Dolphin Acoustic Device Characterisation

Quantifying the Technical Specifications, and Modelling the Usage, of Two Acoustic Devices in New Zealand's Coastal Waters

JASCO Applied Sciences (Australia) Pty Ltd

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Executive Summary

Marine mammal acoustic pingers and deterrent devices are commonly deployed during fishing activities in New Zealand to alert marine mammals to the presence of fishing gear, and/or to deter them from areas of risk or potential feeding opportunities. Hector's and Māui dolphins (*Cephalorhynchus hectori* and *Cephalorhynchus hectori maui*, respectively) are of particular concern for the fishing industry due to their small population sizes and 'endangered' and 'critically endangered' statuses. JASCO Applied Sciences (JASCO) performed a measurement and modelling study of underwater sound levels associated with two devices that are regularly utilised in New Zealand waters: the Netguard Dolphin Pinger (60 – 120 kHz model); and the STM Dolphin Deterrent Device (DDD) (DDD03H model). It is important to determine the accuracy of manufacturer-supplied technical specifications to ensure devices are operating as expected when deployed. Confirming the technical specifications also improves the understanding of the true extent of potential dolphin awareness and potential displacement around commercial fishing activities while using these devices, and aids in recommending how to deploy the devices most effectively.

Three separate devices of each type were measured underwater at a quiet coastal location in Brisbane, Australia. Sound source characterisation aimed to determine the source level, spectra, output pattern, and directivity pattern of each device by using a purpose-built mounting frame that allowed each device to be pivoted with respect to an associated hydrophone and recording equipment. All acoustic data were processed with JASCOs PAMlab software suite, which performed automated analysis of the data to quantify their active and inactive (silent) periods. Statistical measures of the sound during each active period were exported and back-propagated to obtain the source level measurement for each device.

Once the source levels of the devices were known, underwater noise modelling was undertaken to ascertain the propagation of sound from the devices within typical usage environments (i.e. coastal, shallow-water shelf seas). The modelling study specifically assessed distances from the measured devices where underwater sound levels reached thresholds corresponding to behavioural response, impairment (temporary reduction in hearing sensitivity or temporary threshold shift (TTS)) and injury (permanent threshold shift or permanent threshold shift (PTS)) for Hector's and Māui dolphins. The devices considered are generally deployed to trigger behavioural responses in free-ranging animals and are not intended to cause impairment or injury, but nonetheless have the potential to result in these effects if dolphins are exposed to multiple emissions in relatively close proximity. The devices are considered to be intermittent non-impulsive noise sources, and non-impulsive noise effect criteria have therefore been considered as part of the modelling. Estimated underwater acoustic levels for non-impulsive noise sources are presented as sound pressure levels (SPL, L_{p}), as appropriate for assessing behavioural response zones, and as accumulated sound exposure levels (SEL, L_{E}), as appropriate for assessing impairment and injury.

The SPL metric is the root-mean-square pressure level over a stated frequency band over a specified time window; a time window of 1 s was used. To evaluate the potential for accumulated sound exposure levels (SEL), the duration of the SEL accumulation was defined as integrated over a 24-hour period, as per injury and impairment criteria. The SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within 24 hours based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The corresponding SEL_{24h} radii represent an unlikely worst-case scenario. More realistically, marine mammals would not stay in the same location for 24 hours. Therefore, a reported radius for SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be injured, but rather that an animal could be exposed to the sound level associated with impairment if it remained within the ensonified region for 24 hours.

In addition to the noise effect criteria for behavioural response and hearing impairment/injury, the modelling was also used to consider the maximum distance at which Hector's and Māui dolphins would be able to hear and distinguish the sound of each device within a typical underwater noise environment. Device detectability is an important factor in determining appropriate spacing of devices during deployment, particularly for lower-level devices that are only intended to provide dolphins with an awareness that an area contains a high-risk feature (e.g., a set net).

Measurement Results

Manufacturer specifications for the sound source of the Netguard Dolphin Pinger state that the device emits a 'sound pressure level of 145 decibels, frequency between 60 kHz – 120 kHz'. The source level for this device is presented without a reference pressure, it is assumed that this would be 1 µPa for sound pressure level (SPL). The manufacturer specifications for the sound source of the STM DDD comprise '165dB (1 µPa @ 1m), random between 5 and 500 kHz'.

In this measurement study, the signals emitted by the Netguard Pinger were consistent, with short tonal emissions characterized by a narrow frequency band, uniform duration signals and uniform inter-signal silences. Emissions were centred around the 63 kHz decidecade band, with no notable energy emitted in any other frequency band. The signals emitted by the STM DDD were over a much wider frequency band (from 5 kHz to 256 kHz, the limit of the recordings), for random durations (ranging between approximately 5 and 20 s), and varying inter-signal silent intervals.

The results of this measurement study provide decidecade-band source level measurements across three of each type of device allowing for a statistical distribution of source levels. The median source level for the Netguard Pinger was 142.1 dB re 1 µPa and for the STM DDD was 161.1 dB re 1 µPa for measured frequencies between 10 Hz and 256 kHz. All signals from either device were near the levels specified by the manufacturers. This study confirms the acoustic metric applicable to the source level of each device, an aspect which is not always reported by the manufacturers. Neither device displayed strong directionality in its output.

Modelling Results

Using the median measured source levels, the two types of device were modelled in static scenarios across two different geological environments (sand and mud), in four water depths (10, 25, 50, and 100 m), under two sea state conditions (sea state 0 and sea state 4) and at two deployment depths (near the sea surface and near the seafloor).

In these single source scenarios, the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) was exceeded by a single STM DDD to a maximum range of 210 m, whilst the maximum range to the same criterion for a single Netguard Pinger was 18 m (both maximum ranges were associated with modelling conditions of sand seabed, device near the seafloor, and sea state 0) (Table 1). In other combinations of seabed sediment, water depth, sea state and deployment depth, the distances to this criterion were shorter.

The relevant hearing group for Hector's and Māui dolphins for noise effect criteria is the very high-frequency cetacean hearing group outlined by NMFS (2024). In the modelling environment that resulted in the longest propagation distances (sand seabed, device near the seafloor, sea state 0), the accumulated SEL_{24h} criteria for TTS for very high-frequency cetaceans occurred within 191 m of a single static STM DDD and within 10 m of a single static Netguard Pinger (Table 1). In this modelling environment, the accumulated SEL_{24h} criteria for PTS for very high-frequency cetaceans was exceeded within 11 m of the STM DDD (Table 1). The PTS threshold was not exceeded for the Netguard Pinger (Table 1).

