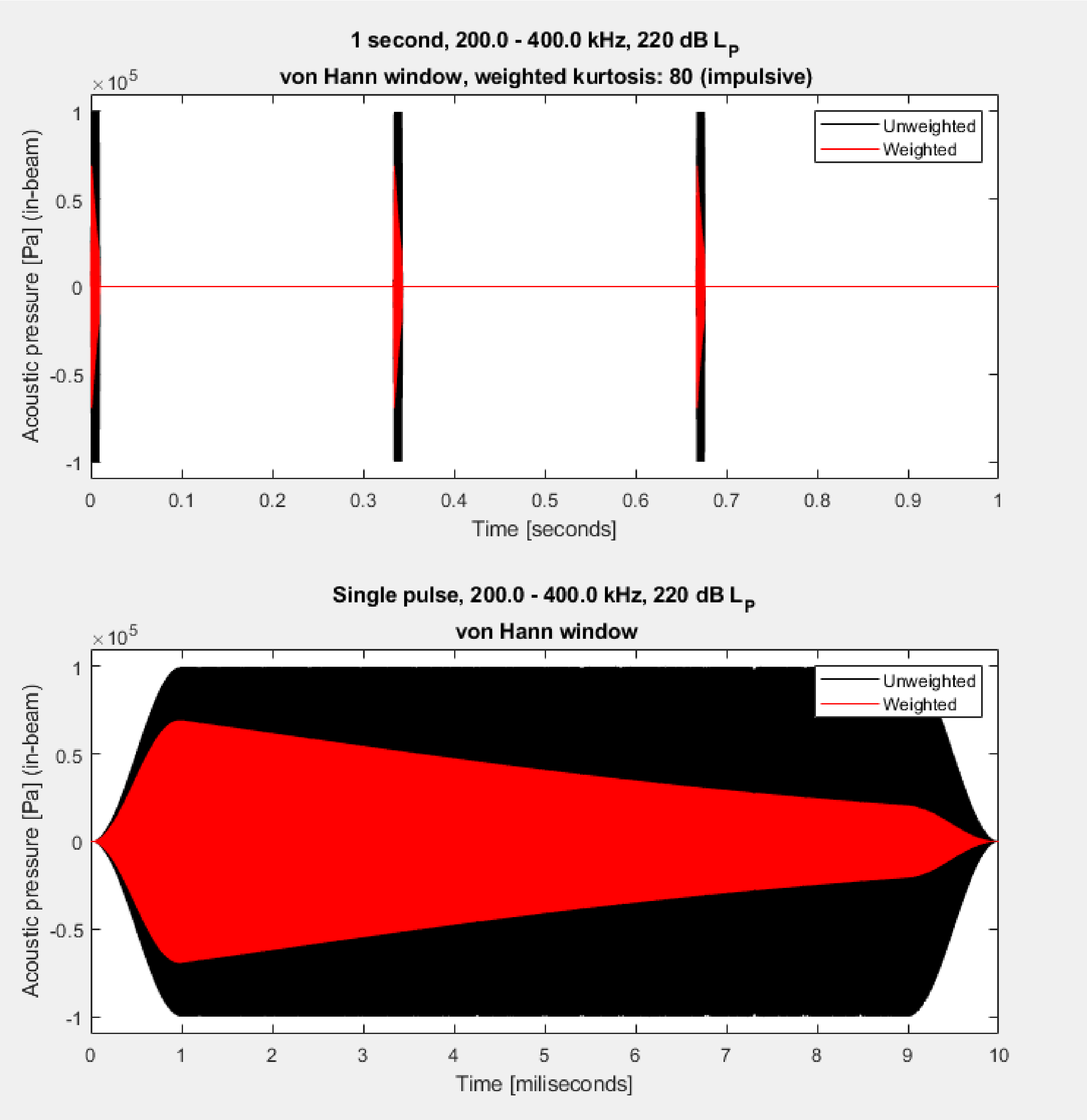

Figure 8-4. Example of a multibeam echosounder at 250 m depth (achieving 3 ping/sec) with a 10 ms ping duration. VHF-weighted kurtosis of 80 – impulsive.

