MARITIME USAGE LICENCE: SUBSEA NOISE TECHNICAL REPORT

Oriel Wind Farm Project

Oriel Windfarm Limited

TETRA TECH

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Executive Summary

This report assesses the impact of underwater noise from the activities related to the site investigation (geophysical and geotechnical campaigns) of the Oriel Wind Farm project (the Project). The assessment presents impact as ranges to exceedance of acoustic thresholds for fleeing animals as well as ranges to onset of behavioural disturbance, reflecting best international practice.

Advanced source modelling and propagation modelling is used to calculate the sound field resulting from the Project, accounting for environmental factors such as depths, seasonality, sediment properties and species-specific characteristics like swimming speeds and hearing sensitivity.

The risk of exceeding auditory injury thresholds (AUD INJ) extends to a range up to 650 m for the VHF group (porpoises) during use of seismic sources. For the USV-based geophysical survey and the geotechnical survey the AUD INJ risk range is limited to 90 m for the VHF group. All other species have AUD INJ risk ranges below 10 m for all activities.

The risk of exceeding auditory temporary impairment thresholds (TTS) extends to 3,300 m for the VHF group where a survey uses a USBL device or a seismic source (sparker and/or boomer). For the remaining hearing groups (including all other marine mammals, fishes and turtles) the risk of exceeding the TTS thresholds extends up to 730 m, with seismic sources, USBL and vibratory coring being the main drivers of risk.

The activities using either USBL or seismic sources have potential to cause behavioural disturbance to ranges exceeding 20,000 m for all marine mammals except for otters with a range of 16,000 m, while the exceedance of the behavioural disturbance threshold for Fishes was exceeded up to 750 m and <10 m for turtles.

The results above assume a 20-minute soft start for sub bottom profilers and a 40-minute soft start for seismic sources (sparker and boomer) is implemented. The modelled 650 m AUD INJ risk ranges for porpoises will be mitigated through MMO efforts (pre-shoot surveys).

Acronyms/Abbreviations

Acronyms/Abbreviations	Definition
AUD INJ	Auditory Injury (synonymous with deprecated “PTS”)
c.	Circa, i.e., approximately
dB	Decibel, ten times the base ten logarithm of an intensity divided by a reference intensity. Also, ten times the base ten logarithm of a pressure squared divided by a reference pressure squared
Fishes	Fish species (here represented by most sensitive marine fish likely to be present)
HF	High Frequency (Cetaceans) (NOAA Fisheries 2024)
LF	Low Frequency (Cetaceans) (NOAA Fisheries 2024)
MF	Mid Frequency (Cetaceans) (deprecated, only for reference to NOAA/NOAA Fisheries 2018 groups)
VHF	Very High Frequency (Cetaceans) (NOAA Fisheries 2024)
NOAA	National Oceanic and Atmospheric Administration
NOAA Fisheries	National Oceanic and Atmospheric Administration Fisheries Service
NMFS	National Marine Fisheries Service (of the USA)
OW/OCW	Otariid pinnipeds (NOAA Fisheries 2024)/Other Carnivores in water (Southall 2019)
PK/L_{pk}/$L_{p,pk}$	Peak Sound Pressure Level [dB re 1 μPa]
PTS	Permanent Threshold Shift (deprecated, see “AUD INJ”)
PW/PCW	Phocid pinnipeds (NOAA Fisheries 2024)/Phocid Carnivores in water (Southall 2019)
RMS	Root Mean Square
SEL/L_E	Sound Exposure Level [dB re 1 μPa^2 s]
SL/L_S	Source Level [dB re 1 μPa m]
SPL	Sound Pressure Level [dB re 1 μPa]
SPL_{rms}/$L_{p,rms}$	Root-mean-squared sound pressure level [dB re 1 μPa] (equivalent to “SPL”)
TTS	Temporary Threshold Shift
TU	Sea Turtles (NOAA Fisheries 2023a)

Technical Terms

Term	Definition
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).
Auditory Injury (AUD INJ)	A total or partial permanent loss of hearing caused by acoustic trauma. AUD INJ results in irreversible damage to the sensory hair cells of the ear and thus often a permanent reduction of hearing acuity. The effect may be to reduce sensitivity to only a narrow frequency band or to cause broader hearing loss, depending on the stimulus.
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 (ISO 2017)
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 (ISO 2017)
Peak Level, Peak Pressure Level (L_{pk})	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 (ISO 2017)
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	Refers to a set 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).

Term	Definition
	Defined in ISO 5479:1997
Typical	Here meaning between 10th and 90th percentile.

Units

Unit[a]	Definition
dB	Decibel (Sound)
Hz	Hertz (Frequency)
kHz	Kilohertz (Frequency)
kJ	Kilojoule (Energy)
km	Kilometre (Distance)
km^2	Kilometre squared (Area)
m	Meter
ms	Millisecond (10^{-3} seconds) (Time)
ms^{-1} or m/s	Meters 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 $(Pa \cdot s)/m^3$]
sec	Second or seconds

[a] Units will generally be enclosed in square brackets in plots and tables (e.g., “[m/s]”)

1.0 Introduction

This report assesses the impact of noise from the activities related to the site investigations of the Oriel Wind Farm project (the Project). The assessment presents impact as ranges to exceedance of acoustic thresholds for fleeing animals as well as ranges to onset of behavioural disturbance, reflecting best international practice.

The main activities and noise source associated with the Project are listed below with Figure 3-1 showing an overview of the assessment area.

The main underwater noise sources are:

- USV-based geophysical survey of mainly shallower areas.
- Geophysical survey using seismic sources (sparker and/or boomer) in addition to either a parametric or chirper/pinger type SBP.
- Geotechnical survey including rotary coring, vibratory coring and various penetration testing methods.

Further details are presented in Section 4.0 Source Levels.

1.1 Purpose of the report

The activities necessary to complete the Project will emit noise with the potential to cause adverse effects on marine life. At close ranges from a noise source with high noise levels, injury or death might occur, while permanent hearing injury or brief hearing impairment is more likely to extend to medium and long ranges. At long ranges (kilometres), the introduction of noise could, for the duration of the activity, potentially cause behavioural disturbance, e.g. changes resulting from reducing the ability of species to communicate and to determine the presence of predators, food and underwater features.

This report provides an overview of the potential effects due to underwater noise from the proposed SI works on the surrounding marine environment based primarily on the NMFS/NOAA 2024 and Popper et al. 2014 frameworks for assessing impact from noise on marine mammals and fishes.

Consequently, the main purpose of this underwater noise assessment is to predict the likely range of onset of temporary auditory impairment (Temporary Threshold Shift [TTS]) and auditory injury (Auditory Injury [AUD INJ]) due to anthropogenic noise resulting from the site investigation activities. 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 (NMFS, 2024; Popper, et al., 2014; Southall, et al., 2019).

1.2 Statement of authority

This report has been prepared by Tetra Tech on behalf of Oriel Windfarm Limited. The technical competence of the authors is outlined below:

Rasmus Sloth Pedersen is a Senior Scientist with Tetra Tech. He holds a master's degree in biology, biosonar and marine mammal hearing from University of Southern Denmark. Rasmus has over 12 years' experience as a marine biologist and over 10 years' experience with underwater noise modelling and marine noise impact assessments. Rasmus has co-developed commercial underwater noise modelling software, as well as developed multiple source models for e.g. impact piling, seismic airgun arrays, explosives and sonars. Rasmus is a member of the Institute of Acoustics and a chartered scientist with the Institution of Environmental Sciences.

John Mahon is a Senior Associate in Acoustics with Tetra Tech. 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. John has 22 years' experience in environmental projects including planning applications and environmental impact assessments for a wide range of strategic infrastructure projects.

Sean Mansfield is a Project Scientist in Acoustics with Tetra Tech. He holds a BA (Hons) in Music Technology from Maynooth University and a Postgraduate Diploma in Acoustics and Noise Control from the Institute of Acoustics. He has over three years' experience working in a wide range of environmental areas, including road, rail, offshore wind, industrial, flood relief, underwater noise, and bat acoustics analysis projects. He is an associate member of the Institute of Acoustics and the Institution of Environmental Sciences.

2.0 Assessment Criteria

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 (NMFS, 2024; Popper, et al., 2014; Southall, et al., 2019).

2.1 Sound Classification

Underwater noise is generally split into two categories, depending on its characteristics:

- **Impulsive sounds:**
  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:**
  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 in the reference). However, the guidance suggests that “all loud sounds of duration less than 10 seconds should be included” as impulsive. This contradicts research on impact from impulsive sounds suggesting that a limit for “impulsiveness” can be set at a kurtosis[1] of 40 (Martin & Klaus Lucke, 2020). See examples in Appendix A, Impulsiveness.

Therefore, a criterion of kurtosis over 40 is used here to identify impulsive sounds. The justification for departing from the MSFD criterion is that the NMFS 2024 and the Popper et al. 2014 frameworks thresholds are based on the narrower definition of impulsive as given in “Impulsive sounds” above.

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

2.2 Sound Impact & Effects

Underwater noise has the potential to affect marine/aquatic life in different ways depending on its noise level and characteristics. We here define five zones of noise impact:

- **The zone of audibility:**
  This is defined as the area within which the animal can detect the sound. Audibility itself does not imply that the sound will affect the animal. There are no agreed thresholds for this level of effect.
- **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

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

relating to how animals detect sound in relation to masking levels (for example, humans can hear tones well below the numeric value of the overall sound level). Continuous sounds will generally have a greater masking potential than intermittent sound due to the latter providing some relative quiet between sounds. Masking only occurs if there is a near-overlap in sound and signal frequency content, such that a loud sound at e.g., 1000 Hz will not be able to mask a signal at 10,000 Hz. [2] There are no agreed thresholds for this level of effect.

- **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 as audibility does not necessarily evoke a reaction. For most species, there is very little data on response, but for species like harbour porpoise there exist several studies showing a relationship between received level and probability of response (Graham IM, 2019; Sarnocinska J, 2020; BOOTH, 2017; Benhemma-Le Gall A, 2021). This zone is quantified here with the use of hearing group specific behavioural thresholds based on UK and Danish guidance (Table 2-2, Section 2.3.1.1 & Table 2-3). However, while the range to exceedance of these thresholds is easy to quantify, given animal habituation and varying ambient noise, these are only relevant alongside an interpretation by a competent marine ecologist.
- **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 Auditory Injury ("AUD INJ"). At even closer ranges, and for very high intensity sound sources (e.g., underwater explosions), physical trauma or acute mortal injuries are possible. In relation to fish, we included the impact "Recoverable Injury" as AUD INJ, as while it is not permanent it is a serious effect and assumed to have associated significant costs to population fecundity.

For this study, it is the zones of temporary adverse auditory effects (TTS) and auditory injury (AUD INJ) that are of primary interest.

Irish Guidance Interpretation of Marine Mammal Thresholds

The NPWS/DAHG "Guidance to Manage the Risk to Marine Mammals from Man-made Sound Sources in Irish Waters" 2014[3] (Department of Arts, Heritage and the Gaeltacht, 2014) prescribes the use of thresholds from a 2007 publication (Brandon L. Southall, 2007), and further argues that TTS can be considered injury. The weightings and thresholds from the guidance have since been superseded (Southall, et al., 2019; NMFS, 2024) and no longer represent best available science or best practice internationally. Thus, the following excerpt from the guidance is relevant:

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

As there has been no such update to date and the guidance clearly states its intention to consider new scientific findings, we have applied the latest guidance for marine mammals (NMFS, 2024), reflecting the

[2] The exact limit of how near a noise can get to the signal 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.

[3] A new iteration of this guidance document is imminent, expected to align further with NMFS2024 & Southall et at. 2019 guidance (DCE, 2025).

current best available method for assessing impact from noise on marine mammals. This means that following current scientific best practice, AUD INJ" (previously "PTS") is the criteria for injury, not "TTS".

It is worth noting that the NPWS 2014 guidance's reliance on Southall et al. 2007 TTS thresholds mean that for most scenarios, the impact ranges are comparable to the AUD INJ threshold from the NMFS 2024 guidance. Where NPWS 2014 is more conservative, it is often the result of including noise at frequencies where the relevant species group is not very sensitive (the weightings from Southall et al. 2007 were very broad, "letting in" a lot of energy not audibly to the animal). The Southall et al. 2007 thresholds and weightings were based on very little evidence compared to the NMFS 2024 weightings).

The TTS thresholds in Southall et al. 2007, Southall et al. 2019 and NMFS 2024 are not direct measurements of an exact exposure level where TTS occurs. Rather the TTS thresholds are based on the level where 6 dB of TTS is expected in the test animal. The 6 dB level itself is found by plotting the exposure level against the amount of TTS caused by that exposure level and then fitting a regression line to estimate the amount of TTS caused per dB increase in exposure level. This line can then be used to estimate the level where 6 dB of TTS is expected.

The PTS/AUD INJ threshold is the received level at which 40 dB of TTS is expected (40 dB TTS is believed to lead to PTS/AUD INJ). This has two important consequences:

1. At received levels equal to the TTS onset threshold, the expected TTS is 6 dB, not 0 dB, meaning that if *any* TTS is considered injury, no guidance currently contains sufficient information to assess impacts according to the NPWS 2014 guidance (where the language implies that any TTS should be considered injury).
2. Received levels below the PTS/AUD INJ thresholds are all seen as recoverable by Southall et al. 2007 & 2019 and NMFS 2024, they give rise to only "TTS". Given the lack of a stated *acceptable level* of TTS in the NPWS guidance, the guidance is open to interpretation as to whether the "*potential to induce TTS"* is at levels likely to cause 0 dB to 40 dB of TTS.

2.3 Auditory Thresholds

Thresholds for effects from peak sound pressure level (L_{pk}) and sound exposure level (SEL) are taken from the NOAA Fisheries *2024 Update to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing* (Version 3.0) (NMFS, 2024), the Acoustical Society of America (ASA) Report titled *Sound Exposure Guidelines for Fishes and Sea Turtles* (Popper, et al., 2014), and *National Marine Fisheries Service: Summary of Endangered Species Act Acoustic Thresholds (Marine Mammals, Fishes and Sea Turtles)* (NMFS [ESA], 2024). These three reports reflect the latest robust scientific consensus and recommended assessment criteria for assessing the effect of noise on marine mammals, fishes, and turtles.

There are generally two categories of auditory effects characterized by being either temporary or permanent in nature. Here defined as:

- **Temporary Threshold Shift (TTS):**
  A loss of hearing sensitivity that affects all, or a part of, the hearing range for a limited time (minutes to hours) but has no permanent adverse effects on the auditory system. This criterion is referred to as "TTS" in both Popper et al. (2014) and NOAA Fisheries (2024).
- **Auditory Injury (AUD INJ):**
  An injury to the auditory system that may be associated with a permanent loss of hearing sensitivity that affects all, or part of, the hearing range permanently. This criterion was previously referred to as "PTS" (permanent threshold shift) but has been renamed in NOAA Fisheries (2024) to acknowledge that auditory injury can occur with no measurable loss of hearing function. For the purpose of this report, AUD INJ (NOAA Fisheries 2024) is equivalent to "Recoverable Injury" in Popper et al. (2014).

While the above two effects are often used as simple on/off limits, it's important to stress that they are *onset thresholds*. This means that at received levels matching the TTS threshold, 6 dB of TTS is expected to have occurred – this is the effective onset of TTS. Thus, some TTS might occur below that threshold, and more TTS (> 6dB) will likely occur above that threshold. The AUD INJ threshold is set as the received level where 40 dB of TTS is expected (not 40 dB above the TTS onset threshold).