Table 1. Summary of single source modelling results: Summary of maximum (R_{max}) horizontal distances (in metres), from single static modelled devices to the marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) and frequency-weighted VHF-cetacean SEL_{24h} TTS and PTS thresholds (161 and 181 dB re 1 µPa²·s, respectively). Ensonified areas (in km²) are also provided for TTS and PTS thresholds.

Device	Description	Marine Mammal Behavioural Response - SPL [a] R_{max} (m)	VHF-cetacean TTS - SEL_{24h} [b]		VHF-cetacean PTS - SEL_{24h} [b]	
			R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
Netguard Pinger	Sand seabed, device near seafloor, sea state 0	18	10	/	–	/
STM DDD	Sand seabed, device near seafloor, sea state 0	210	191	0.115	11	0.001

Noise exposure criteria: [a] NOAA (2024) and [b] NMFS (2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

In addition to single-source modelling, this study also considered two examples of typical multi-source deployments. Nine Netguard Pingers were modelled within one scenario, three each on three static bottom-mounted set nets. Each modelled set net was 600 m long with 200 m spacing between pingers along each net, with 2 km spacing between the set nets. An 18-hour soak time was considered.

The second multi-source scenario consisted of two STM DDD's mounted at each wing-end of a trawl net. The two devices were modelled 30 m apart, moving along a straight track at 2.2 knots for 10 hours, to simulate a trawl net being pulled behind a vessel for two five-hour trawls.

Both scenarios were modelled in typical environmental conditions: the modelled set net scenario was undertaken in 50 m water depth over a mud seabed; while the trawling scenario was undertaken in 25 m water depth over a sand seabed. Both scenarios considered sea states of 0; this is a conservative approach to obtain longer ranges to thresholds; corresponding results for sea state 4 would result in smaller ensonified areas, as shown in the single source modelling. Distances to the marine mammal behavioural response, TTS and PTS criteria are summarised in Table 2.

Table 2. Summary of multi-source modelling results: Summary of maximum (R_{max}) horizontal distances (in metres), from modelled devices to the marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) and frequency-weighted VHF-cetacean SEL_{24h} TTS and PTS thresholds (161 and 181 dB re 1 µPa²·s, respectively). Ensonified areas (in km²) are also provided for TTS and PTS thresholds.

Scenario Description	Environment	Marine Mammal Behavioural Response - SPL [a] R_{max} (m)	VHF-cetacean TTS - SEL_{24h} [b]		VHF-cetacean PTS - SEL_{24h} [b]	
			R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
Nine Netguard Pingers, 3 each on 3 static set nets	50 m water depth, mud seabed, device near seafloor, sea state 0	11	7	0.0011	–	/
Two STM DDDs, one at each end of a 30 m trawl net, trawling for 10 hours at 2.2 knots	25 m water depth, sand seabed, device near seafloor, sea state 0	203	–	/	–	/

Noise exposure criteria: [a] NOAA (2024) and [b] NMFS (2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Detectability of Devices by Hector's and Māui Dolphins

For the consideration of the distances at which each device is likely to be audible to Hector's and Māui dolphins in a typical ambient environment, this study took into account ambient sound level in an exemplar location (Queen Charlotte Sound / Tōtaranui), critical ratio values (how loud a sound must be above ambient noise to be distinguishable to a dolphin), and the audiogram for very high-frequency cetaceans. For both devices, over all considered frequencies, the sum of the ambient level and critical ratio exceeded the corresponding audiogram values and hence ambient sound would be the limiting factor for detectability. The furthest range that a Hector's or Māui dolphin is expected to hear a single static Netguard Pinger in a typical ambient noise environment is 60 m, and the equivalent range for a single static STM DDD is 375 m. These longest ranges occur in the furthest propagating sound environment of 10 m water depth, sand seafloor, sea state 0 with the device deployed near the seafloor. The shortest detection ranges were also calculated based on the modelled scenarios, but in reality the shortest detection ranges could be influenced by external variables, such as increased ambient noise masking the sound of the device.

Within the multi-source modelling, which was conducted for typical deployment conditions rather than maximum propagation conditions, the maximum detectability distance for Hector’s and Māui dolphins was 30 m from each of the Netguard Pingers and up to 345 m for the two STM DDDs mounted 30 m apart on a trawl net.

Summary

The results of this measurement study provide decidecade-band source level measurements across three of each type of device allowing for a statistical distribution of source levels. The median SPL was 142.1 dB re 1 µPa for the Netguard Pinger and 161.1 dB re 1 µPa for the STM DDD (10 Hz – 256 kHz). These reported levels are similar to the manufacturer-reported source levels, but are unlikely to be directly comparable as the manufacturer-report levels are presented without specifying the frequency domain, statistical measures used, or whether the reported levels reflect a design target or the actual performance of manufactured units.

Modelling the propagation of the devices enables a more robust assessment than could be achieved by an in-situ measurement study as all conditions can be controlled. For single static devices, the maximum distance to the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) was 210 m for the STM DDD (modelling environment: sand seabed, device near the seafloor, sea state 0). The maximum range to the same criterion for the Netguard Pinger was 18 m (sand seabed, device near the seafloor, sea state 0). The maximum distance for accumulated SEL_{24h} scenarios for TTS (NMFS, 2024) for very high-frequency cetaceans was 191 m for the STM DDD and 10 m for the Netguard Pinger (sand seabed, device near the seafloor, sea state 0). The maximum distance for accumulated SEL_{24h} criteria for PTS for very high-frequency cetaceans was 11 m for the STM DDD (sand seabed, device near the seafloor, sea state 0). The PTS threshold was not exceeded for the Netguard Pinger.

In the multi-source modelling scenarios under typical deployment conditions, the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) was exceeded up to 11 m for each of nine static Netguard Pingers and up to 203 m from two trawl net-mounted STM DDDs. Of the NMFS (2024) criteria, only the SEL_{24h} TTS criteria was exceeded and only within the net-mounted pinger scenario which resulted in a TTS range of 7 m around each device for the 18-hour soak time modelled.