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.

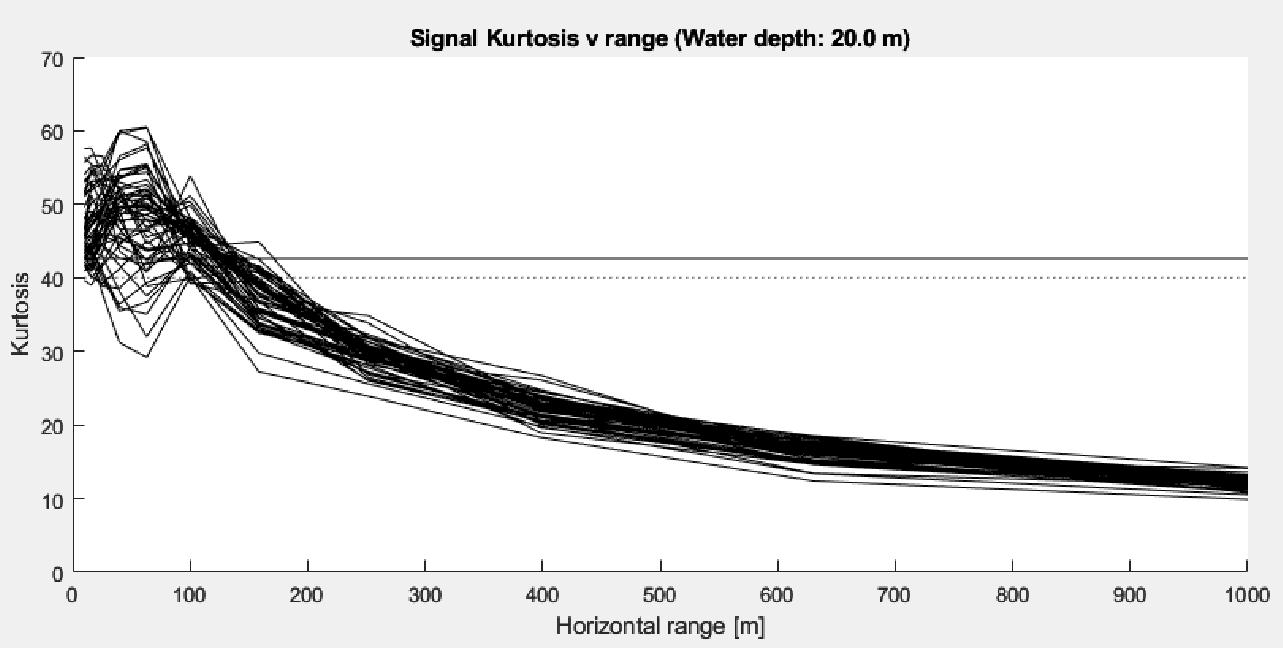

Figure 8-5. Example of USBL signal kurtosis decreasing with range at 20 m depth. Multiple lines are various combinations of source and receiver depths.