The criteria for peak pressure level are based on the unweighted peak pressure level (dB L_{pk}) as received by the animal, likely to elicit the effect (TTS or AUD INJ/Recoverable Injury).

The criteria for SEL are based on unweighted[4] (fishes) or weighted (marine mammals and turtles) SEL as received by the animal, likely to elicit the effects (TTS or AUD INJ/Recoverable Injury).

2.3.1 Marine Mammal Thresholds

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

- **Low Frequency (LF) cetaceans:**
  Marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*).
- **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/PC):**
  True 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/OC):**
  Including otariid pinnipeds (e.g., sea lions and fur seals), otters and polar bears; in-air hearing is considered separately in the group Other Marine Carnivores in Air (OCA).
- **Sirenians (SI):**
  Manatees and dugongs.
- **Turtles (TU):**
  All marine turtles (NIWC Pacific, 2024)

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

[4] Note that a weighting applies >10 kHz, see section 2.3.2

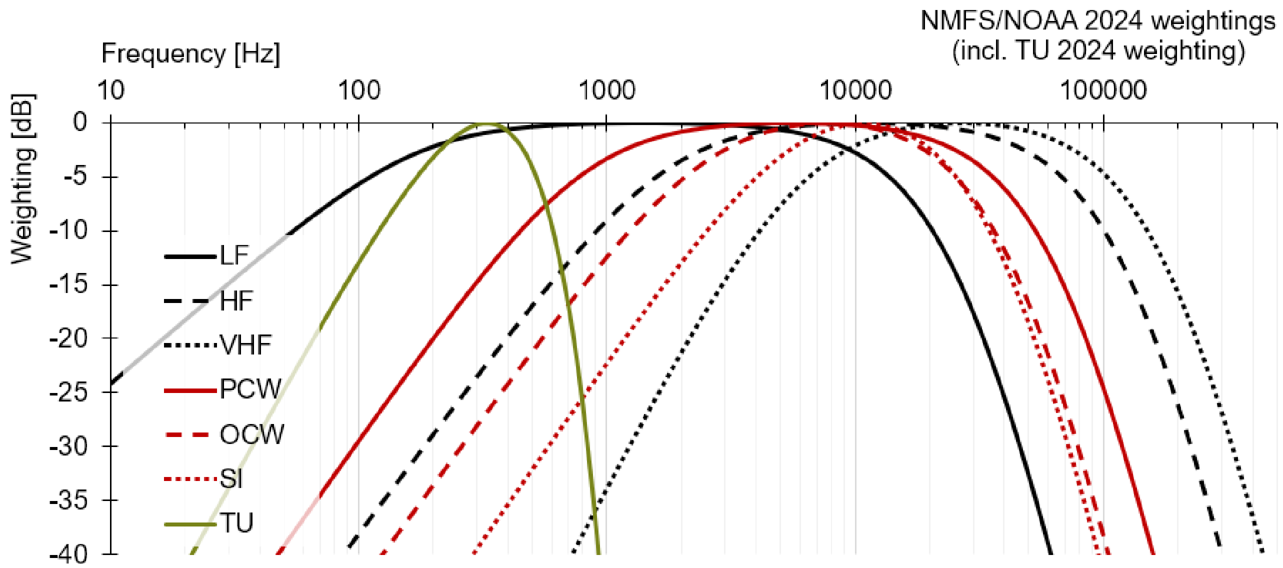

Figure 2-1. Auditory weighting functions for seals, whales and sirenians (NMFS, 2024). Turtles from (NIWC Pacific, 2024; Finneran, 2024).

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

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

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

Southall et al. 2019 vs NMFS 2024

The NMFS 2024 weightings and thresholds are used in this assessment. These are based on the same approach as Southall et al. 2019 but represent the product of a review process not including European partners, and as such, some countries still prescribe the use of Southall et al. 2019 (e.g. Denmark). The main difference is that the HF group weighting (most dolphins) includes more energy at lower frequencies but combined with higher thresholds. The net result for assessment purposes is small, but as the NMFS 2024 guidance represents broader evidence base and uses the same methods as Southall et al. 2019, we recommend the use of those weightings and thresholds.

2.3.1.1 Disturbance to Marine Mammals

The noise thresholds for disturbance onset of marine mammals are not as mature as the AUD INJ and TTS onset thresholds and several different approaches exist. A conservative but realistic approach based on a review of Danish and UK guidance documents, as well as scientific reviews, has been applied and reflects the approach of the Danish guidance (Danish Centre for Environment and Energy, 2021) and a review submitted to the JNCC (Joint Nature Conservation Committee) of the UK (Nedwell, et al., 2007). A review for Natural Resources Wales (Sinclair, Kazer, Ryder, New, & Verfuss, 2023) also acknowledges this approach as suitable.

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

It is important to state that while these thresholds are good indicators of onset of behavioural disturbance, they are not diagnostic of realised behavioural effects. In this way, they are qualitatively different to the thresholds for TTS and AUD INJ, where individual animal preference and learning is irrelevant.

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

Effect	Non-impulsive Threshold [SPL]	Impulsive Threshold
Low frequency (LF) cetaceans	120	120
High frequency (HF) cetaceans	113	106
Very high frequency (VHF) cetaceans	103	98
Phocid carnivores in water (PCW)	120	120
Other marine carnivores in water (OCW)	120	120

Contrary to the NOAA level B harassment levels, where the threshold for impulsive noise (160 dB SPL[5]) is higher than for non-impulsive noise (120 dB SPL), thresholds presented here are lower for noises that are impulsive at the source, as this matches the observed tendency for impulsive noise to generate a greater behavioural response than non-impulsive noise (Danish Centre for Environment and Energy, 2021; Sinclair, Kazer, Ryder, New, & Verfuss, 2023; Nedwell, et al., 2007).

[5] SPL duration of 90-95% energy of a single pulse.

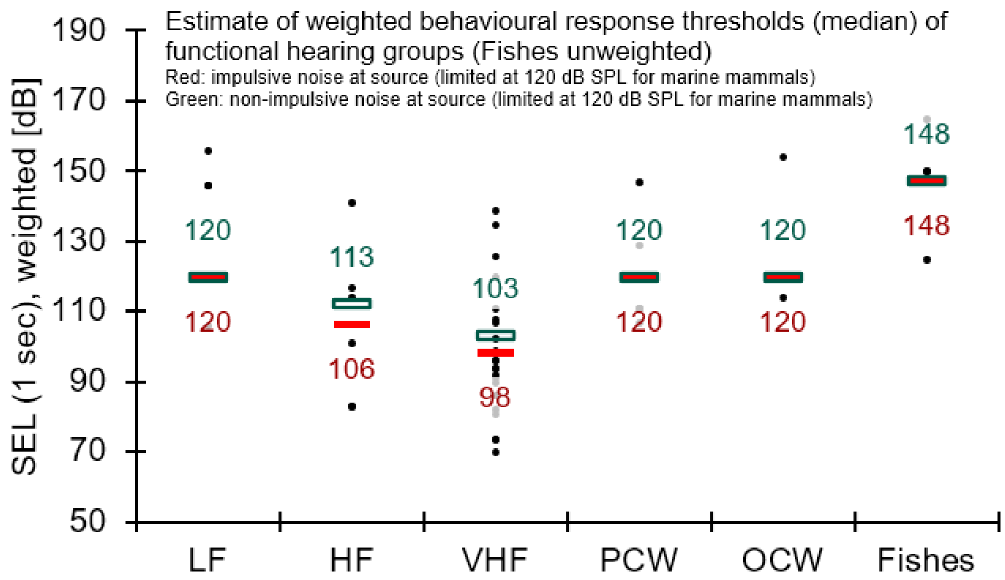

Figure 2-2. Data and behavioural disturbance thresholds. Lines/values given are median values or 120 dB SPL, whichever is lower. Red is impulsive. Green is non-impulsive.

2.3.1.2 Habituation and Animal Preference

The estimates for behavioural disturbance onset thresholds use data from animals both naïve and accustomed to anthropogenic noise, so the large variation in level required to elicit a response is likely to be, at least partly, due to real differences in sensitivity to noise types according to animal tolerance, rather than conventional measurement uncertainty. Thus, noises which are familiar to the animal, but not associated with discomfort, are expected to elicit responses only at higher received levels than noises which are novel, and noises which might be associated with discomfort that expected to elicit a response at lower received levels (e.g. impact pile driving or explosions).

Without field studies in the Project area, determining site-specific behavioural disturbance thresholds is not possible, and thus the thresholds are estimates reflecting the levels where 50 % of animals in the referenced studies reacted to a measurable degree. The thresholds do not necessarily indicate the onset of adverse effects, but rather show the potential received level where animals are likely to notice an activity and potentially adapt their behaviour in response.

As the thresholds are well below TTS levels, the behavioural response of an animal is to a large degree determined by the animal itself and the resulting behaviour pattern is based on much more than simply the received level (e.g. hunger, curiosity, migration).

2.3.2 Fishes Thresholds

The injury criteria used in this noise assessment are based on Popper et al. 2014 and are given in Table 2-3 for impulsive noises (L_{pk}) and Table 2-4 for continuous noise (SEL).

There are not generally agreed weightings for fishes, but it is important to clarify that this lack of weighting for fishes reflects a lack of scientific consensus about the best method for applying frequency dependence to received levels for fishes, rather than a statement that fishes can hear all frequencies equally well. Thus, fishes generally cannot hear above 10 kHz, and if they can, the sensitivity is generally very poor (Figure 2-3, (Nedwell, Edwards, Turnpenny, & Gordon, 2004)). Where received levels at frequencies above 10 kHz are the driver of risk ranges for fishes, an effective filter for noise above 10 kHz is applied (Figure 2-3).

While there is no accepted guidance that prescribes a suitable weighting for fish, it remains unrealistic to allow high-frequency noise from continuous noise drive large risk for fishes, as they evidently cannot register it and their acoustic system is not adversely affected by it. This is not true for peak pressure, and L_{pk} thus remain completely unweighted.

Thresholds presented in tables for L_{pk} are unweighted while SEL criteria are unweighted below 10 kHz.

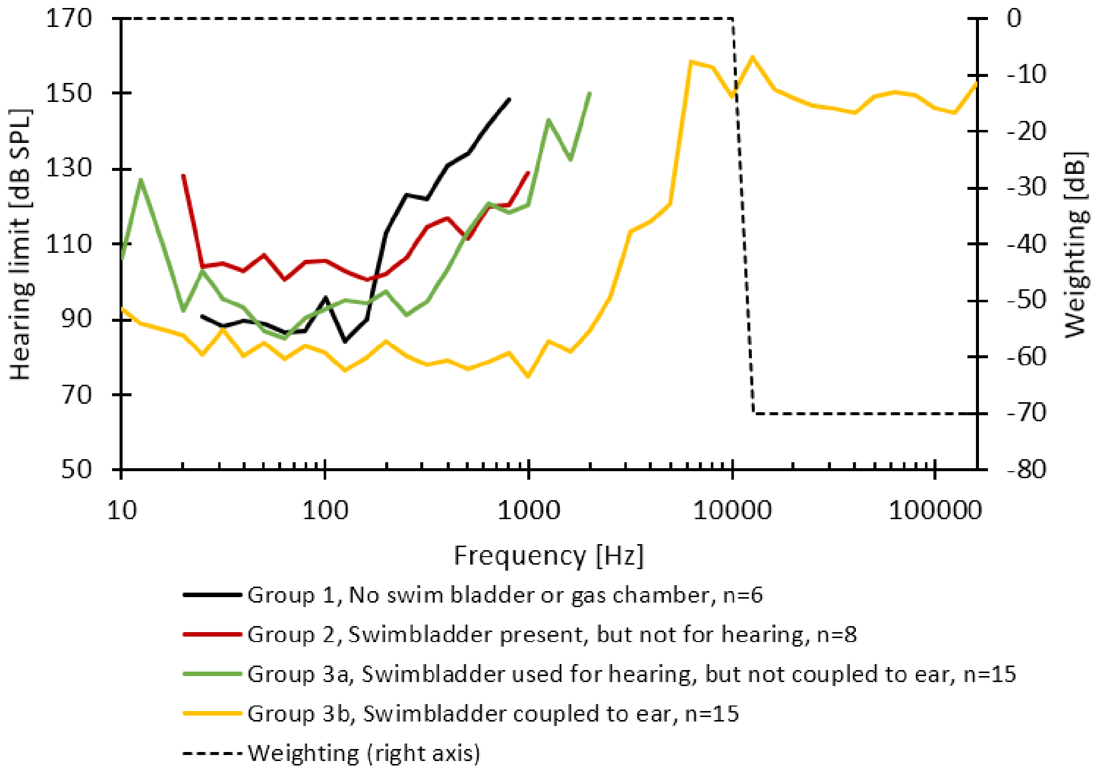

Figure 2-3. Generalised hearing thresholds for fishes grouped by the presence of a swim bladder and its role in hearing.

Popper et al. 2014 does not set out specific TTS limits for L_{pk} nor for behavioural disturbance for impulsive noise. 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) are used to determine limits for these:

- **Threshold for behavioural disturbance from impulsive noise as SPL:**
  The Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual (WSDOT, 2020) 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. Data from UK and Danish studies suggest 148 dB SPL as a suitable threshold for onset of behavioural disturbance and NIWC Pacific suggests 150 dB SPL.

- **Behavioural disturbance threshold from impulsive noise as Lpk:**
  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 Lpk, the 10th percentile level for behavioural response was 160 dB Lpk (rounded to nearest 5 dB to reflect large variation in data).
- **TTS thresholds for Lpk:**
  The report titled "Canadian Department of Fisheries and Ocean Effects of Seismic energy on Fish: A Literature review" (Worcester 2006), was used to estimate likely TTS thresholds (Figure 2-4). This review resulted in an estimate of TTS for fishes of 193 dB Lpk. Note that this is a 14 dB difference from the Recoverable Injury (207 dB Lpk) threshold, not a 6 dB difference as for marine mammals. For ethical reasons, auditory injury of marine mammals was not evaluated experimentally, so AUD INJ thresholds are conservatively estimated to occur at 6 dB above the TTS threshold, which was established from experiments on terrestrial mammals that show onset of injury at similar levels (Southall 2007). For fish, there *has been* direct observation of auditory/recoverable injury in experiments, so there is no need to estimate the injury threshold from the TTS threshold.

Following the analyses above:

- Behavioural disturbance thresholds for fishes for impulsive noise are 160 dB L_{pk}, and 148 dB SPL.
- TTS onset threshold for L_{pk} is 193 dB L_{pk}.