Generally, the purpose of pingers and acoustic deterrent devices is to alter the behaviour of marine mammals, such that they are more alert, or feel encouraged to leave an area. Accordingly, the marine mammal behavioural response criteria might be considered the most relevant metric. However, the maximum distance at which an animal is able to hear and distinguish the sound of a device within the underwater environment is also an important consideration as behavioural effects may occur at lower sound levels, and responses to noise can be highly context dependent.

The Netguard Pinger was modelled as being detectable to a maximum of 30 to 60 m from the source depending on the modelling environment, and the STM DDD was detectable to a maximum of 95 to 375 m. In the multi-source modelling scenario, which was considered representative of a typical deployment, the maximum detectable distance of each Netguard Pinger was 30 m; as the modelled spacing of devices was 200 m, this implies that some areas of each net were not covered by the acoustic warning system. Based on the minimum detectability of the devices and other factors, such

as the average swim speed of the dolphins, the maximum separation spacing for the Netguard Pinger considering a static straight net is recommended as 59 m in a typical propagation environment. If the STM DDD were deployed on a set net in a similar way, the maximum separation spacing is recommended as 160 m. These spacings are pertinent to the most conservative modelling scenario results (i.e. the modelling scenarios that resulted in the shortest propagation ranges), but it should be noted that in reality the shortest detection ranges could be influenced by external variables, such as increased ambient noise masking the sound of the device, which would result in a need to space the devices more closely together.

Deployment of the STM DDD is likely to be context dependent, but the results presented here suggest that deploying two devices 30 m apart at each wing-end of a trawl net is unlikely to be much more effective than deploying a single device in the centre of the trawl headline; there is little added advantage from deploying a second device in close proximity, and introducing excess noise into the marine environment should be avoided.

1. Introduction

Marine mammal acoustic pingers and deterrent devices are commonly deployed during fishing activities in New Zealand to alert marine mammals to the presence of fishing gear, and/or to deter them from areas of risk or potential feeding opportunities. Hector's and Māui dolphins (*Cephalorhynchus hectori* and *Cephalorhynchus hectori maui*, respectively) are of particular concern for the fishing industry due to their small population sizes and 'endangered' (Reeves et al. 2013) and 'critically endangered' (Constantine 2023) statuses. JASCO Applied Sciences (JASCO) performed a measurement and modelling study of underwater sound levels associated with two marine mammal acoustic deterrent devices that are regularly utilised in New Zealand waters: the Netguard Dolphin Pinger (60 – 120 kHz model); and the STM Dolphin Deterrent Device (DDD03H model). The Netguard Pinger, a lower-level acoustic device, is commonly deployed on bottom-mounted set nets to warn marine mammals of the presence of the net that may otherwise be unnoticed, potentially leading to bycatch scenarios. The STM DDD is a louder device which emits a different, more complex signal, and is often deployed with the intention of encouraging marine mammals to move away from an area of potential danger (e.g. a moving trawl net). It is important to determine the accuracy of manufacturer-supplied technical specifications to ensure devices are effective when implemented and are not causing unexpected levels of noise pollution. Confirming the technical specifications also improves the understanding of the true extent of potential dolphin displacement around commercial fishing activities while using these devices, and aids in recommendations for how to deploy the devices most effectively.

Underwater noise modelling of the measured devices was undertaken to ascertain the propagation of sound from the devices within typical usage environments (i.e. coastal, shallow-water shelf seas). Modelling the devices enables a more robust assessment compared to an in-situ measurement study as all conditions can be controlled, and source propagation can be accurately assessed across all horizontal and vertical planes. Furthermore, the modelled sound fields can be compared to hearing thresholds for species of interest, in this case Hector's and Māui dolphins, along with information on typical ambient noise conditions to consider the overall detectability of each device.

This report is further structured as follows, the remainder of Section 1 provides further details on the measurement and modelling work, Section 1.3 explains the metrics used to represent underwater acoustic fields and the effect criteria considered. Section 2 details the measurement methodology used to obtain the source levels of the devices, and the methods used to model their sound propagation under specific environmental conditions. Section 3 presents the measurement results and the modelled results, the latter as tabulated ranges to thresholds and sound level contour maps. Section 3 also presents detectability results for the devices in relation to critical ratio considerations. The results of the study are then discussed in Section 4, along with recommendations for deployment of the devices in real-world situations.

1.1. Device Measurement

Manufacturer reported source information for both devices measured are presented in Table 3.

Table 3. Device manufacturer specifications.

Manufacturer	Device	Quoted Source Level	Quoted Source Frequency Range
Netguard	Dolphin Pinger	"Sound pressure level: 145 decibels" [1]	"Frequency 60 kHz–120 kHz" [1]
STM	Dolphin Deterrent Device	"165dB (1 μPa @ 1m)" [2]	"Random between 5 and 500 kHz" [2]

[1] https://www.futureoceans.com/our-pingers/

[2] https://www.stm-products.com/en/products/fishing-technology/ddd-03-1/ddd-03h-ddd-03u~50.html

The aim of this project was to verify the manufacturer source information, and to quantify source level, frequency spectra, output patterns and directivity patterns of the devices.

Three separate units of each type of device were measured underwater at a quiet coastal location in Brisbane, Australia using an Ocean Sound Meter 2 (OSM-2; manufactured by JASCO Applied Sciences). Sound source characterisation aimed to determine the source level, spectra, output pattern, and directivity pattern of each device by using a purpose-built mounting frame that allowed each device to be pivoted with respect to an associated hydrophone and recording equipment.

Data were analysed using JASCO's PAMlab software suite. Following the initial processing, the dataset was filtered to include only periods when the devices were actively emitting sound. The filtered data were then correlated with the orientation of the devices relative to the recorder, and relevant metrics – defining the source level of the devices – were subsequently exported.

1.2. Modelling Scenarios

Underwater noise modelling using the measured median source levels was undertaken to ascertain the propagation of sound from the devices within typical usage environments (i.e. coastal, shallow-water shelf seas). The modelling study specifically assessed distances from the measured devices where underwater sound levels reached thresholds corresponding to behavioural response, impairment (temporary reduction in hearing sensitivity or temporary threshold shift (TTS)) and injury (permanent threshold shift or permanent threshold shift (PTS)) for Hector's and Māui dolphins. These noise effect criteria thresholds are summarised and explained in Section 1.3. The devices considered are generally deployed to trigger behavioural responses in free-ranging animals and are not intended to cause impairment or injury, but nonetheless have the potential to result in these effects if dolphins are exposed to multiple emissions in relatively close proximity. The devices are considered to be intermittent non-impulsive noise sources, and non-impulsive noise effect criteria have therefore been considered as part of the modelling.