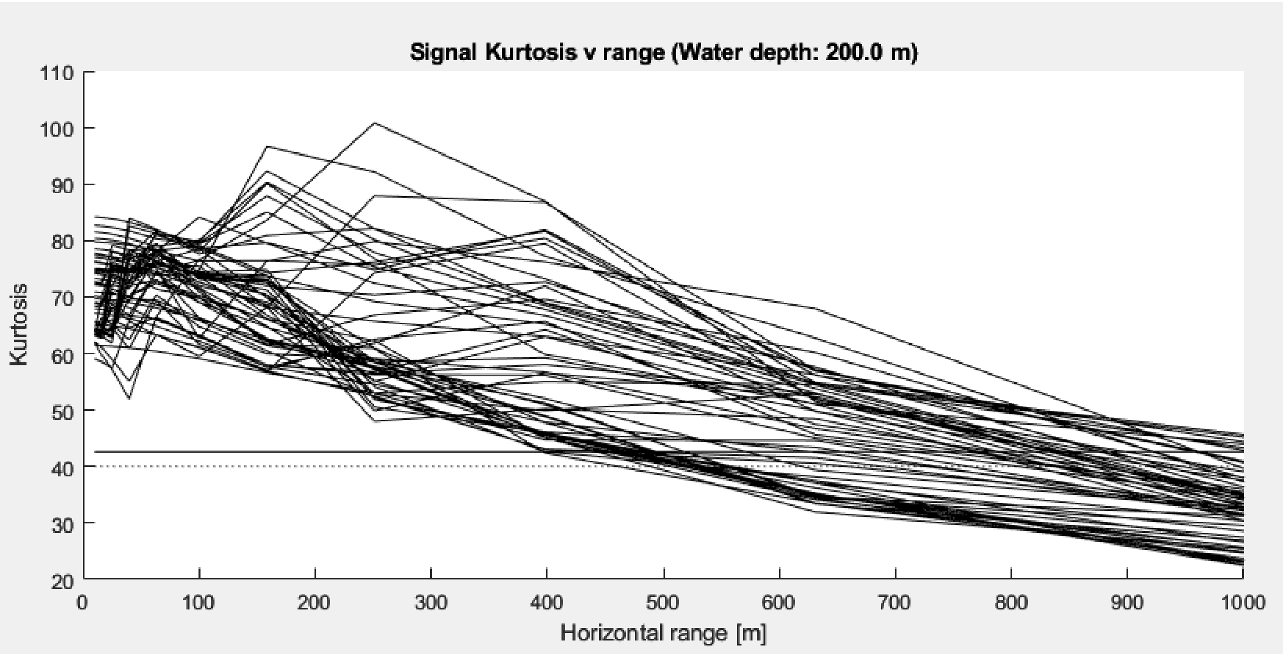

Figure 8-6. Example of USBL signal kurtosis decreasing with range at 200 m depth. Multiple lines are various combinations of source and receiver depths.

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[12] 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 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[13]) 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).

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[12] 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.

[13] 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.

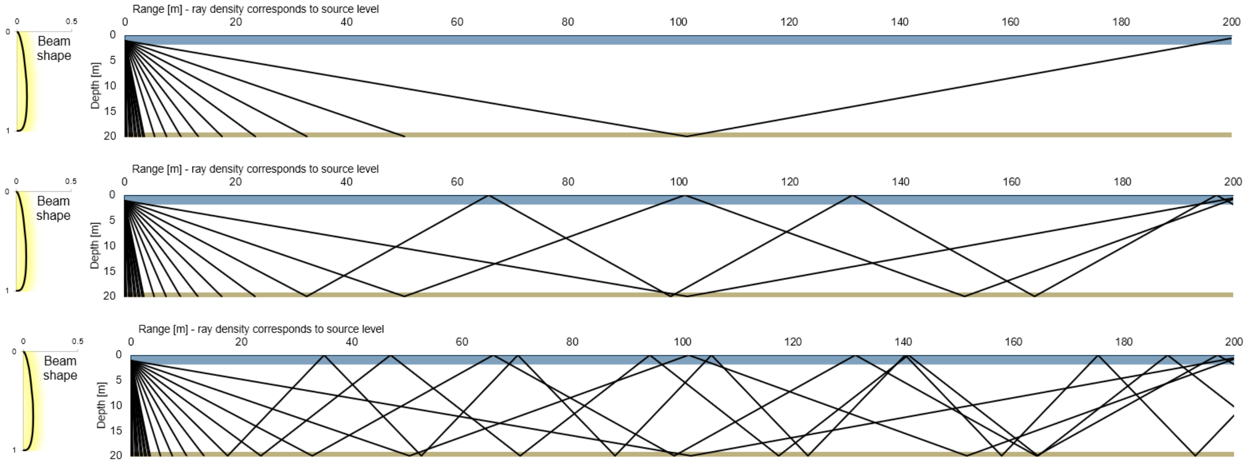

Figure 8-7: Schematic of the effect of sediment on sources with narrow beams. Sediments range from fine silt (top panel), sand (middle panel), and gravel (lower panel).