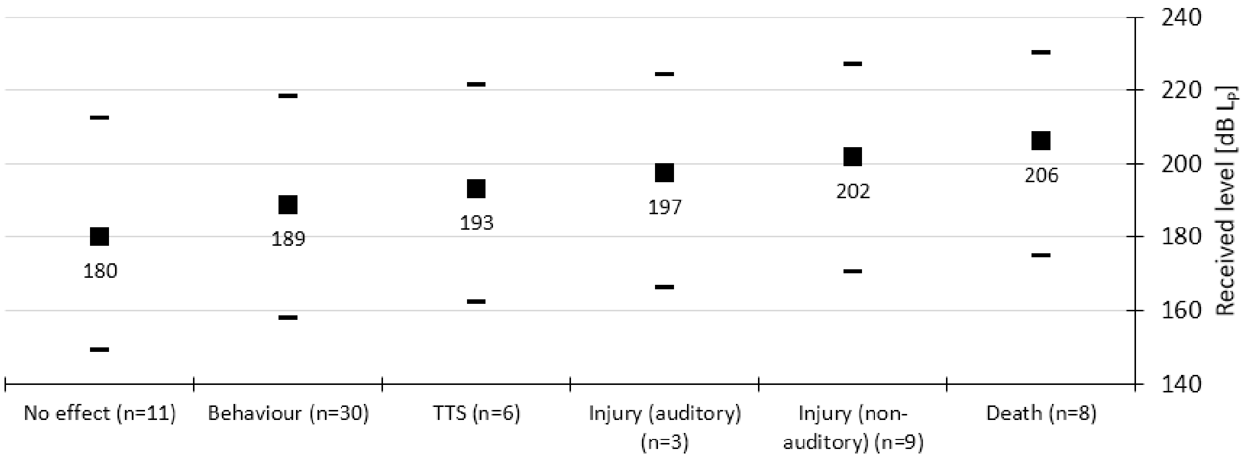

Figure 2-4. Effects of impulsive noise on fish from Effects of Seismic Energy on Fish: A Literature Review (Worcester 2006). Mean values (squares) and 10th & 90th percentile (lines).

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

Table 2-3 presents the criteria for onset of injury to fishes due to impulsive noise. Where Popper et al. 2014 present limits as ">" 207 or ">>" 186, we have ignored the "greater than" and used the threshold level as given.

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

Type of Animal	Unit	Mortality and Potential Mortal Injury [dB]	Recoverable Injury (AUD INJ) [dB]	TTS [dB]	Behavioural [dB]
Fish: no swim bladder (particle motion detection) Example: Sharks.	SEL	219[1]	216[1]	186[1]	150[3]
	L_{pk}	213[1]	213[1]	193[2]	160[2]
Fish: where swim bladder is not involved in hearing (particle motion detection). Example: Salmonoids.	SEL	210[1]	203[1]	186[1]	150[3]
	L_{pk}	207[1]	207[1]	193[2]	160[2]
Fish: where swim bladder is involved in hearing (primarily pressure detection). Example: Gadoids (cod-like).	SEL	207[1]	**203[1]**	**186**	**148[4] [SPL]**
	L_{pk}	207[1]	**207[1]**	**193[2]**	**160[2]**
Sea turtles	SEL	210[1]	(*Near*) High* (*Mid*) Low (*Far*) Low	-	-
	L_{pk}	207[1]		-	-
Eggs and larvae	SEL	210[1]	(*Near*) Moderate (*Mid*) Low (*Far*) Low	-	-
	L_{pk}	207[1]		-	-

[1] (Popper et al. 2014) table 7.4, [2] (Worcester, 2006), [3] (WSDOT, 2020), [4] (Danish Centre for Environment and Energy, 2021; Sinclair, Kazer, Ryder, New, & Verfuss, 2023; Nedwell, et al., 2007)

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

Relevant thresholds for non-impulsive noise for fishes relating to AUD INJ, TTS, and behaviour are given in Table 2-4. Note that not all of these thresholds exist exactly as stated in the guidance but had to be derived with regard to exposure time.

Table 2-4. Criteria for fish (incl. sharks) due to non-impulsive noise from Popper et al. 2014 (Table 7.7 & 7.5) and UK & Danish guidance.

Type of Animal	Unit	Mortality and Potential Mortal Injury [dB]	Recoverable Injury (AUD INJ) [dB]	TTS [dB]	Behavioural [dB]
All fishes	SEL	(Near) Low (Mid) Low (Far) Low	222[b]	204[b]	-
All Fishes	SPL	>193[c]	193[d]	193[d]	148[a]

[a] Based on review in Section 2.3.1.1, also Figure 2-2.

[b] Based on 48 hours of 170 dB SPL and 12 hours of 158 dB SPL

[c] "greater than" 193 dB SPL as no effect was seen at this level, so the threshold must lie above this.

[d] Given as ">193 dB SPL" in Popper et al 2014 but applied in this assessment as 193 dB SPL. An SPL level of 193 dB for 2 hours (the exposure time for this report) equals 222 dB SEL.

3.0 Site and Environment

This section sets out the general location of the underwater noise modelling as well as acoustically relevant parameters.

3.1 Modelling Locations

The area of relevance for this underwater noise impact assessment is presented in Figure 3-1, and includes the Project MUL area (red line), with an additional 20 km buffer (not shown) to allow for sufficient range for modelling of fleeing.

For the noise modelling the area has been split into four representative sectors based on characteristic depths (10^{th}, 50^{th} and 90^{th} percentile depth) and sediment types (sandy mud to rocks & boulders) to ensure sufficient coverage of the variations within the MUL area (Table 3-1).

Table 3-1. Modelling locations and sediment properties

Sector name	Typical depth [m]	Sediment type ISO (14688-1:2017)	Density [kg/m³]	Soundspeed [m/s]	Approx. easting (UTM 29N)	Approx. northing (UTM 29N)
Shallow	15	Coarse substrate	2968	2224	684849	5972828
Mid depth, West	25	Sandy mud	1554	1545	687424	5974599
Mid depth, North-East	25	Coarse substrate	2968	2224	693756	5980579
Deep	32	Rock & boulders	3685	2599	692977	5976534

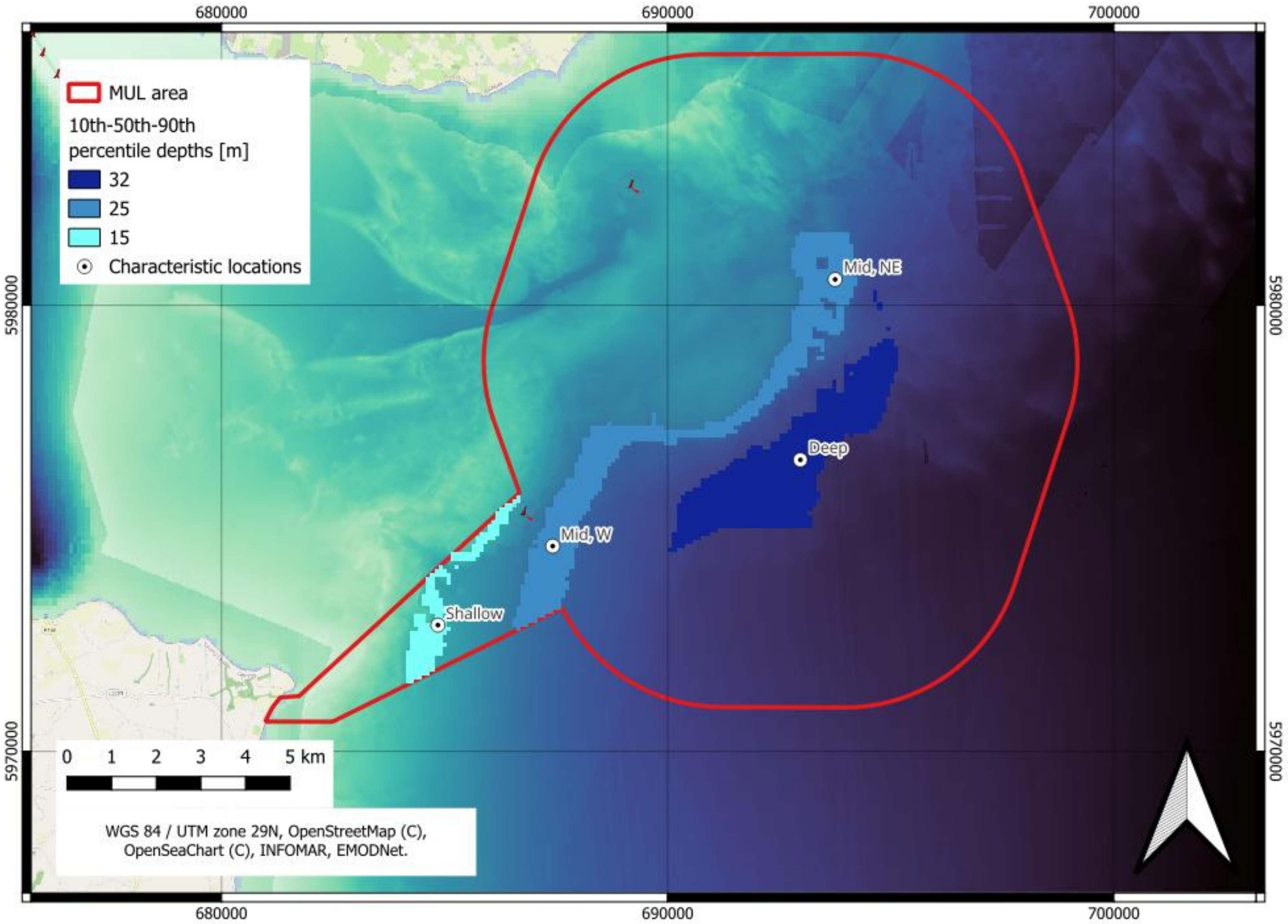

Figure 3-1. MUL area (incl. 4 km around offshore wind farm area) and characteristic locations and depths.

3.2 Environment

3.2.1 Water Properties

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

- Temperature: 7 – 13 degrees Celsius – temperatures given by Met Eireann for the north Irish Sea[6].
- Salinity: 34 psu.
- Soundspeed profile: Winter profile assumed, with slight increase in soundspeed with increasing depth throughout the water column. This is conservative compared to the likely downward refracting soundspeed profiles seen during summer months, causing increased loss to the sediment (higher temperature in the surface leads to higher soundspeeds).

3.2.2 Sediment Properties

Sediment properties are based on sediment data from the EMODnet[7] "Folk 7-class Classification", nautical charts[8] and British Geological Survey (British Geological Survey, 2023). A sediment model (Ainslie, 2010) was used to derive the acoustic properties of the sediments from the grain size associated with the sediment classification leading to the lowest transmission loss (larger grain size). Sediment properties are given in Table 3-1 above. Note that only surface sediment information is given as for high-frequency propagation, only the first few centimetres to meters are relevant for sound propagation. An upward refracting soundspeed profile in the sediment is assumed (increasing sediment density and soundspeed with increasing depth).

[6] https://www.met.ie/climate/average-monthly-sea-temperature-at-malin-head/

[7] https://emodnet.ec.europa.eu/ sediment model "Folk 7-class" classification.

[8] https://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-charts-navigation.html

4.0 Source Levels

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

For a large sound source, this imagined point at 1 m from this acoustic centre does not exist, the energy is distributed across the source (like a ship's hull) and does not all emanate from this imagined acoustic centre point. Rather it's the position in space that would lead to the equivalent received level at range (usually from ranges greater than the largest dimension of the source). Therefore, the stated sound pressure level at 1 m does not exist for large sources. For such 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 as presented in Figure 4-1, which presents the received level trend from a line source versus the modelled level assuming an equivalent monopoint source (Appendix A: Acoustic concepts and terminology, Near field and far field).

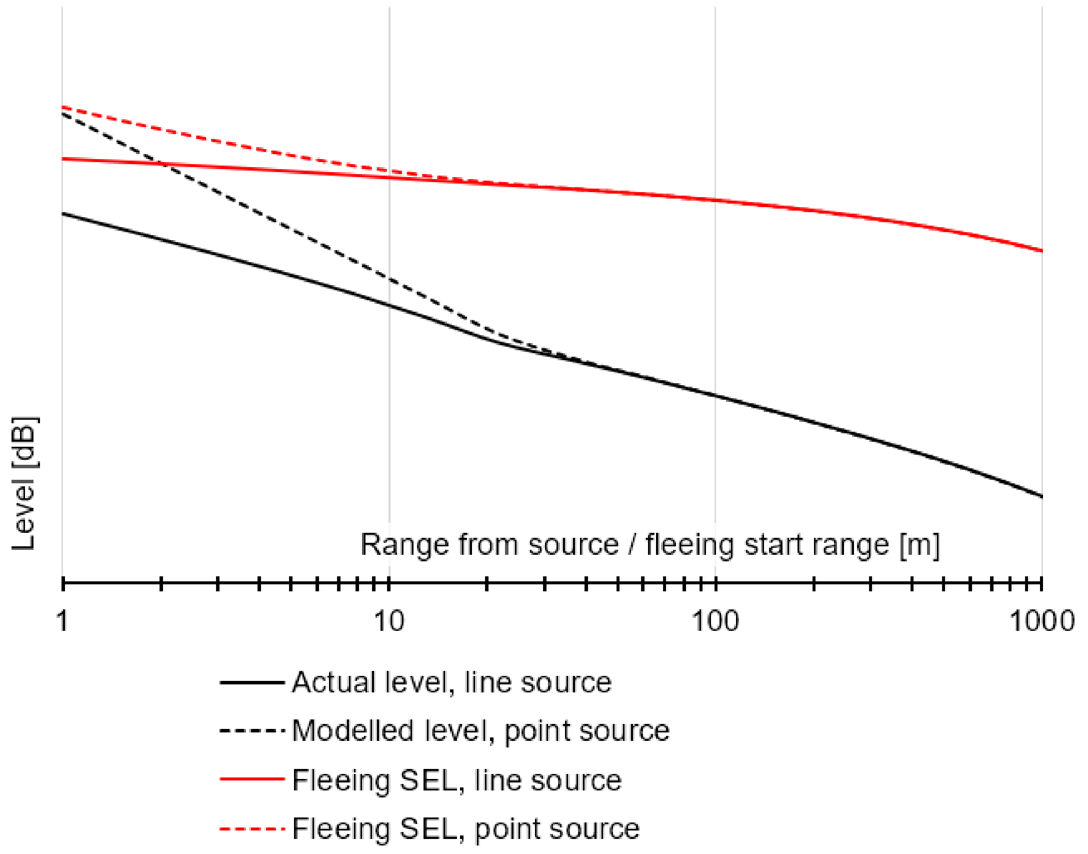

Figure 4-1. Schematic of the actual received level trend from a line source versus the modelled level assuming an equivalent monopoint source. Lines shown for both instantaneous received level and for cumulative level while fleeing.

4.1 Source levels

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

Source levels for the active equipment were band-wise, logarithmically summed to produce a “combined” source that represents the total noise emissions from any given activity or combination of activities.

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

Table 4-1. Summary of noise sources and activities included in the subsea noise assessment.