The two devices (static and singular) were modelled across two different geological environments (sand and mud), in four water depths (10, 25, 50, and 100 m), under two sea state conditions (sea state 0 and sea state 4) and at two deployment depths (near the surface and near the seafloor). Table 4 outlines the modelling scenarios.

Table 4. Description of modelled sites and scenarios.

Device	Seabed Sediment	Water Depth (m)	Sea State	Device depth
Netguard Pinger or STM DDD	Sand or Mud	10	0	Surface
				Seafloor
			4	Surface
				Seafloor
		25	0	Surface
				Seafloor
			4	Surface
				Seafloor
		50	0	Surface
				Seafloor
			4	Surface
				Seafloor
		100	0	Surface
				Seafloor
			4	Surface
				Seafloor

In addition to single-source modelling, this study also considered two examples of typical multi-source deployments. Nine Netguard Pingers were modelled within one scenario, three each on three static bottom-mounted set nets. Each modelled set net was 600 m long with 200 m spacing between pingers along each net, with 2 km spacing between the set nets. The set nets were modelled with a soak time of 18 hours.

The second multi-source scenario consisted of two STM DDD's mounted at each wing-end of a trawl net. The two devices were modelled 30 m apart, moving along a straight track at 2.2 knots for 10 hours, to simulate a trawl net being pulled behind a vessel for two five-hour trawls. These trawling parameters are based on typical trawls as considered by Warren et al. (2023).

Both multi-source scenarios were modelled in typical environmental conditions: the modelled set net scenario was undertaken in 50 m water depth over a mud seabed; while the trawling scenario was undertaken in 25 m water depth over a sand seabed. Both scenarios considered sea states of 0 and the devices were modelled near to the sea floor.

1.3. Noise Effect Criteria

To assess the potential effects of a sound-producing activity, it is necessary to first establish exposure criteria (thresholds) for which sound levels may be expected to have an adverse effect on animals. Whether acoustic levels might injure or disturb marine fauna is an active research topic. Since 2007, several expert groups have developed SEL-based assessment approaches for evaluating auditory injury, with key works including Southall et al. (2007), Finneran and Jenkins (2012), Popper et al. (2014), United States National Marine Fisheries Service (NMFS 2018), Southall et al. (2019) and

NMFS (2024). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

Two sound level metrics, SPL and SEL, are commonly used to evaluate non-impulsive noise and its effects on marine life. In this report, the duration of the SEL accumulation is defined as integrated over a 24-hour period. Appropriate subscripts indicate any frequency weighting applied (see Appendix A.4). The acoustic metrics in this report reflect the ANSI and ISO standards for acoustic terminology, ANSI S1.1 (S1.1-2013) and ISO 18405:2017 (2017).

The following thresholds and guidelines for this study were chosen because they represent the best available science:

1. Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from NMFS (2024) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals for non-impulsive sound sources.
2. Marine mammal behavioural threshold based on the NOAA (2024) criterion for marine mammals of 120 dB re 1 µPa (SPL; L_p) for non-impulsive sound sources.

Section 1.3.1, along with Appendices A.3 and A.4, expand on the relevant thresholds, guidelines, and sound levels applicable to Hector's and Māui dolphins.

1.3.1. Hector's and Māui Dolphins

The criteria applied in this study to assess possible effects of non-impulsive noise sources on marine mammals are summarised in Table 5. Hector's and Māui dolphins are classified as very high-frequency cetaceans by NMFS (2024). Details on thresholds related to auditory threshold shifts or hearing loss and behavioural response are provided in Appendix A.3, with frequency weighting explained in detail in Appendix A.4.

Table 5. Criteria for effects of non-impulsive noise exposure for very high-frequency cetaceans: unweighted SPL and weighted SEL_{24h} thresholds.

Hearing group	NOAA (2024)	NMFS (2024)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)
Very High-frequency (VHF) cetaceans	120	181	161

L_p denotes sound pressure level and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa²·s.

1.3.1.1. Behavioural Response

The NOAA continuous noise criterion was selected for this assessment because it represents the most commonly applied behavioural response criterion by regulators. The distances at which behavioural responses could occur are therefore determined by areas ensonified above an unweighted SPL of 120 dB re 1 µPa (NOAA 2024). Appendix A.3 provides more information about the development of this criterion.

1.3.1.2. Injury and Hearing Sensitivity Changes

There are two categories of auditory threshold shifts or hearing loss: permanent threshold shift (PTS), a physical injury to an animal's hearing organs; and temporary threshold shift (TTS), a temporary reduction in an animal's hearing sensitivity as the result of receptor hair cells in the cochlea becoming fatigued.

To assist in assessing the potential for effect on Hector's and Māui dolphins, this report applies the criteria recommended by NMFS (2024), considering both PTS and TTS (see Table 5). Appendix A.3 provides more information about these criteria.

1.4. Detectability Assessment

The acoustic modelling outlined in Section 1.2 aimed to quantify distances from the devices to specific noise effect criteria thresholds. Generally, the purpose of pingers and acoustic deterrent devices is to alter the behaviour of marine mammals, such that they are more alert, or feel encouraged to leave an area. Accordingly, the marine mammal behavioural response criteria might be considered the most relevant metric. However, the maximum distance at which an animal is able to hear and distinguish the sound of a device within the underwater environment is also an important consideration as behavioural effects may occur at lower sound levels, and responses to noise can be highly context dependent.

To estimate ranges and regions over which each device is detectable by Hector's and Māui dolphins, the modelled sound fields were compared to an exemplar ambient noise measurement obtained from a known Hector's dolphin habitat, and to hearing thresholds estimated for Hector's and Māui dolphins. Section 2.3 expands on the methodology and data sources used in this analysis. Device detectability is an important factor in determining appropriate spacing of devices during deployment, and this is discussed in Section 4.3.

2. Methods and Parameters

2.1. Measurement Methodology

Three of each type of device were measured for this study, resulting in a total of six devices measured. Underwater measurements were undertaken at a quiet coastal location in Brisbane, Australia (Figure 1). Sound source characterisation aimed to determine the source level, spectra, output pattern, and directivity pattern of each device by using a purpose-built mounting frame that allowed each device to be pivoted with respect to an associated hydrophone and recording equipment.