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.

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.

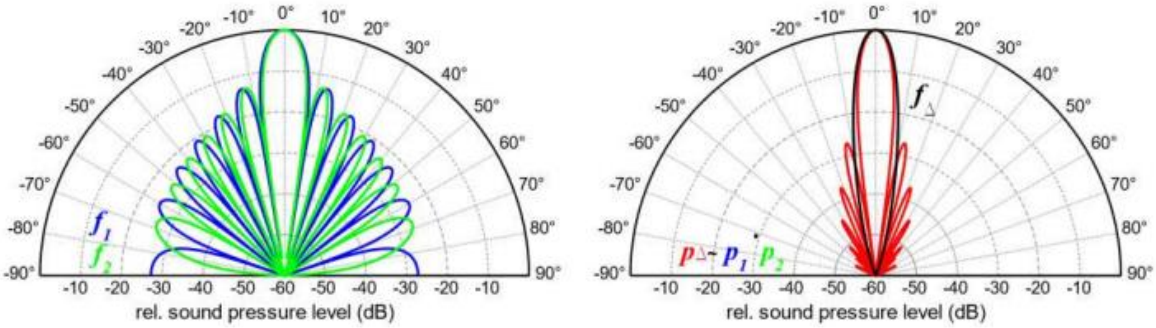

Figure 8-8. Example of a beam pattern on an Innomar SES 2000. Primary frequencies left (f1 & f2), the interference pattern between the primary frequencies means that the beam pattern for the secondary frequency (right plot) is very narrow (Source: Innomar technical note TN-01).

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.

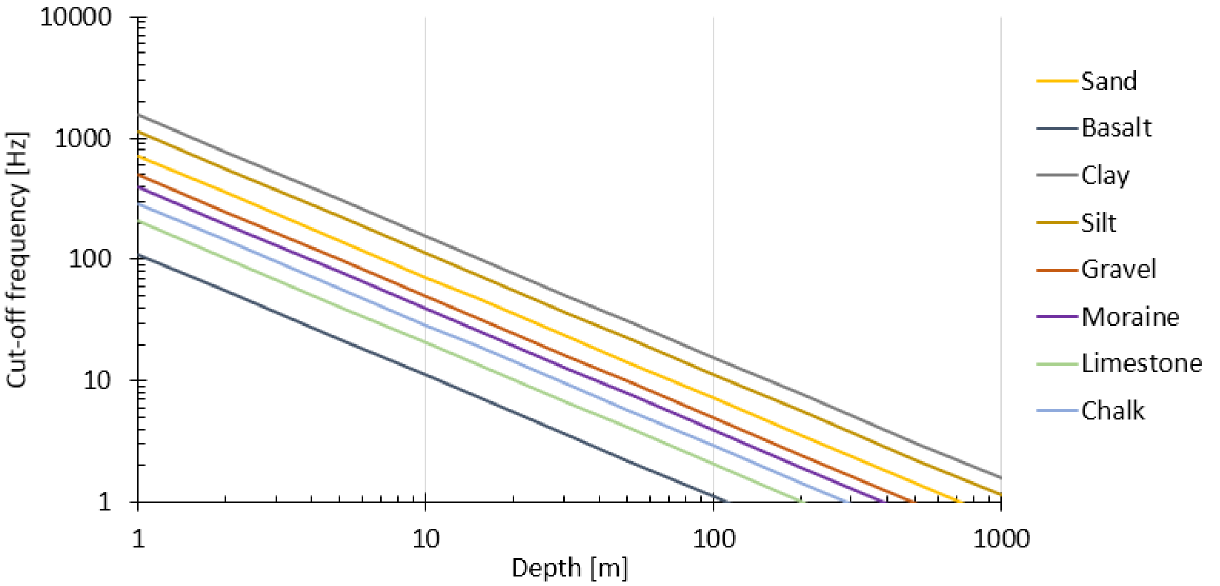

Figure 8-9: Lower cut-off frequency as a function of depth for a range of seabed types.