Equipment/ Activity	Source level [SPL]	Proxy for additional activities	Source model details/example systems	Impulsive/ non-impulsive
USV, Unmanned Surface Vehicle (based on small outboard engine vessel)	165	Small vessels <15 m length	(Heitmeyer, 2001; Simard, RoyCédric, & Giard, 2016; Wittekind, 2014; Audoly & Rizzuto, 2015; MacGillivray & de Jong, 2021; Liefvendahl, Feymark, & RE, 2015)	Non-impulsive
Geophysical survey vessel (<60 m length)	187	Vessel <60 m length, speed <6 kn.	(Heitmeyer, 2001; Simard, RoyCédric, & Giard, 2016; Wittekind, 2014; Audoly & Rizzuto, 2015; MacGillivray & de Jong, 2021; Liefvendahl, Feymark, & RE, 2015)	Non-impulsive
Geotechnical survey vessel (<110 m length)	189	Vessel <110 m length, speed <6 kn.	(Heitmeyer, 2001; Simard, RoyCédric, & Giard, 2016; Wittekind, 2014; Audoly & Rizzuto, 2015; MacGillivray & de Jong, 2021; Liefvendahl, Feymark, & RE, 2015)	Non-impulsive
MBES, Multibeam EchoSounder	182	-	Kongsberg EM series, Kongsberg Geoswath series, R2 Sonic series & Reson Teledyne Seabat series	Non-impulsive*
SSS, SideScan Sonar	165	-	Edgetech FS-4200 series, C-Max CM2 series and Klein System 3900-5000	Non-impulsive*
USBL, UltraShort BaseLine positioning	190	-	Edgetech BATS, ORE offshore trackpoint, Sonardyne Fusion/Ranger/Scout, IxBlue GAPS, Kongberg HiPAP	Non-impulsive*

Equipment/ Activity	Source level [SPL]	Proxy for additional activities	Source model details/example systems	Impulsive/ non-impulsive
SBP-P, Parametric SubBottom Profiler	202-205 (depth dependent) (soft start, 199-202)	-	Innomar smart, quattro (QBM) sixpack (HBM), Innomar SES 2000 compact light, Innomar standard quattro (DBM) sixpack (DBM), Innomar medium 100	Non-impulsive*
SBP-C, Chirper/Pinger SubBottom Profiler	180 (soft start, 170-180)	-	Kongsberg Geopulse, Edgetech 424/512, Knudsen 3202, Klein K-Chirp	Non-impulsive*
Boomer	188 (soft start, 178-188) (L_{pk}: 234)	-	Geoforce Stabletow, Applied Acoustics AA-series, Geo-Boomer 300-500, CAT200 Boomer	Impulsive to c. 700 m
Sparker	187 (soft start, 177-187) (L_{pk}: 224)	-	GeoSource series	Impulsive to c. 700 m
Rotary coring (diameter <1 m)	162	Other non-percussive drilling including Cone penetration testing & Piezo-cone penetration testing	(L-F, et al., 2023; Erbe & McPherson, 2017; Fisheries and Marine Service, 1975; MR, M, M, & I, 2010; Ward & Needham, 2012)	Non-impulsive
Vibratory coring	189		(L-F, et al., 2023; Reiser, Craig, Funk, Rodrigues, & Hannay, 2010)	Non-impulsive
STP, Standard Penetration Testing (diameter <0.1 m)	177	Seismic cone penetration testing, Cable percussive drilling	(L-F, et al., 2023; Erbe & McPherson, 2017)	Impulsive to c. 700 m
Acoustic altimeter of Magnetometer	Not modelled, main energy >200 kHz	-	-	-
ADCP (Acoustic doppler current profiler)	Not modelled, main energy >300 kHz	-	-	-

*While impulsive to near-impulsive on its own, when operated together with other sonar-based equipment the resulting signal is non-impulsive due to the high repetition rate of emitted impulses.

4.2 Soft starts

The parametric SBP, chirper/pinger SBPs, the boomer and sparker sources have been modelled assuming 20-40-minute soft starts are implemented.

4.2.1 Parametric SBP

The Innomar parametric SBP can be configured to perform a 20-min soft start where the primary frequency ramps up from c. 50 % power to 100 % power over 20 minutes. For the modelling, five steps of 10 % increase are assumed (4 minutes at 50 %, 4 minutes at 60 % etc.). The main effect is on the primary frequencies (80-120 kHz), with a smaller effect on the secondary frequencies (2-20 kHz).

4.2.2 Chirper/pinger SBP

The modelling assumes a soft start procedure starting at 10 % sound energy increasing over five steps of 4 minutes each to full power, 20 minutes total.

4.2.3 Sparker and boomer

For the sparker and boomer systems, the exact method of soft start depends on the models used during the project. The modelling assumes a soft start procedure starting at 10 % sound energy increasing over five steps of 8 minutes each to full power (40 minutes total). The reduction in output will likely have to be a combination of reduction in firing energy and reduction in firing rate. As an example, 10 % sound output can be realised by:

- Keeping the firing rate constant and reducing firing energy to 10 %.
- Halving the firing rate and dropping firing energy to 20 % (50 % x 20 % = 10 %).
- Dropping firing rate to c. 32 % and firing energy to c. 32 % (32 % x 32 % ≈ 10 %).

4.3 Geophysical survey, USV-based, parametric SBP.

The offshore geophysical survey noise signature consists of a range of sources simultaneously active:

- USV (light vessel <15 m)
- MBES
- SSS
- SBP-P (parametric)

The total broadband source level is 205 dB SPL, with the SBP-P dominating the high-frequency range (>50 kHz), and the vessel the lower frequencies (<5 kHz). No USBL is active as all equipment is mounted to the hull of the vessel.

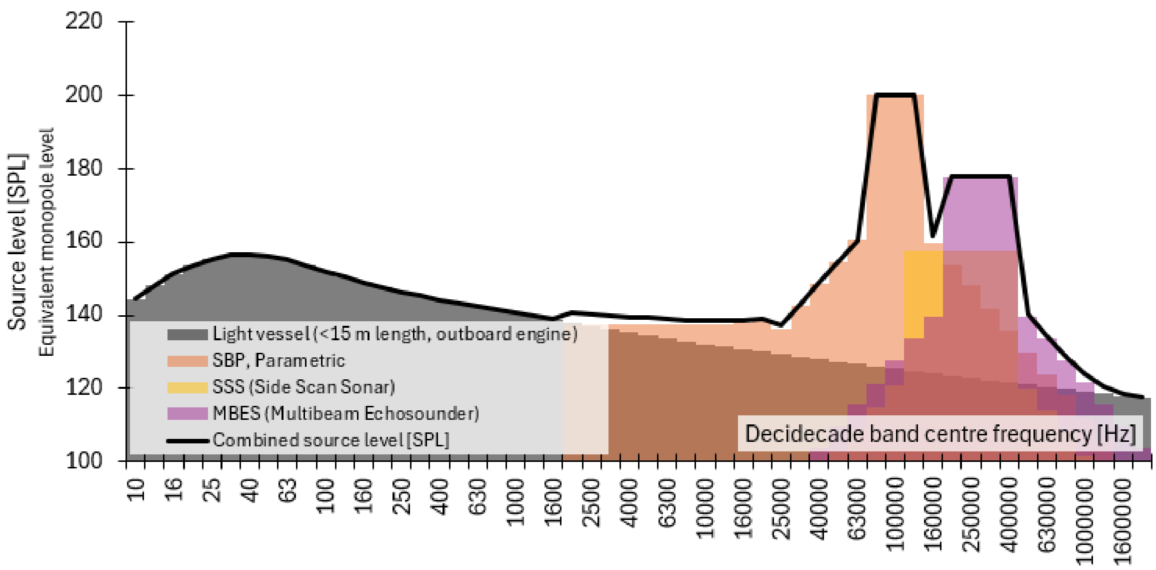

Figure 4-2. Band levels, inshore geophysical survey with USV (light vessel <15 m) and parametric SBP.

4.4 Geophysical survey, large vessel, parametric SBP

The offshore geophysical survey noise signature consists of a range of sources simultaneously active:

- Geophysical vessel (<60 m)
- MBES
- SSS
- USBL
- SBP-P (parametric)
- Sparker
- Boomer

The total broadband source level is 203 dB SPL, with the SBP-P dominating the high-frequency range (>50 kHz), the USBL the mid-frequency range (5-50 kHz) and the sparker, boomer and vessel the lower frequencies (<5 kHz). Note that, because the sparker and boomer are impulsive, the assessment thresholds are lower, so for the purposes of risk ranges their impact is larger, than their immediate source level would indicate, when compared to the remaining sources.

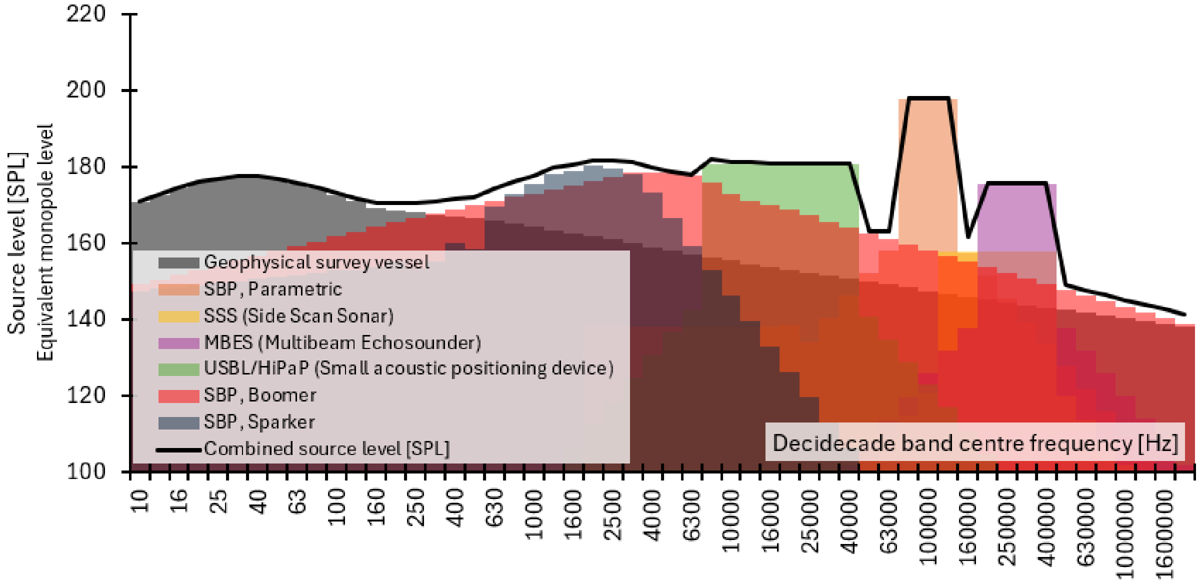

Figure 4-3. Band levels, offshore geophysical survey with parametric SBP.

4.5 Geophysical survey, large vessel, chirper/pinger SBP

The offshore geophysical survey noise signature consists of a range of sources simultaneously active:

- Geophysical vessel (<60 m)
- MBES
- SSS
- USBL
- SBP-C (chirper/pinger)
- Sparker
- Boomer

The total broadband source level is 194 dB SPL, with the MBES dominating the high-frequency range (>50 kHz), the USBL the mid-frequency range (5-50 kHz) and the sparker, boomer and vessel the lower frequencies (<5 kHz). Note that, because the sparker and boomer are impulsive, the assessment thresholds are lower, so for the purposes of risk ranges their impact is larger, than their immediate source level would indicate, when compared to the remaining sources.

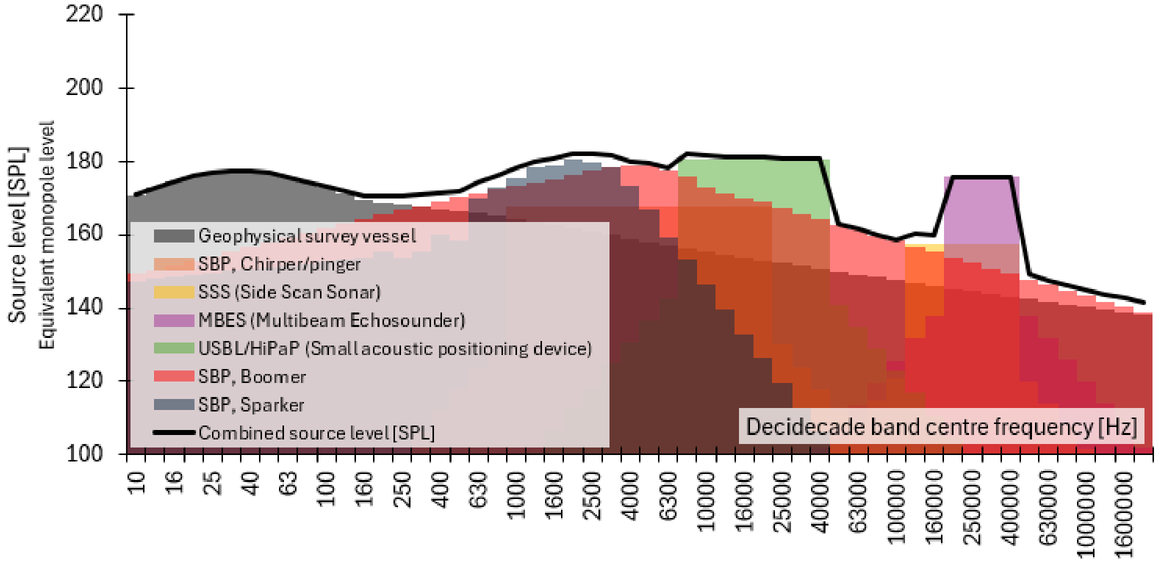

Figure 4-4. Band levels, offshore geophysical survey with chirper/pinger SBP.

4.6 Geotechnical survey

The geotechnical survey noise signature consists of a range of sources simultaneously active:

- Geotechnical vessel (<110 m)
- Rotary coring (also proxy for cone- & and piezo-cone penetration testing)
- Vibratory coring
- Standard penetration testing
- USBL/HiPAP

The total broadband source level is 194 dB SPL.

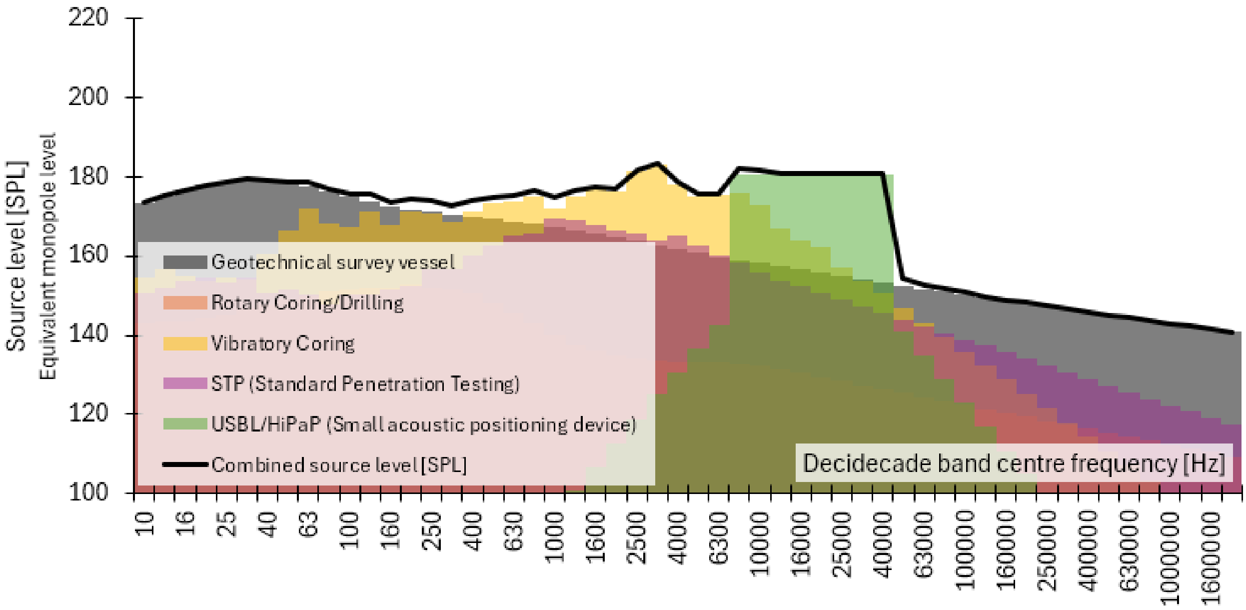

Figure 4-5. Band levels, geotechnical survey.

5.0 Sound Propagation Modelling Methodology

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

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 computational speed of these simpler models is preferred over the higher accuracy of numerical models and are routinely used for these types of assessments.