Measurements were conducted with a field-calibrated Ocean Sound Meter-2 (OSM-2; manufactured by JASCO Applied Sciences). The OSM-2 was configured to record with a sample rate of 512 ksps, the limit of the recorder. This produces a recording bandwidth of 10 – 256,000 Hz.

Figure 1. Map of the measurement location in Brisbane, Australia.

Each device was mounted in a purpose-built frame allowing full rotation of the source to measure directivity, and ensuring a fixed distance of 2 m to the recording hydrophone (Figures 2 to 4). The entire apparatus was suspended approximately 2 m deep within the water column. Each device was measured in both the horizontal and vertical planes. In the horizontal plane, the devices were rotated from ‘midpoint’ to ‘midpoint’ and measured at set angles (0°, 30°, 60°, 90°, 120°, 150°, 180°).

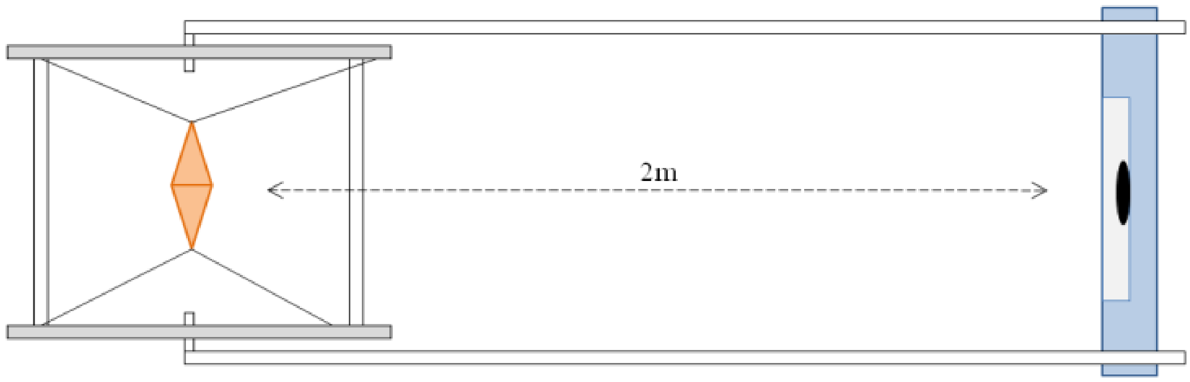


Figure 2. Side view of the measurement apparatus, with acoustic device (orange) in vertical position and hydrophone mounted in blue tube (right).

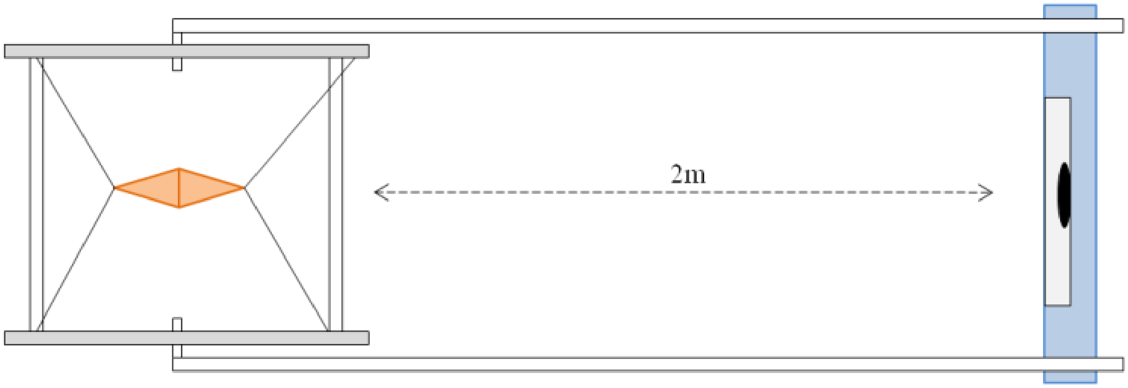


Figure 3. Side view of the measurement apparatus, with acoustic device (orange) in horizontal position and hydrophone mounted in blue tube (right).

Figure 4. Top view of the measurement apparatus, showing the apparatus reference rotation angles and hydrophone mounted in blue tube (right).

2.1.1. Automated Acoustic Data Analysis

The Ocean Sound Meter (OSM) collected approximately 11.7 GB of acoustic data during this study. All acoustic data were processed with JASCOs PAMlab software suite, which processes acoustic data hundreds of times faster than real time. PAMlab performed automated analysis of recorded sound data to extract SEL over a fixed time window.

To analyse the data, the recordings were converted to units of micropascals (μPa) by applying the hydrophone sensitivity, the analog circuit frequency response, and the digital conversion gain of the AMAR. Summaries of sound statistics were computer for each 1 s period.

To determine the periods when the devices were active, spectrograms were examined to identify frequencies with a clear distinction between active emissions and ambient noise. A threshold was then defined for each device as the mean value of the ambient and active levels corresponding to said frequency. If, during a 1 s period, the level at the identified frequency exceeded the threshold, the period was classified as the device being active. Periods where the device was inactive were discarded.

To estimate source levels from these data, active time periods were grouped by device type (i.e., Netguard Pinger or STM DDD) and orientation of the device relative to the recorder, consolidating individual signals across time and similar devices (i.e., same device but differing serial numbers). Statistical measures were then exported for each device–orientation combination. For either device, the typically loudest orientation was selected, and the median levels were exported for each frequency band where the active device clearly exceeded ambient levels.

Measurements were made with 2 m separation between the device and hydrophones. To adjust the received levels to be source levels (i.e., levels a 1 m), the measured levels were back–propagated assuming spherical geometric spreading, adding a dB–shift of $20 \cdot \log_{10}(2) = +6$ dB.

As the devices emit sound intermittently, a classification of the proportion of time spent emitting sound versus silent inter-signal durations was required to calculate cumulative–time metrics (SEL_{10min}, SEL_{1h}, and SEL_{24h}). To determine this, the mean duration of signals for either device was measured in PAMlab across multiple recording periods. For the Netguard Dolphin Pinger, the mean duration of silences between signals was also measured. In contrast, the STM DDD's manual reports a mean silent time between signals of 40 s. The quotient of these quantities gave the percentage time that either device was active, to be applied when computing ranges to cumulative sound thresholds (TTS and PTS for marine mammals) in the acoustic modelling.