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.

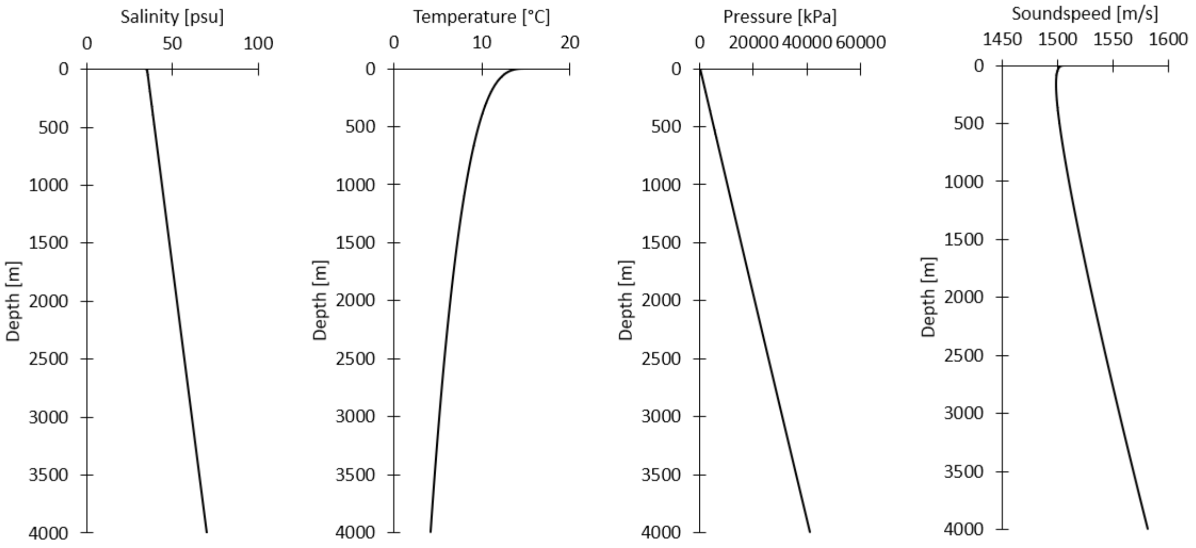

Figure 8-10: Soundspeed profile as a function of salinity, temperature and pressure.

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.