These models 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. Animals fleeing the area will not return within a 12-hour period.
2. Animals fleeing for up to 12 hours, after which they will be over 20 km away (assuming minimal fleeing speeds of 0.5 m/s).
3. Sources are modelled as point sources. This leads to overestimation of received levels near the source but is equal at ranges over c. 2 times the length of the source (see Section 4.0 Source Levels).
4. Modelling is done for high tide conditions, as deeper water decreases the propagation loss, increasing the received levels, thus a conservative assumption.
5. Sea state lower than sea state 2 is assumed, meaning the water surface is a perfect reflector and there are no significant bubbles in the surface layer. This is a conservative assumption, with increases in wind speed having a strong attenuating effect on the sound propagation.

5.2 Exposure Calculations (dB SEL)

To compare modelled levels with the impact assessment frameworks (NMFS 2024 & Popper et al. 2014) it is necessary to calculate received levels as exposure levels (SEL), weighted for marine mammals and turtles, and unweighted for fishes. For ease of implementation, sources have been presented and calculated as SPL levels, meaning it was necessary to convert between SPL and SEL for a single, or multiple events:

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

$$SEL = \mathrm{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \quad (03)$$

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

$$SEL_{n\ events} = SEL_{single\ event} + 10 \cdot Log_{10}(n) \quad (04)$$

And SPL from SEL:

$$SPL = \mathrm{SEL} + 10 \cdot Log_{10}\left(\frac{1}{t_2 - t_1}\right) \quad (05)$$

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

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

For very long fleeing durations, the ambient sound itself can exceed the thresholds, e.g., an ambient sound level of 122.4 dB, weighted for the VHF group, will exceed the non-impulsive TTS threshold of 161 dB SEL after 2 hours' exposure[9]. For this assessment, we consider fleeing durations of 12 hours, meaning that continuous weighted received levels of at least 114.6 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	TU	0.56-0.84 & 0.78-2.8	(F, P, E, & GR, 1997; SA, 2002)

9 122.4 dB SPL + 10*log10(3600 seconds) = 161 dB SEL, TTS non-impulsive threshold for the VHF group is 161 dB SEL.

5.3 Multiple sources

Where multiple sources are active simultaneously there is no simple way of calculating the resulting risk ranges, rather the total area exceeding a threshold is strongly dependent on the relative position of the sources. Here and example with two sources is shown as the separation distance reduces, the total area above the threshold (red area) changes (Figure 5-1).

The two sources are chosen as:

- Source A, 194 dB SPL at 2.5 kHz
- Source B, 204 dB SPL at 10 kHz

Area separation distance and area of exceedance:

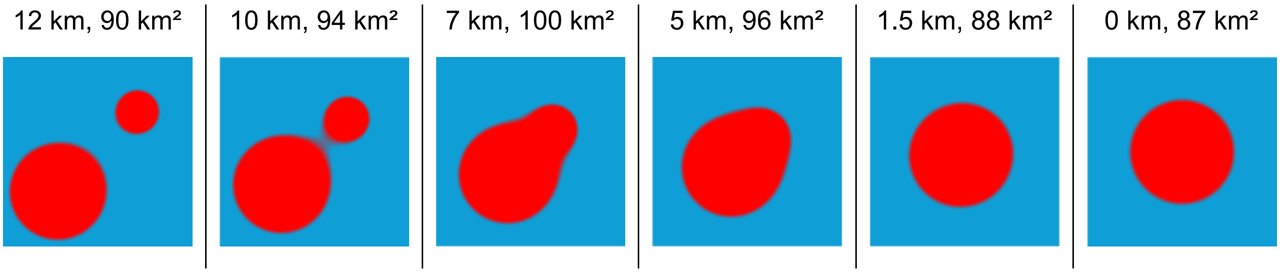

Figure 5-1. Area exceeding threshold as a function of separation distance.

Where sources are far apart the risk ranges from the individual sources are not affected by the presence of another source at ranges over c. 2x the risk range, while at ranges shorter than this the area between the sources will experience elevated received levels and the total area exceeding the threshold is increased. When sources again are very close (<1 x risk range apart) the total impacted area tends to decrease.

Thus, for scenarios with multiple sources, a single risk range cannot be simply calculated as it depends on the relative levels and ranges of the sources to each other as well as the sensitive receiver.

However, the example above shows that the cumulative effect is limited to when the source-to-source distance is “just right” and that for many scenarios, including the current Project, the separation between concurrently operating sources will tend to be more than 2x the risk ranges.

6.0 Impact Assessment

Results are presented here as the geographical "risk range" to an auditory threshold (AUD INJ/ TTS/ Behavioural), as given in Table 2-1, Table 2-2, Table 2-3 and Table 2-4.

A given risk range specifies the expected range, within which, a fleeing receiver would exceed the relevant threshold.

Risk ranges for SEL are given for the 90th percentile value of all modelled radials (example in Figure 6-1).

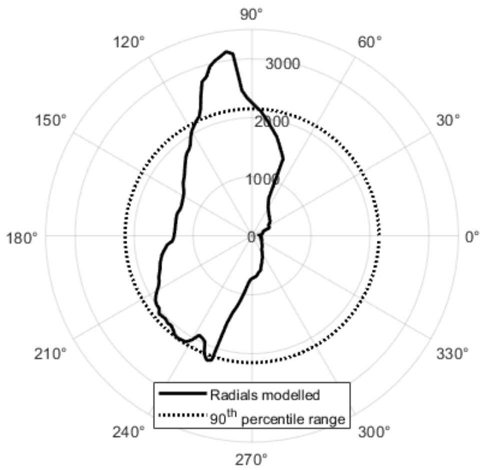

Figure 6-1. Example of ranges to a threshold modelled along radials (solid line) and 90th percentile range (dotted line) from a sound source in the centre.

Several result types are presented for each activity in Table 6-1 to inform this assessment and to provide flexibility in mitigation.

Table 6-1. Result types of summary.

Condition	Description
Behavioural disturbance	The range at which the behavioural/harassment limit for the marine mammals, fishes (including sharks) or turtles is exceeded.
TTS, sound exposure, fleeing receiver, 12 hours, including soft start. 90th percentiles provided	The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/ AUD INJ threshold. Animals are moving away from the source at a constant speed of 1.5 m/s (0.0 or 0.5 m/s for fish[10], including sharks and turtles).
AUD INJ, sound exposure, fleeing receiver, 12 hours, including soft start. 90th percentiles provided	

[10] Under Scottish regulation fish are to be modelled as stationary

6.1 Assumptions and notes on results

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

- Results are rounded up to the nearest 2 significant digits (i.e. 12.5 to 13, 249 to 250 and 1584 to 1600. This can lead to apparent overlaps in risk ranges.
- A minimal range is given at 10 m as this is the modelling resolution. Thus, risk ranges shorter than 10 m are given as “<10 m”.
- Modelling is limited to a range of 20 km from the activities assessed.
- Behavioural disturbance range will occasionally be shorter than TTS exceedance ranges for cumulative exposure. This is a reflection of the cumulative nature of TTS SEL exposure calculation (fleeing animals over a long duration) and the instantaneous nature of the assessment of exceedance of e.g. single pulse $SPL_{90\%}$.
- Where a range of values are presented, e.g.: “10 – 120 m” these indicate the variability in exceedance ranges found at the various locations throughout the modelling area, primarily because of variation in depths and sediment properties. The larger range should be used where a single exceedance range is needed.
- No results for exceedance of L_{pk} thresholds are shown as all risk ranges are smaller than the risk ranges from SEL threshold exceedances.

6.2 Results

In the following, the results from modelling of the four different representative activities are given as ranges to risk of exceeding the relevant threshold.

6.2.1 Summary of all locations

Table 6-2 presents risk ranges for all modelled activities.

The ranges represent the minimal to maximal 90th percentile range observed for all models at all locations.

Where “<10” is entered it means all models showed risk ranges below 10 m.

Table 6-2. Threshold exceedance risk ranges summary for all modelled activities.

Criteria	Metric	LF	HF	VHF	PW	OW	Fishes	TU
Exceedance of behavioural disturbance onset threshold (SPL)	90th percentile ranges [m]	290 - >20,000	1,400 - >20,000	1,800 - >20,000	740 - >20,000	420 - 16,000	730 - 750	<10
TTS risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	420 - 470	42 - 130	510 - 3,300	590 - 730	130 - 360	<14	31 - 83
AUD INJ risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	<10	<10	40 - 650	<10	<10	<10	<10

6.2.2 Geophysical survey, USV-based, parametric SBP.

Table 6-3 presents risk ranges for this activity.

Behavioural disturbance ranges are expected to be exceeded to between 290 m and 1,800 m for marine mammals and <10 m for fishes and turtles.

TTS exceedance risk ranges for fleeing receivers are up to 510 m for the VHF group, 42 m for the HF group and <10 all remaining groups.

AUD INJ exceedance risk ranges for fleeing receivers are up to 90 m for the VHF group and <10 m for all remaining groups.

Table 6-3. Threshold exceedance risk ranges, USV based geophysical survey.

Criteria	Metric	LF	HF	VHF	PW	OW	Fishes	TU
Exceedance of behavioural disturbance onset threshold (SPL)	90th percentile ranges [m]	290	1,400	1,800	740	420	<10	<10
TTS risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	<10	42	510	<10	<10	<10	<10
AUD INJ risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	<10	<10	90	<10	<10	<10	<10

6.2.3 Geophysical survey, large vessel, parametric SBP

Table 6-4 presents risk ranges for this activity.

Behavioural disturbance ranges are expected to be exceeded to over 20,000 m for marine mammals except for otters (OW) with a range of 16,000 m, 730 m for fishes and <10 m for turtles.

TTS exceedance risk ranges for fleeing receivers are up to 2,900 m for the VHF group, 130-590 m for the remaining marine mammal groups, 14 m for the Fishes group and up to 83 m for the TU group.

AUD INJ exceedance risk ranges for fleeing receivers are up to 650 m for the VHF group and <10 m for all remaining groups.

Table 6-4. Threshold exceedance risk ranges, geophysical survey, large vessel, parametric SBP

Criteria	Metric	LF	HF	VHF	PW	OW	Fishes	TU
Exceedance of behavioural disturbance onset threshold (SPL)	90th percentile ranges [m]	>20,000	>20,000	>20,000	>20,000	16,000	730	<10
TTS risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	460	130	2,900	590	360	14	83
AUD INJ risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	<10	<10	650	<10	<10	<10	<10

6.2.4 Geophysical survey, large vessel, chirper/pinger SBP

Table 6-5 presents risk ranges for this activity.

Behavioural disturbance ranges are expected to be exceeded to over 20,000 m for marine mammals except for otters (OW) with a range of 16,000 m, 750 m for fishes and <10 m for turtles.

TTS exceedance risk ranges for fleeing receivers are up to 3,000 m for the VHF group, 98-600 m for the remaining marine mammal groups, 14 m for the Fishes group and up to 83 m for the TU group.

AUD INJ exceedance risk ranges for fleeing receivers are up to 650 m for the VHF group and <10 m for all remaining groups.

Table 6-5. Threshold exceedance risk ranges, geophysical survey, large vessel, chirper/pinger SBP

Criteria	Metric	LF	HF	VHF	PW	OW	Fishes	TU
Exceedance of behavioural disturbance onset threshold (SPL)	90th percentile ranges [m]	>20,000	>20,000	>20,000	>20,000	16,000	750	<10
TTS risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	470	98	3,000	600	360	14	83
AUD INJ risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	<10	<10	650	<10	<10	<10	<10

6.2.5 Geotechnical survey

Table 6-6 presents risk ranges for this activity.

Behavioural disturbance ranges are expected to be exceeded to over 20,000 m for marine mammals except for otters (OW) with a range of 16,000 m, 730 m for fishes and <10 m for turtles.

TTS exceedance risk ranges for fleeing receivers are up to 3,300 m for the VHF group, 95-730 m for the remaining marine mammal groups, <10 m for the Fishes group and up to 31 m for the TU group.

AUD INJ exceedance risk ranges for fleeing receivers are up to 40 m for the VHF group and <10 m for all remaining groups.

Table 6-6. Threshold exceedance risk ranges for misc. larger vessels

Criteria	Metric	LF	HF	VHF	PW	OW	Fishes	TU
Exceedance of behavioural disturbance onset threshold (SPL)	90th percentile ranges [m]	>20,000	>20,000	>20,000	>20,000	16,000	730	<10
TTS risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	420	95	3,300	730	130	<10	31
AUD INJ risk range, fleeing receiver (SEL based)	90th percentile ranges [m]	<10	<10	40	<10	<10	<10	<10

7.0 Discussion & Conclusion

This report assesses the impact of noisy activities associated with the geophysical and geotechnical surveys planned as part of the site investigations of the Project. The impact is quantified as the range to exceedance of species-specific thresholds for fleeing mammals and fish receivers.

The below exceedance ranges refer to the range of the 90th percentile, 10% of results showed longer ranges, 90 % showed shorter ranges.

Probable behavioural disturbance

Exceedance of the behavioural disturbance thresholds for marine mammals extend to ranges of 290-1,800 m for the USV-based geophysical survey, while for the larger vessels using both USBL and seismic sources these ranges extended from 16,000 m to over 20,000 m. Exceedance of disturbance to the Fishes group thresholds were typically <10 m for the USV-based survey and 730-750 m for the remaining activities. The TU group had ranges below 10 m for all activities.

TTS

TTS exceedance ranges were up to 510 m for the VHF group for the USV-based survey, with the remaining groups below 50 m. The larger vessels use a USBL for equipment positioning information and have active seismic impulsive equipment. This drives TTS risk ranges up to 3,300 m for the VHF group and 95 m to 730 m for the remaining marine mammal groups. TTS risk ranges for the Fishes group were <20 m, and for the TU group up to c. 90 m where seismic sources were used.

AUD INJ

Only the VHF group has AUD INJ risk ranges extending beyond 10 m, with risk of exceeding the AUD INJ threshold to 90 m for the USV-based survey and to 650 m for the geophysical surveys using seismic sources. The geotechnical survey's use of USBL exceeds the VHF group's AUD INJ threshold to 40 m.

7.1 Conclusion

The risk of exceeding auditory injury thresholds (AUD INJ) extends to a range up to 650 m for the VHF group (porpoises) during use of seismic sources. For the USV-based geophysical survey and the geotechnical survey the AUD INJ risk range is limited to 90 m for the VHF group. All other species have AUD INJ risk ranges below 10 m for all activities.

The risk of exceeding auditory temporary impairment thresholds (TTS) extends to 3,300 m for the VHF group where a survey uses a USBL device or a seismic source (sparker and/or boomer). For the remaining hearing groups (including all other marine mammals, fishes and turtles) the risk of exceeding the TTS thresholds extends up to 730 m, with seismic sources, USBL and vibratory coring being the main drivers of risk.

The activities using either USBL or seismic sources have potential to cause behavioural disturbance to ranges exceeding 20,000 m for all marine mammals except for otters with a range of 16,000 m, while the exceedance of the behavioural disturbance threshold for Fishes was exceeded up to 750 m and <10 m for turtles.

The results above assume a 20-minute soft start for sub bottom profilers and a 40-minute soft start for seismic sources (sparker and boomer) is implemented. The modelled 650 m AUD INJ risk ranges for porpoises will be mitigated through MMO efforts (pre-start monitoring surveys).

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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 A-1 , below.

Table A-1: Comparing sound quantities between air and water.

	Constant intensity		Constant pre	
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 A-8-1 and reflect the units as given in ISO 18405:2017, “Underwater Acoustics – Terminology”.