2.2. Modelling Methodology

To enable the study to be representative of a range of coastal NZ environments, the two devices were modelled statically and independently within an arbitrary underwater environment in water depths of 10, 25, 50 and 100 m. The seabed sediment of the modelling area was set twice, once as sand and once as mud to enable a comparison of sound propagation across two common sediment types in coastal NZ waters. Further details on the associated geoacoustic properties used in this modelling study are provided in Appendix B.1.3.

Sea surface roughness conditions for sea state 0 (windspeed of 0 knots) and sea state 4 (windspeed of 13.5 knots) were modelled at each modelled site to allow the effect of wave activity on sound propagation to be assessed.

A composite, indicative sound speed profile was generated using measurements obtained off the coast of Timaru (a representative Hector's dolphin habitat). The month of July was selected due to properties of the sound speed profile that were most favourable for sound propagation, resulting in the largest ranges to considered isopleths criteria. Additional detail can be found in Appendix B.1.2.

In addition to the single-source modelling, two scenarios of typical multi-source deployment conditions were also modelled; nine Netguard Pingers were modelled as though deployed on set nets, and two STM DDDs were modelled as though attached to a moving trawl net. For full details, refer to Section 1.2.

2.2.1. Modelled Noise Sources

The modelled noise sources were obtained from the measurement study and subsequent analysis described in Section 2.1.

Figure 5 presents a summary plot of both considered source spectra for comparison purposes. The source spectra plot shows the distribution of sound across the decidecade frequency bands that the modelling considers.

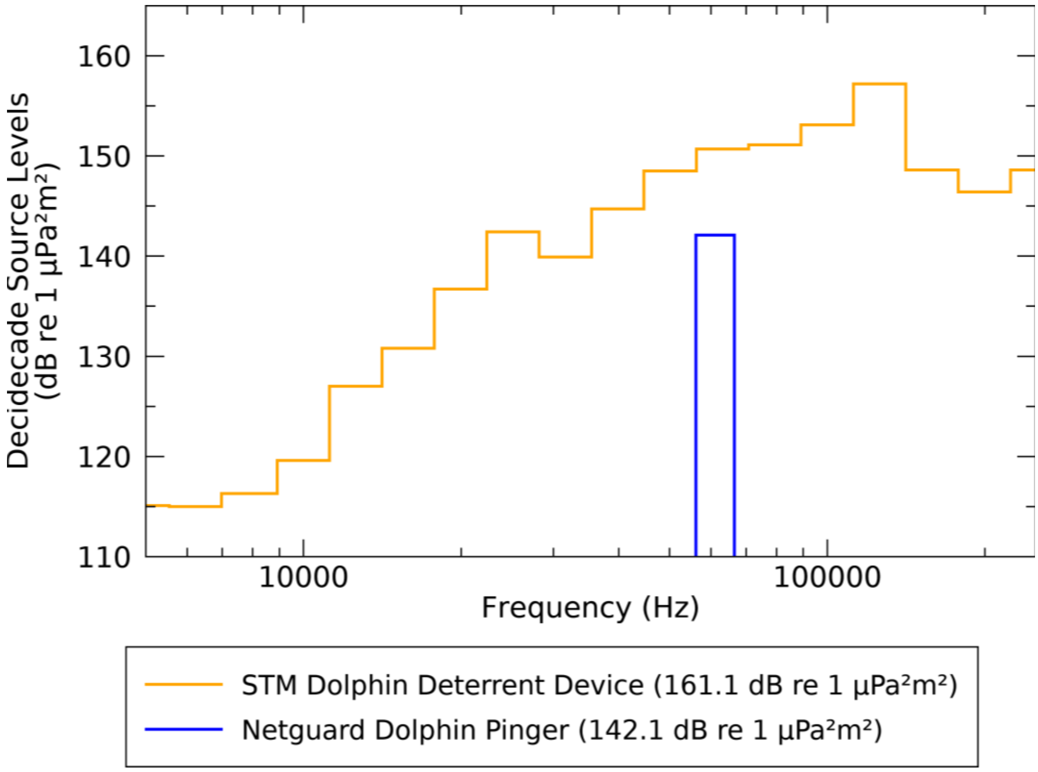


Figure 5. Monopole source level (MSL) spectra (in decidecade frequency-band) for both devices.

2.2.2. Geometry and Modelled Regions

JASCO's Marine Operations Noise Model (MONM-BELLHOP; see Appendix B.2.2) was used to predict the acoustic field at frequencies of 10 kHz to 250 kHz.

The sound field modelling calculated propagation losses up to 2 km from the source, with a horizontal separation of 5 m between receiver points along the modelled radials. The sound fields were modelled with a horizontal angular resolution of $\Delta\theta$ = 2.5° for a total of N = 144 radial planes. Receiver depths were chosen to span the entire water column over the modelled areas, from 2 m to a maximum of 100 m.

To produce the maps of received sound level isopleths, and to calculate distances to specified sound level thresholds, the maximum-over-depth level was calculated at each sampling point within the modelled region. The radial grids of maximum-over-depth levels were then resampled (by linear triangulation) to produce a regular Cartesian grid. The contours and threshold ranges were calculated from these grids of the modelled acoustic fields.

2.2.3. Accumulated SEL

The reported source levels are usually in terms of sound pressure levels (SPL), representing the average instantaneous acoustic level of a considered source. The evaluation of the cumulative sound field (i.e., in terms of SEL_{24h}) depends on the number of seconds of operation during the accumulation period.

The SPL modelling results were converted to SEL by the duration of the measurement, which is appropriate for a non-impulsive noise source, and the proportion of time the devices were emitting sound. Here, SEL was assessed over 10 minutes, 1 hour and 24 hours. For the static single-source modelling, the conversion from SPL was obtained by increasing the levels by $10*\log_{10}(T*P)$, where T is 600, 3,600, or 86,400 (the number of seconds in 10 min, 1 hour and 24 hours) and P is the proportion of time the devices were active. For the multi-source DDD scenario where the devices were transiting along a track, a similar adjustment to the SPL was applied, however the time factor was determined based on the step size along the track, the trawling speed and the proportion of time the devices were active. See Appendix B.4 for details. It should be noted that the sound produced by the trawling vessel itself has not been included in the modelling in order to focus on the sound footprints associated with the acoustic devices, as they are the new/novel source, not the vessel.