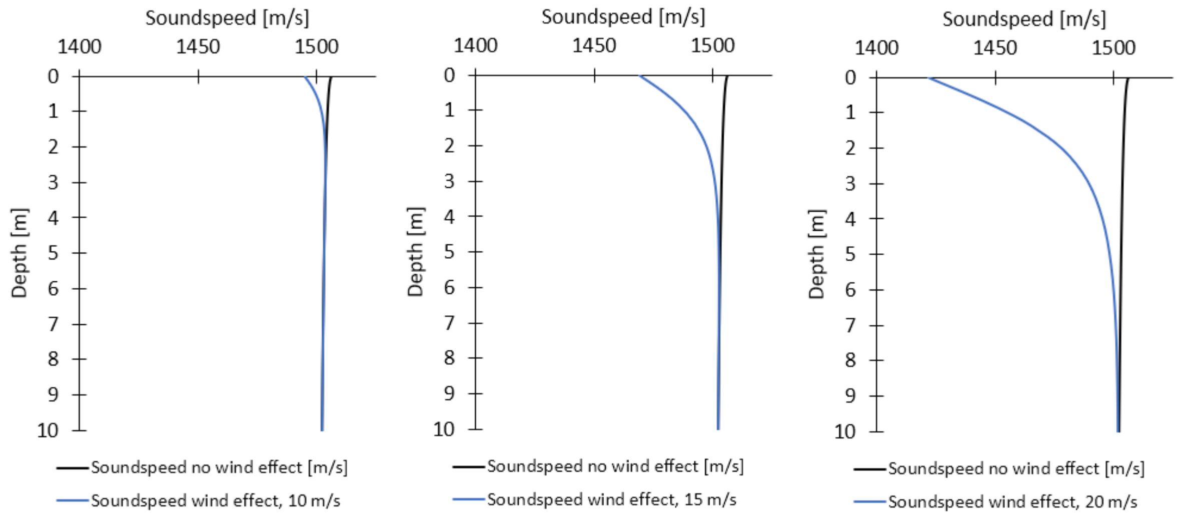

Figure 8-11: Effect of wind (at 10 m height) on upper portion of soundspeed profile.

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.

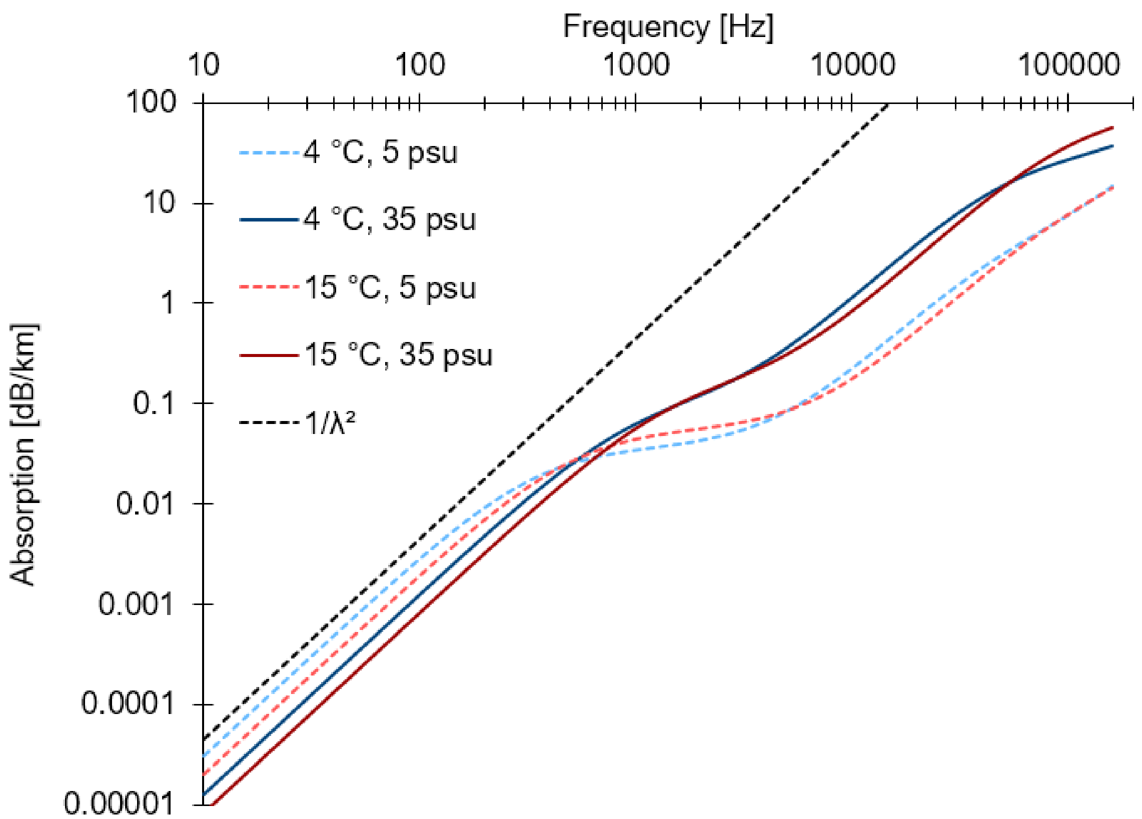

Figure 8-12: Absorption loss coefficient (dB/km) for various salinities and temperature.