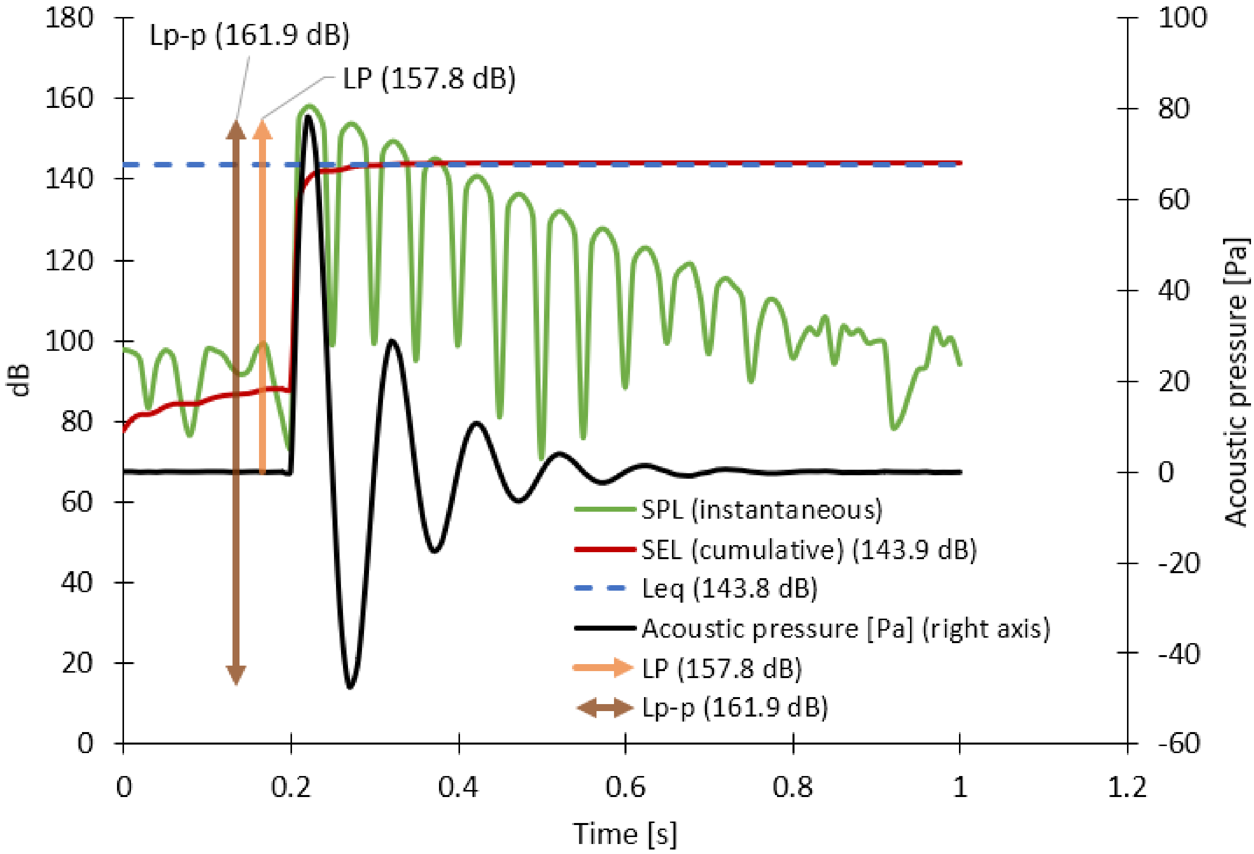

Figure A-8-1: Graphical representation of acoustic wave descriptors.

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

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

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

The peak sound pressure level, L_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_{pk} metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events over e.g. a 24-hour period to be taken into account. The SEL is defined as follows (ISO 18405:2017, 3.2.1.5):

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

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

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

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

Converting from a single event to multiple events for SEL:

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

The frequency, or pitch, of the sound is the rate at which these oscillations occur and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dB(A). However, the hearing faculties of marine mammals and fish are not the same as humans, with marine mammals hearing over a wider range of frequencies, fish over a typically smaller range of frequencies and both with different sensitivities. It is therefore important to understand how an animal's hearing varies over the entire frequency range to assess the effects of sound on marine life. Consequently, use can be made of frequency weighting scales to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure A-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.

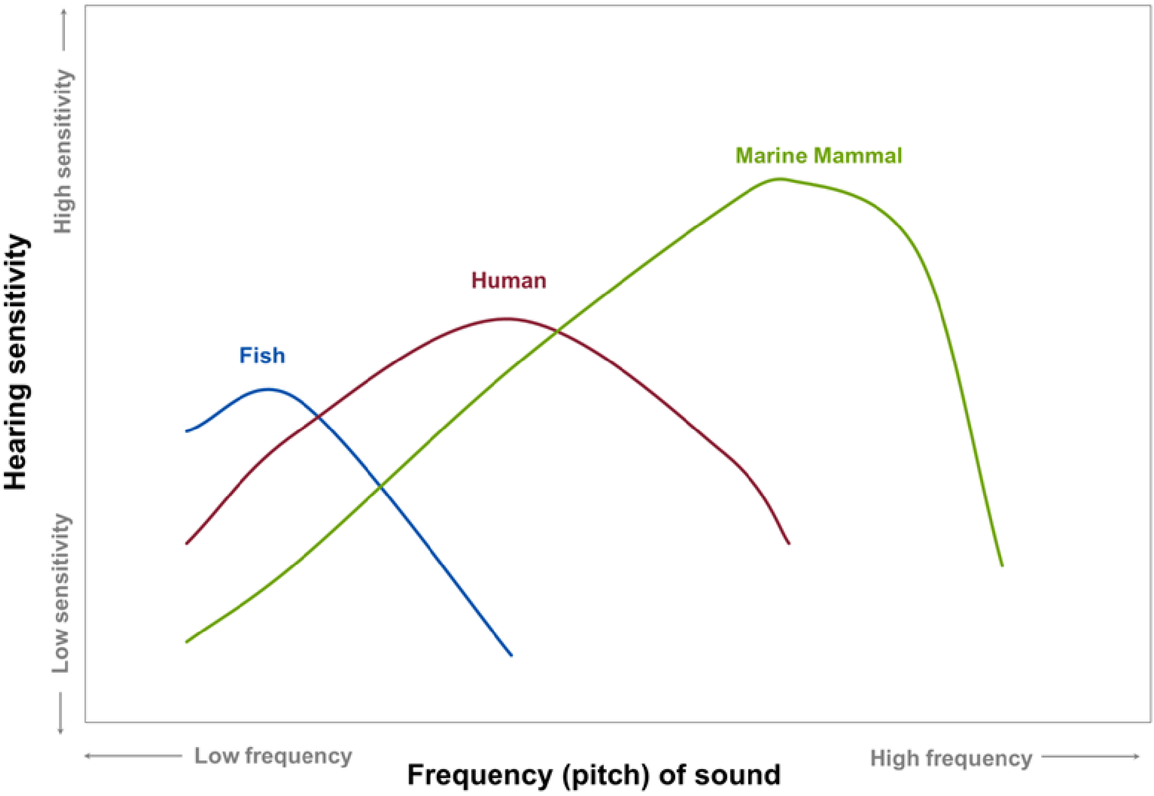

Figure A-8-2: Comparison between hearing thresholds of different marine animals and humans.

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 on 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 A-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.

Figure A-8-3 shows an example where this leads to a non-impulsive source, to be compared to the thresholds for non-impulsive noise.

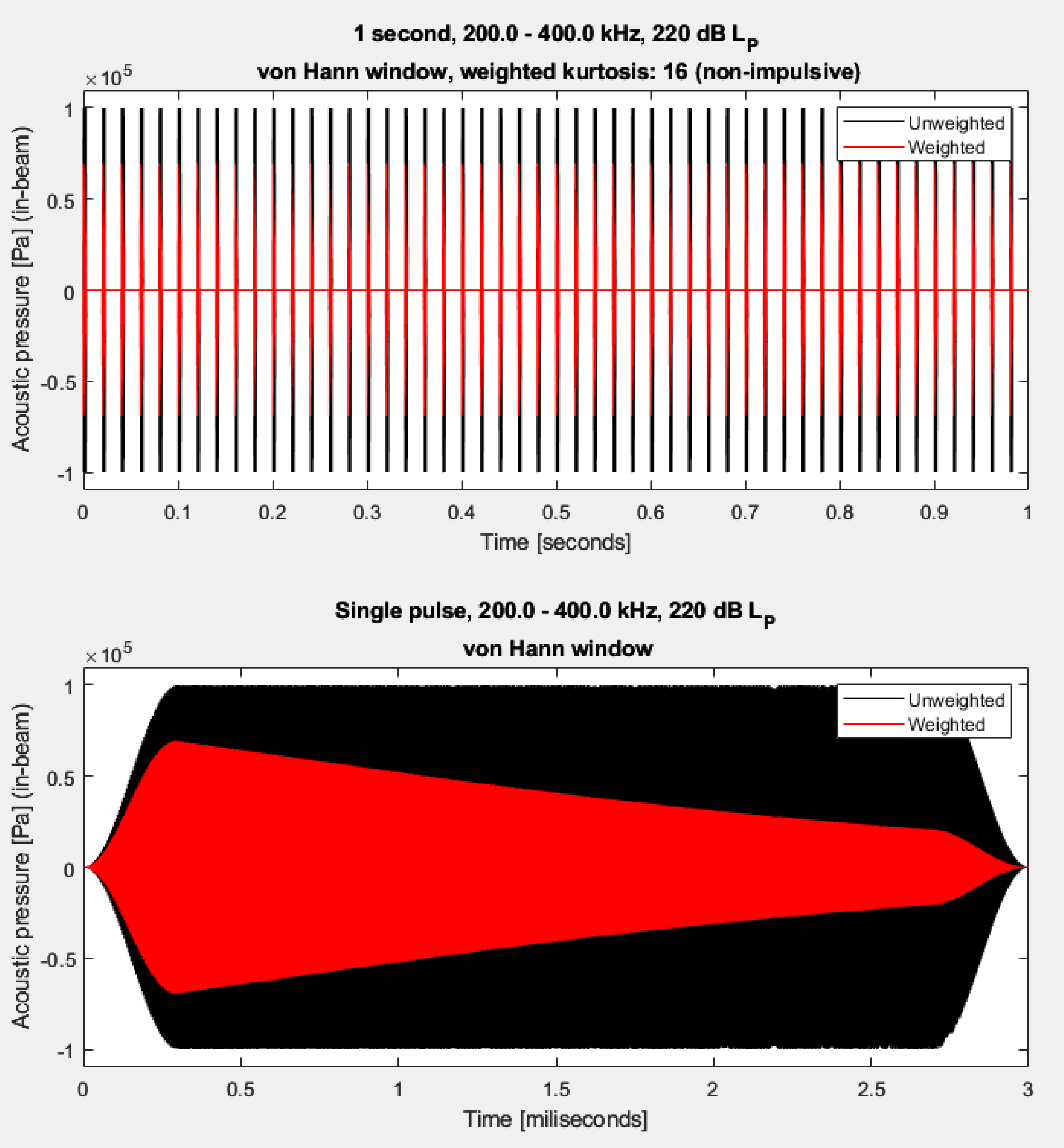

Figure A-8-3: Example of a multibeam echosounder at 15 m depth (achieving 50 ping/sec) with a 3 ms ping duration. VHF-weighted kurtosis of 16 – non-impulsive.

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 A-8-4 shows an example where this combination resulted in an impulsive source, to be compared to the thresholds for impulsive noise.

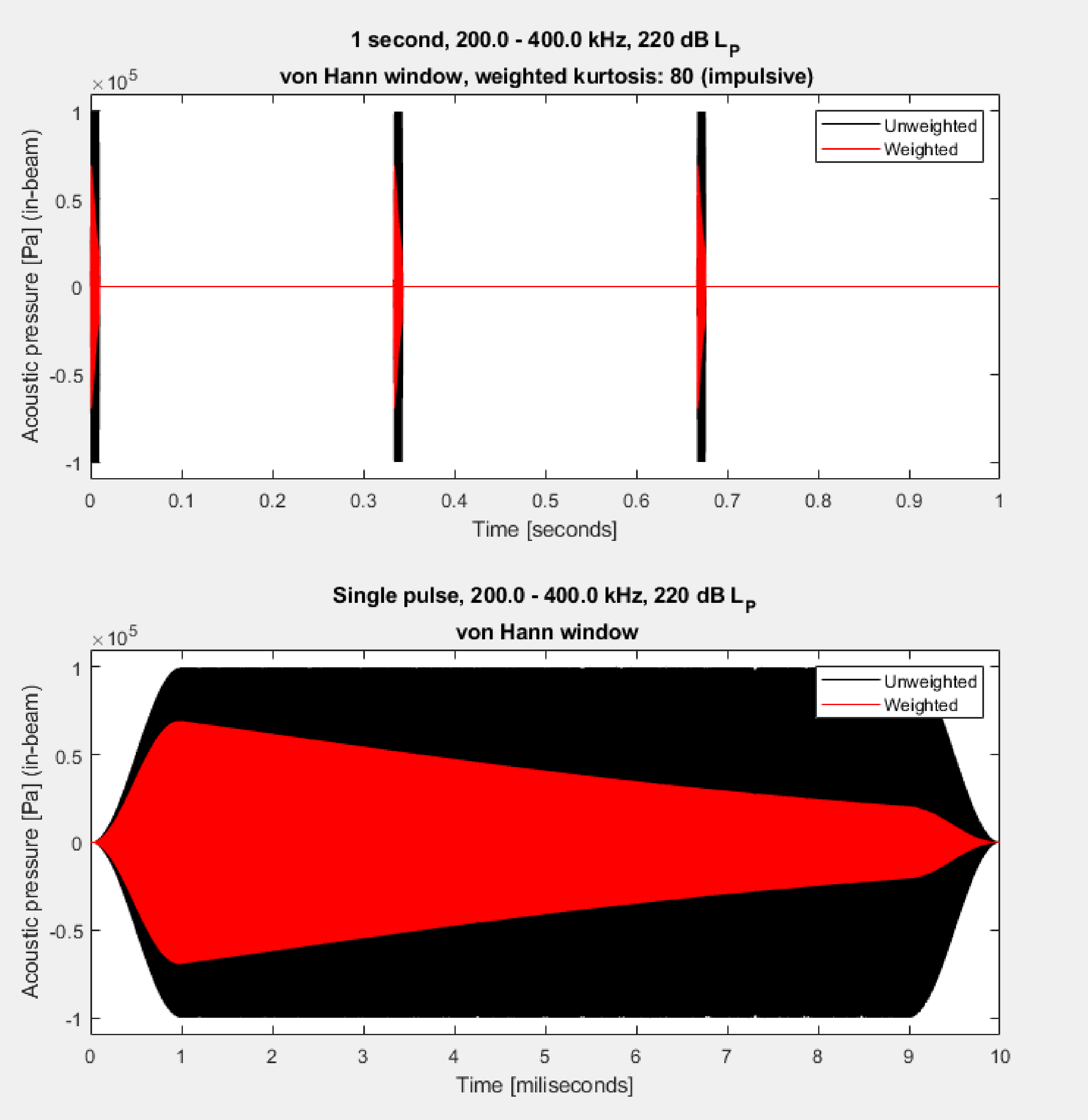

Figure A-8-4: Example of a multibeam echosounder at 15 m depth (achieving 50 ping/sec) with a 3 ms ping duration. VHF-weighted kurtosis of 16 – non-impulsive.

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 A-8-5 & Figure A-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.