2.3. Detectability Methodology

To estimate the ranges at which Hector’s and Māui dolphins are likely to be able to acoustically detect each device within typical ambient noise conditions, audiograms and critical ratios that are relevant to Hector’s and Māui dolphins were gathered through a literature review.

An audiogram is a graphical representation of a marine mammals hearing sensitivity. It illustrates the minimum sound levels required at various frequencies for the animal to detect a sound, providing a threshold that must be exceeded for the sound to be perceived. Appendix A of NMFS (2024) provides equations and parameters for defining an audiogram for very-high-frequency cetaceans, and this is summarised in Appendix A.4 of this report.

A critical ratio is the decibel difference between the sound pressure level of a pure tone just audible for a marine mammal in the presence of a continuous noise of constant spectral density, and the sound pressure spectrum level for that noise. From our literature review, critical ratio information is not currently available for Hector’s and Māui dolphins specifically, however Erbe et al. (2016) provides frequency-specific critical ratio values for harbour porpoises (*Phocoena phocoena*), another very-high-frequency cetacean species. In this study we have applied the harbour porpoise critical ratio information in the absence of Hector’s and Māui dolphin specific information. Critical ratios were extracted from Erbe et al. (2016) corresponding to significant frequencies identified in the signals of the devices and ranged from 27 to 34 dB.

In this study, we have considered a typical ambient noise environment for Hector’s dolphin habitat based on publicly available underwater sound level measurements of the Queen Charlotte Sound / Tōtaranui, New Zealand (Goetz and Hupman 2017). The ambient soundscape of the Queen Charlotte Sound / Tōtaranui was documented in a study by the National Institute for Water and Atmospheric Research (NIWA, New Zealand) supported by JASCO in 2016 (Delarue et al. 2017, Goetz and Hupman 2017). Data were recorded at a sampling rate of 375 ksps, giving ambient levels for frequencies exceeding the dominant frequencies of both devices considered in the present study. Queen Charlotte Sound / Tōtaranui is a representative habitat for Hector’s dolphins; their vocalisations were detected in the acoustic dataset.

Practically, critical ratios indicate how much higher the intensity of the device tone must be than the intensity of the ambient soundscape for the device to be audible within the constraints of the dolphins’ hearing capabilities. The detection threshold at a given frequency is the higher of either the audiogram at said frequency or the sum of the ambient level and critical ratio. The detection range is hence the range over which this threshold is exceeded.

3. Results

3.1. Measurement Results

Example spectrograms for recordings of both the Netguard Pinger and the STM DDD are shown in Figures 6 to 10. Tables 6 and 7 present the calculated source levels within each decidecade band for the Netguard Pinger and STM DDD, respectively, along the azimuth where received levels were loudest (0-degrees for the Netguard Pinger and 90-degrees for the STM DDD). The median level presented in these tables was utilised as the source level during modelling (Section 3.2). The broadband level for both devices, summed over frequencies where signals were emitted, is presented in Table 8. Figures 11 and 12 present the broadband source levels for either device along each azimuth that they were measured, along with the manufacturers reported source level. Table 9 presents the signal and inter-signal silent durations and corresponding 'time active' percentage for both device types.

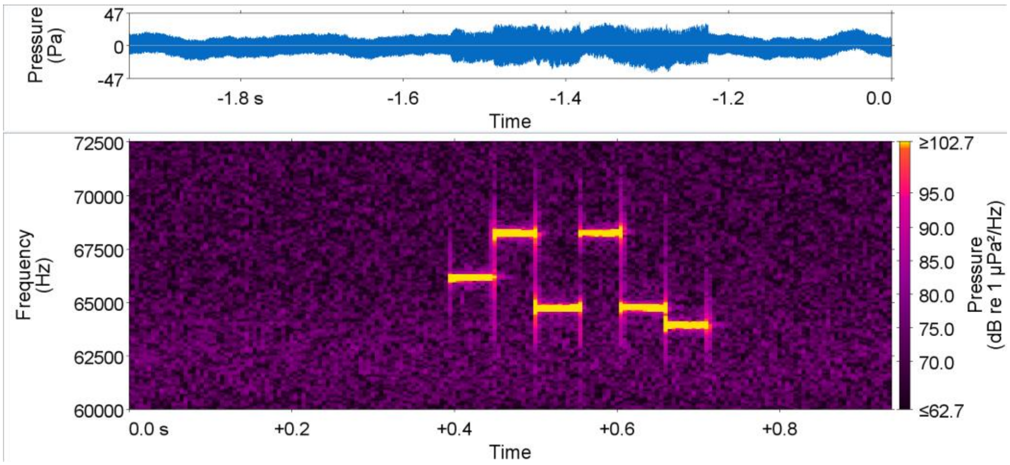


Figure 6. *Netguard Pinger* waveform (top) and spectrogram (bottom) showing a first example signal (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window).

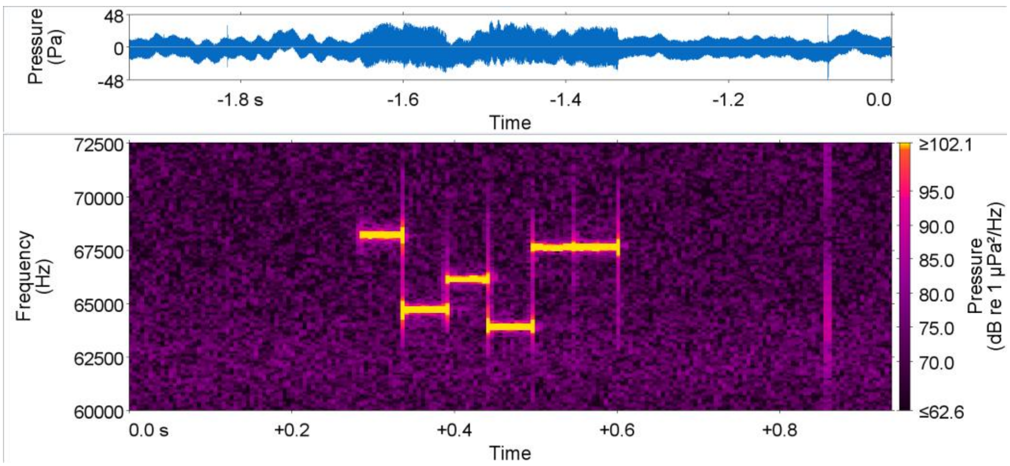


Figure 7. *Netguard Pinger* waveform (top) and spectrogram (bottom) showing a second example signal (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window).