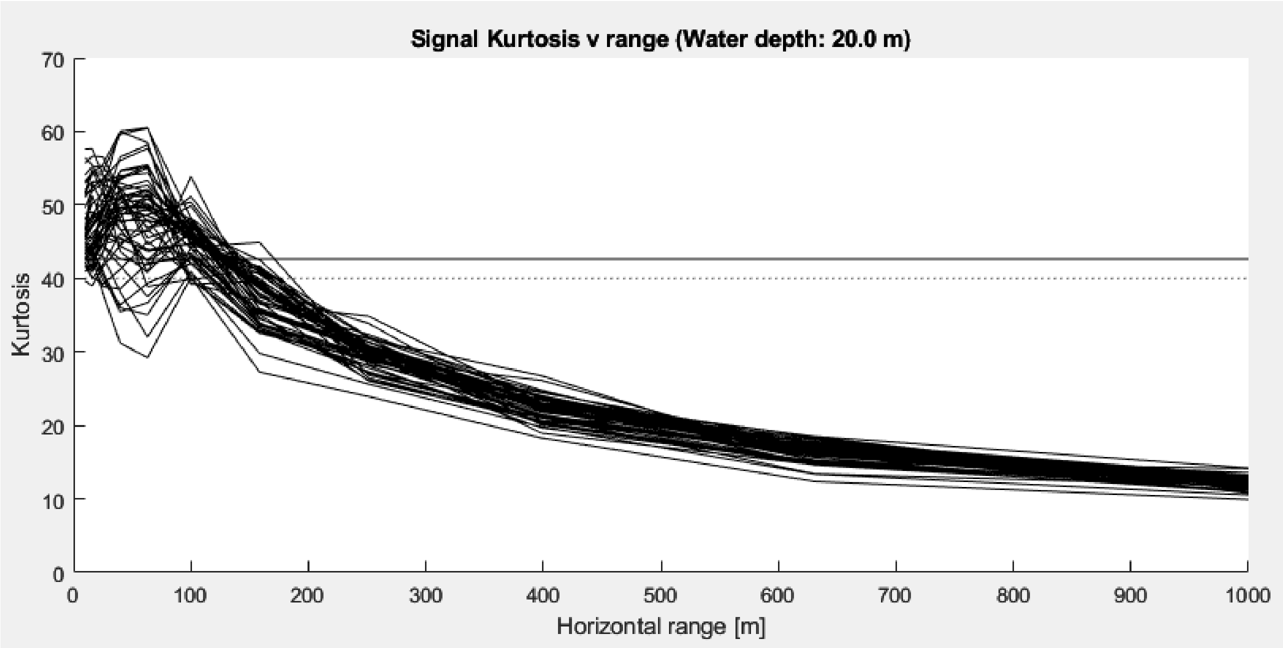

Figure A-8-5. Example of USBL signal kurtosis decreasing with range at 20 m depth. Multiple lines are various combinations of source and receiver depths.

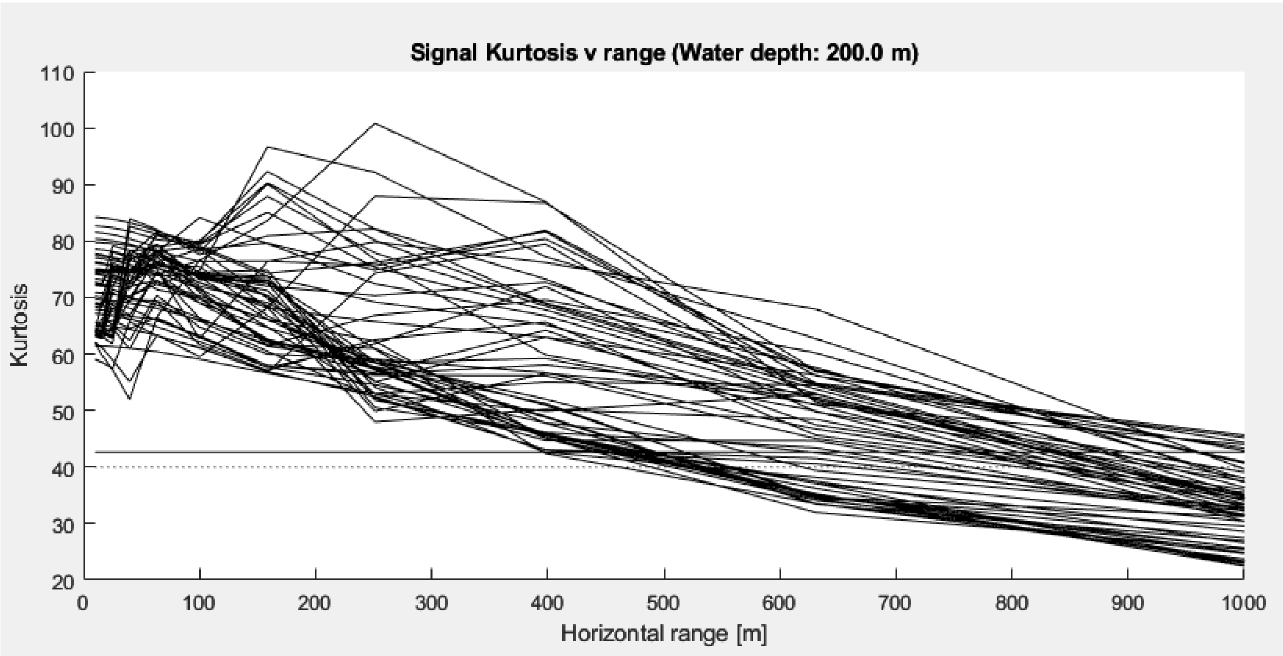

Figure A-8-6. Example of USBL signal kurtosis decreasing with range at 200 m depth. Multiple lines are various combinations of source and receiver depths.

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 A-8-7[13]) and frequency of the sound (Cole, 1965;

[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.

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).

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.

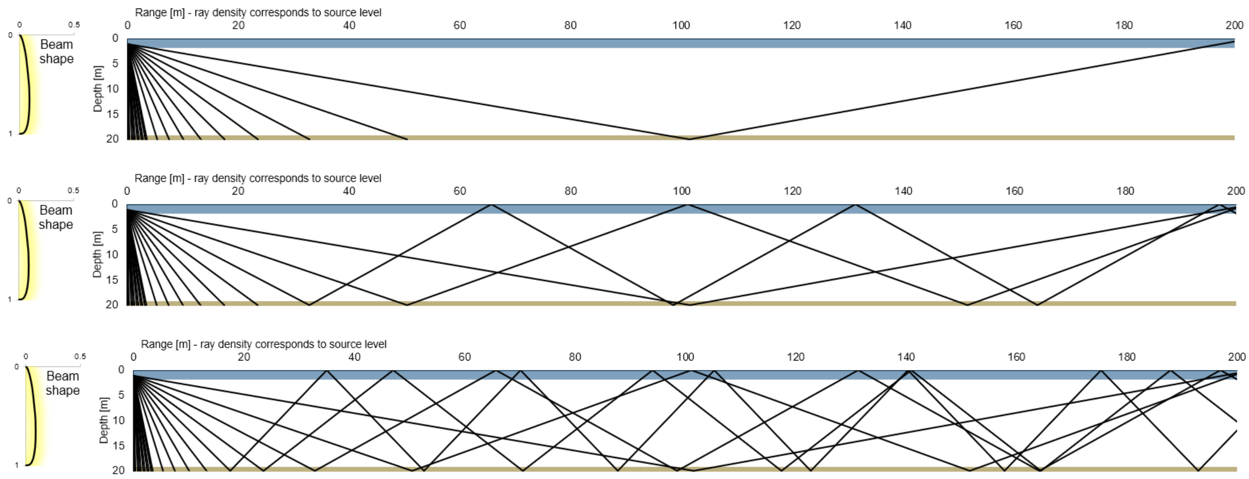

Figure A-8-7: Schematic of the effect of sediment on sources with narrow beams. Sediments range from fine silt (top panel), sand (middle panel), and gravel (lower panel).

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 A-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 A-8-7) to reduce the effective source level accordingly.

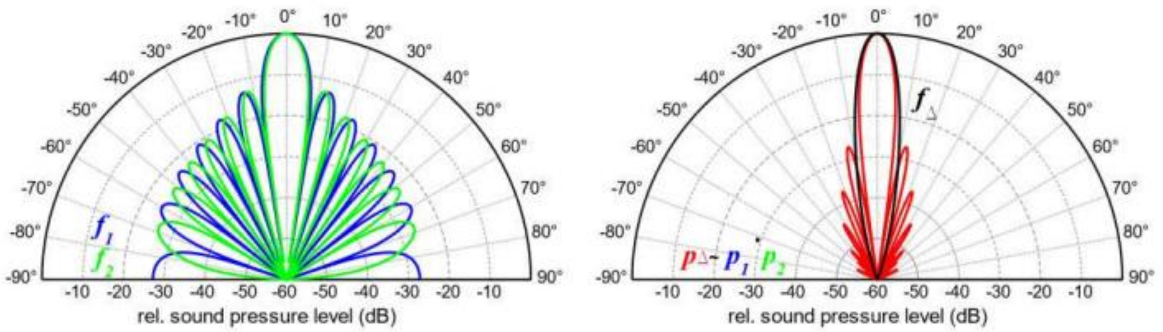

Figure A-8-8. Example of a beam pattern on an Innomar SES 2000. Primary frequencies left (f1 & f2), the interference pattern between the primary frequencies means that the beam pattern for the secondary frequency (right plot) is very narrow (Source: Innomar technical note TN-01).

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 A-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.

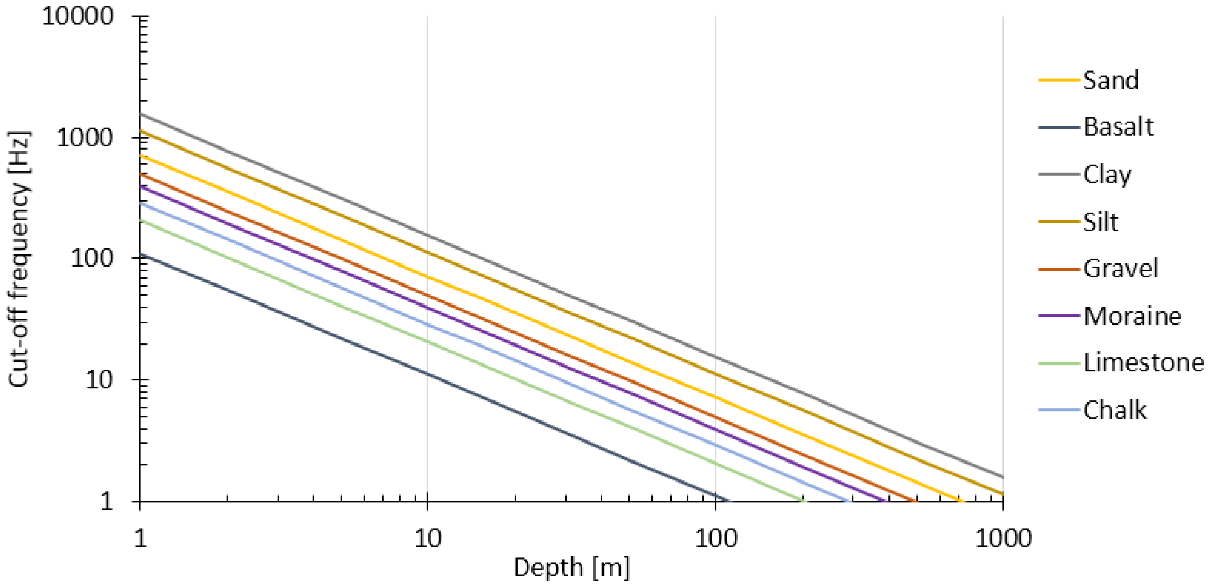

Figure A-8-9: Lower cut-off frequency as a function of depth for a range of seabed types.

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.

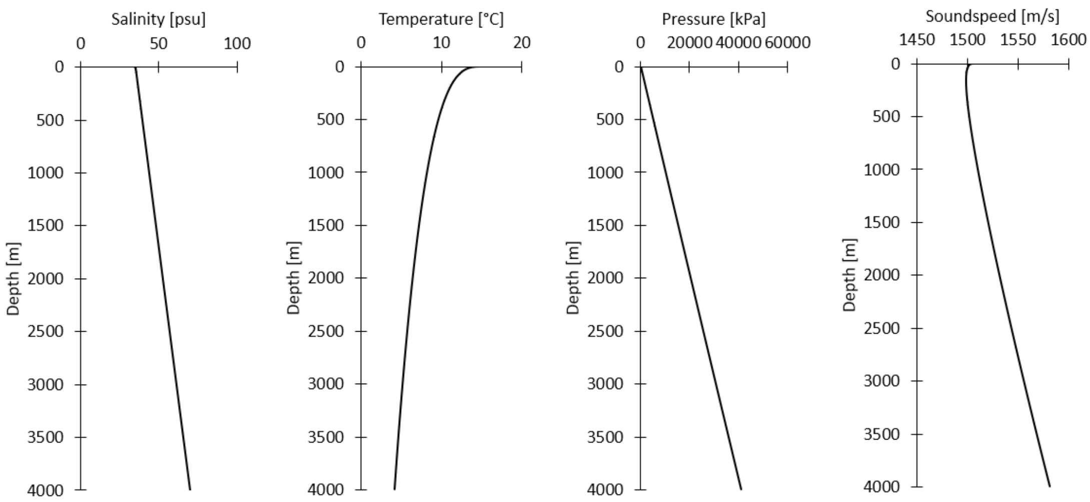

Figure A-8-10: Soundspeed profile as a function of salinity, temperature and pressure.

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.

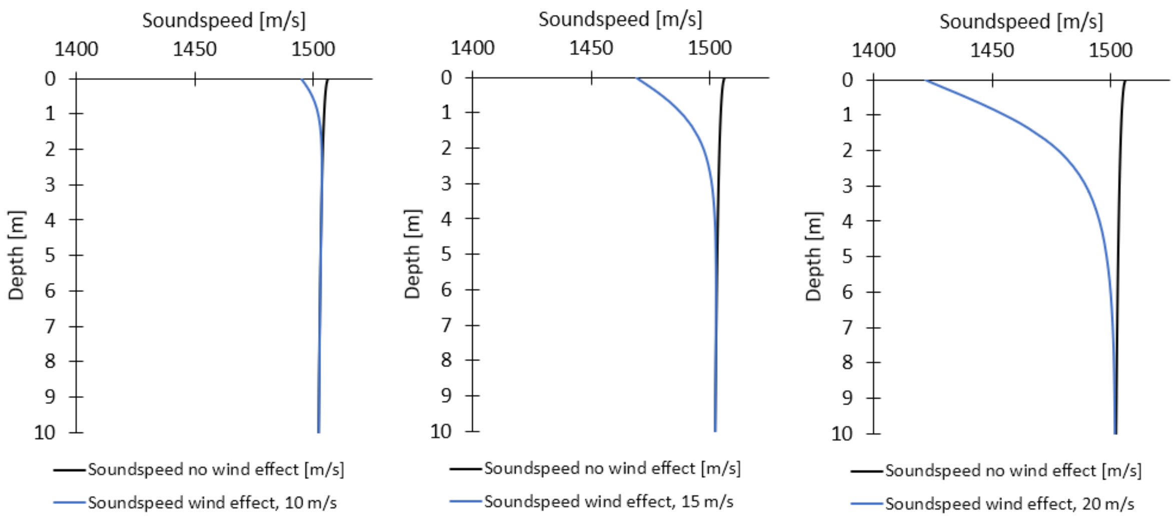

Figure A-8-11: Effect of wind (at 10 m height) on upper portion of soundspeed profile.

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 A-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.

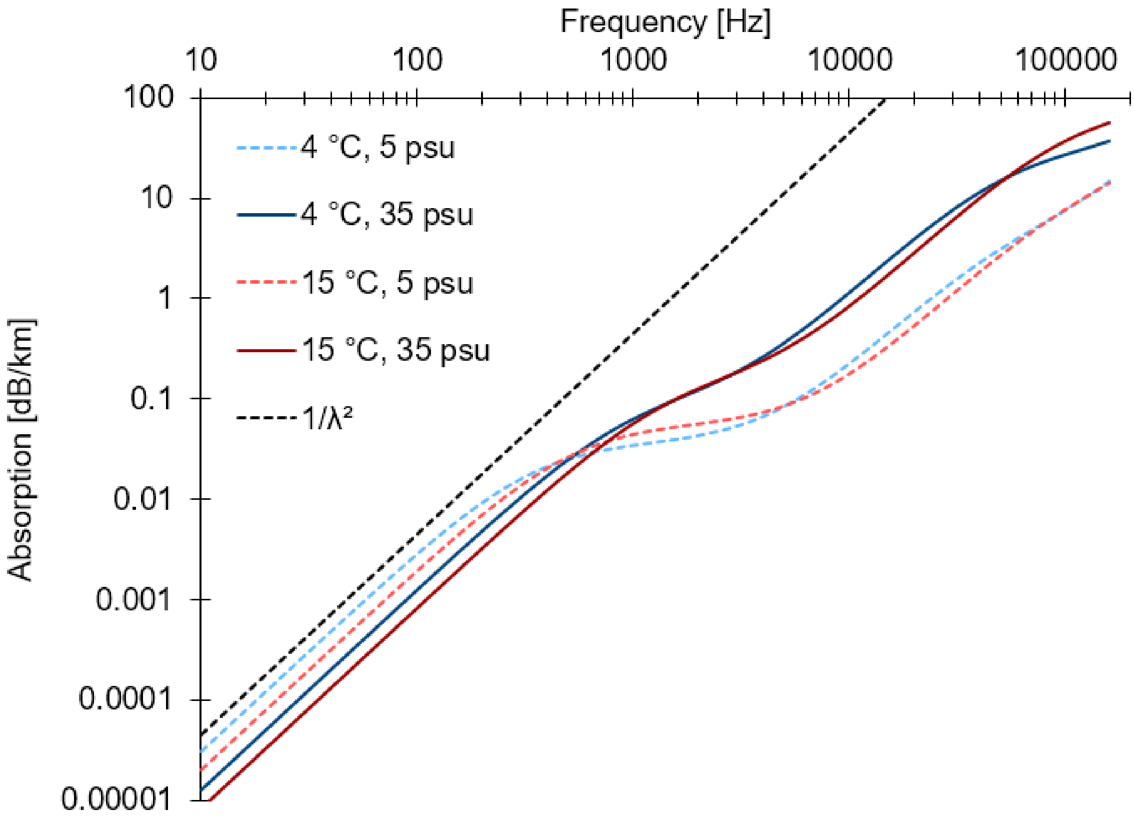

Figure A-8-12: Absorption loss coefficient (dB/km) for various salinities and temperature.

Near field and far field

Depending on the frequency the propagation of the sound from a source will have several different zones of propagation patterns. These can be approximated by the following equations.

- Near field, reactive zone: $Range < \frac{\lambda}{2\times\pi}$
- Near field, radiative zone (within Fresnel range): $\frac{\lambda}{2\times\pi} \rightarrow \frac{L^2}{4\times\lambda}$
- Transition zone: $\frac{L^2}{4\times\lambda} \rightarrow \frac{2\times L^2}{\lambda}$
- Far field: $Range > \frac{2\times L^2}{\lambda}$

Where "L" is the largest dimension of the sound source and "λ" is the wavelength. Lower frequencies (with larger wavelengths) are under far-field conditions at shorter ranges than higher frequencies, but the higher frequencies will tend to have increasingly denser "lobes" (tendency to form beams), eventually being a smooth field for practical purposes – lobe spacing is approximately $\Delta\theta=\lambda/L$ in radians – c. 200 lobes for a vessel of 50 m at 1000 Hz.

Within the near field there is no simple relation between distance from source and received level, while in the far field the received level will decrease predictably with increase in distance to the source.

Appendix B: Weston Propagation Model

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

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

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

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

Source:

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

Case 1

Depth 100 m, max range 40 km.

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

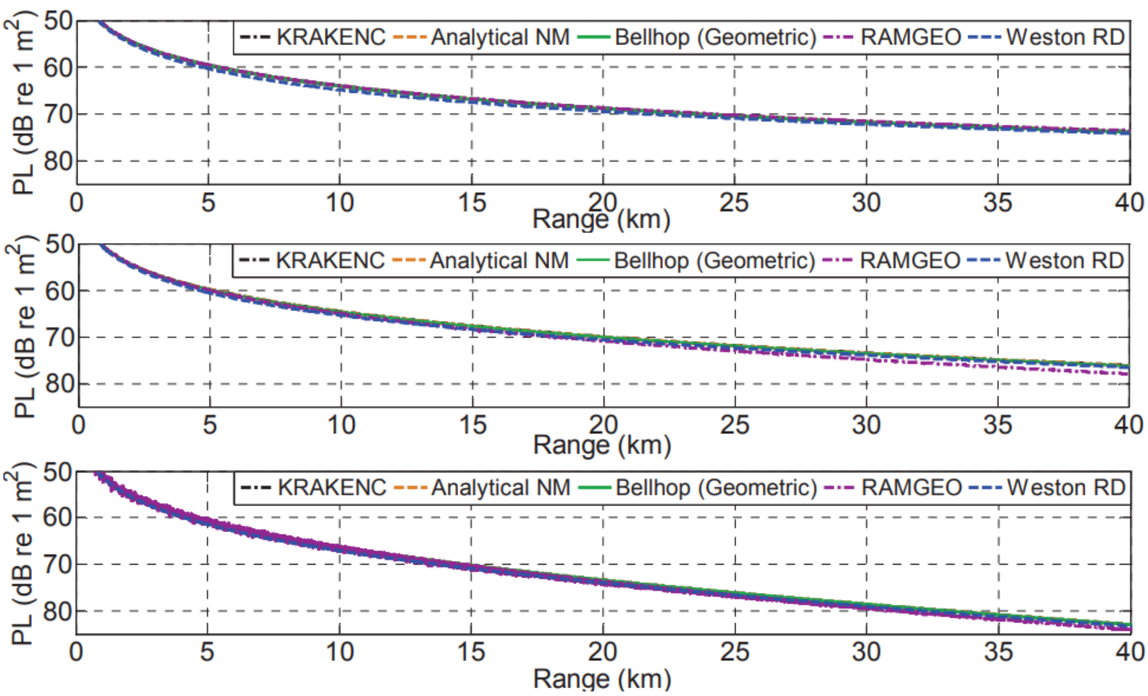

Figure 5. Depth-averaged (over receiver depth)PL vs range for Case 1 (f=250 Hz (top), f=1 kHz (middle), f=3.5 kHz (bottom)). Source depth = 30 m.

Case 2

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

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

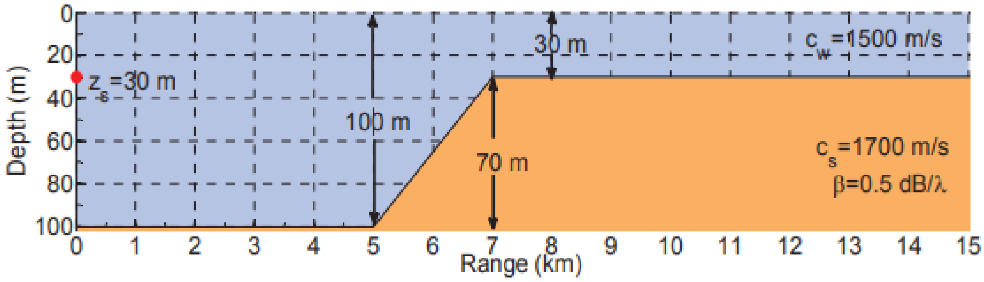

Figure 6. The bathymetry of Case 4

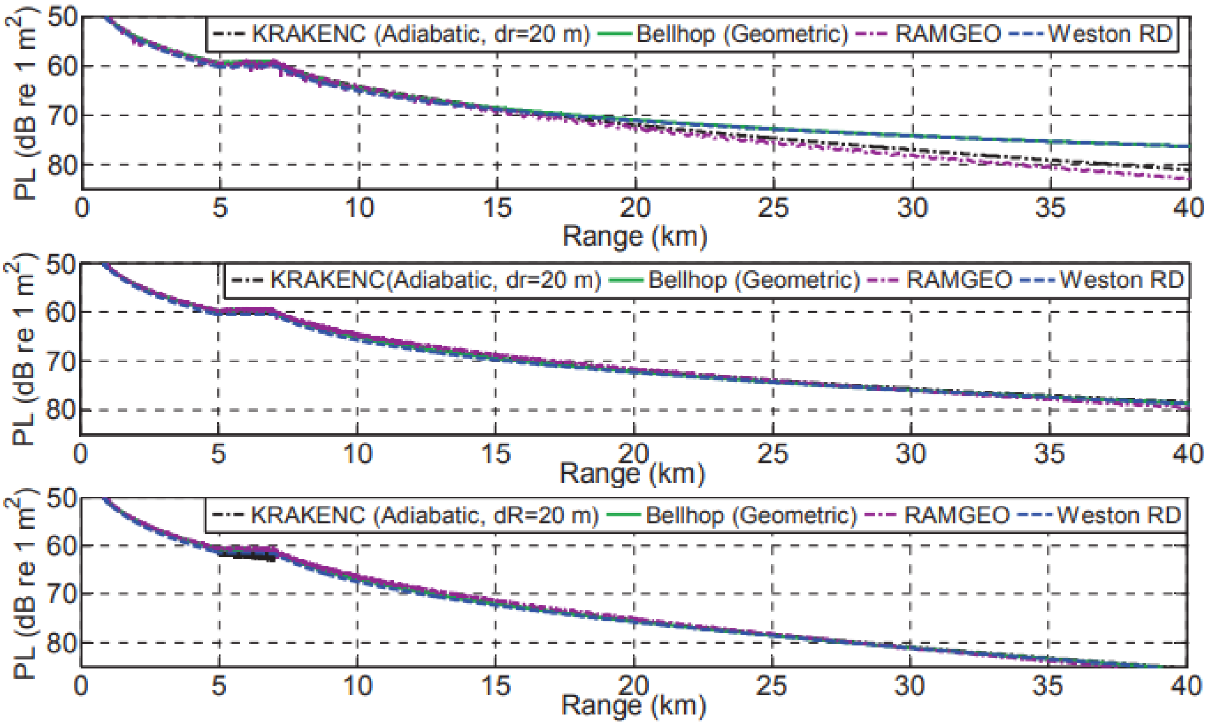

Figure 7. Depth-averaged (over receiver depth)PL vs range for Case 4 (f=250 Hz (top), f=1 kHz (middle), f=3.5 kHz (bottom)). Source depth = 30 m.

Case 3

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

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

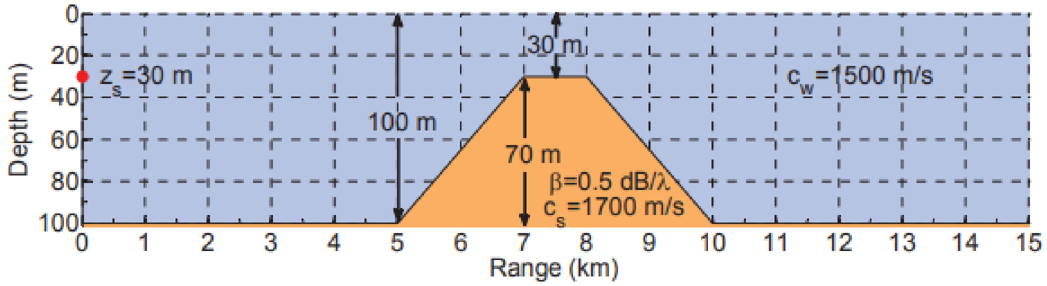

Figure 8. The bathymetry of Case 9

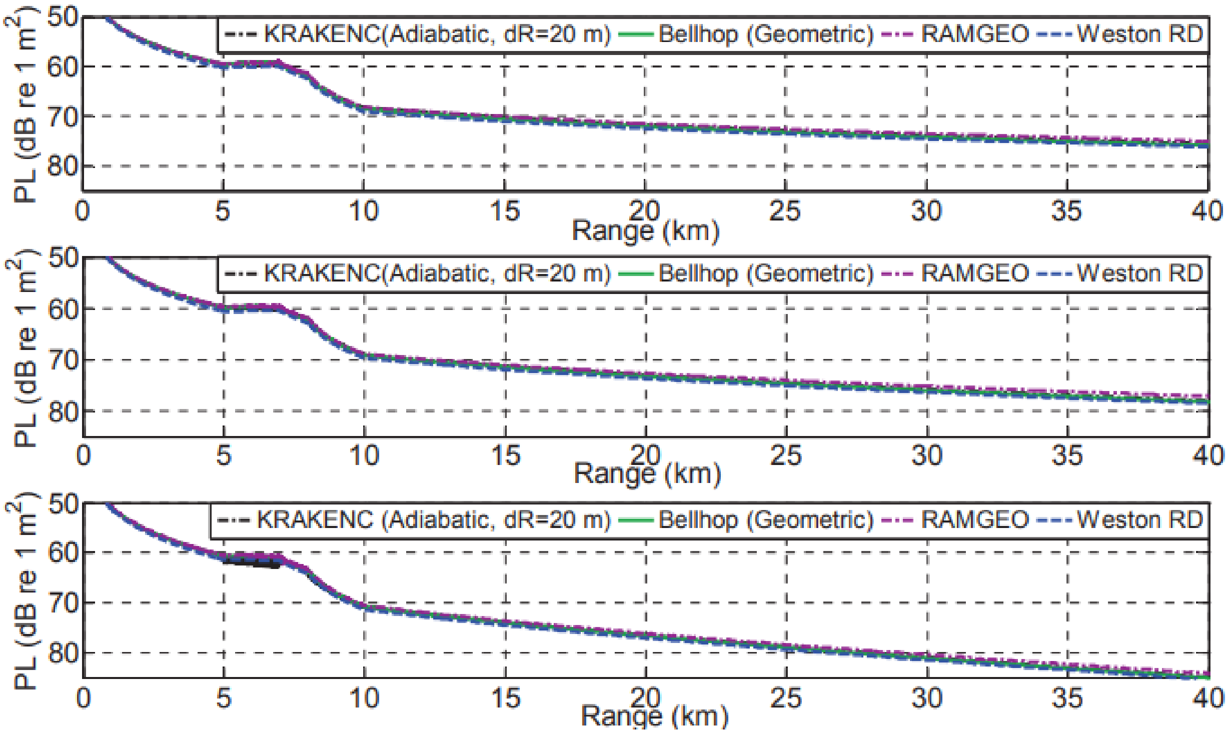

Figure 9. Depth-averaged (over receiver depth) PL vs range for Case9 (f=250 Hz (top), f=1 kHz (middle), f=3.5 kHz (bottom)). Source depth = 30 m.

Broadband comparison with various commercial models

Source:

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

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

Case 1

50 m depth to 100 km range.

Broadband levels versus range

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