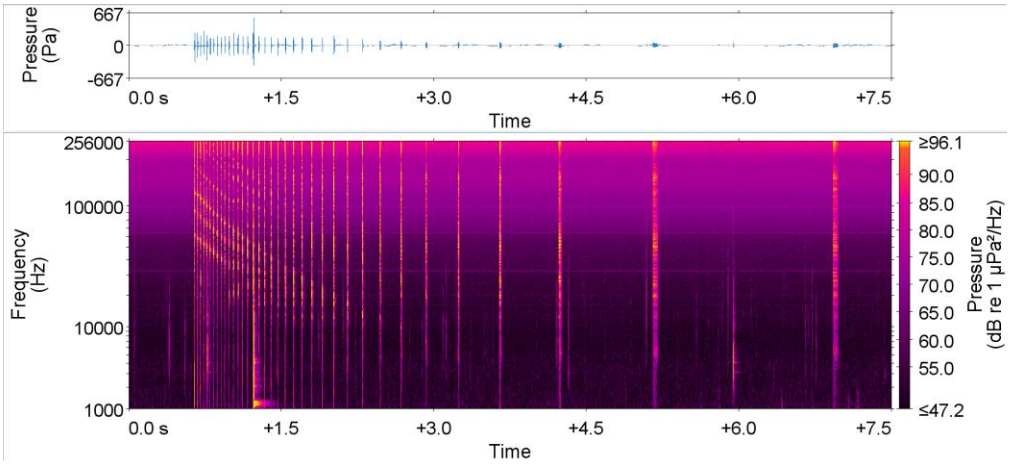


Figure 8. *STM DDD* waveform (top) and spectrogram (bottom) showing a first example signal (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window).

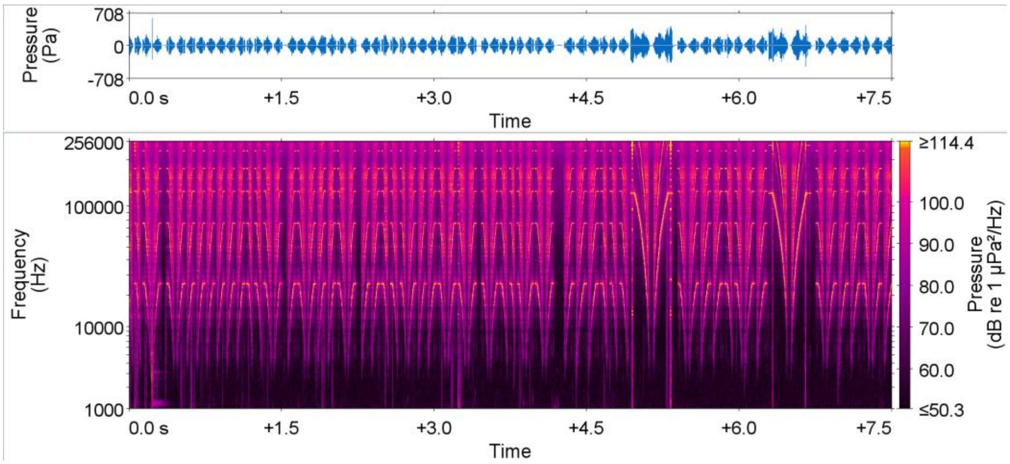


Figure 9. *STM DDD* waveform (top) and spectrogram (bottom) showing a second example signal (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window).

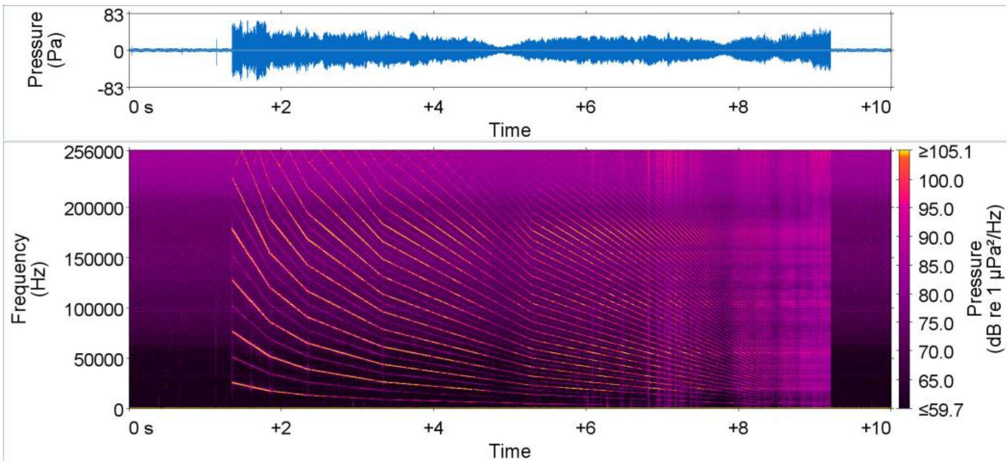


Figure 10. *STM DDD* waveform (top) and spectrogram (bottom) showing a third example signal with minor aliasing evident above 200,000 Hz (64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window).

Table 6. Decidecade-band source level measurements for the Netguard Dolphin Pinger along the 0-degree azimuth. Levels in SPL (dB re 1µPa), back-propagated to 1 m from source.

Percentile	Decidecade band centre frequency (kHz)
	63
Maximum	147.8
95%	146.7
75%	145.7
Median	142.1
25%	138.5
5%	128.1
Minimum	126.5

Table 7. Decidecade-band source level measurements for the STM Dolphin Deterrent Device along the 90-degree azimuth. Levels in SPL (dB re 1µPa), back-propagated to 1 m from source.

Percentile	Decidecade band centre frequency (kHz)																	
	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200	250
Maximum	125.6	126.3	128.4	130.6	144.4	142.7	146.3	151.9	152.6	158.7	157.9	161.5	162.1	164.5	170.4	160.5	155.0	164.6
95%	122.8	122.5	123.3	127.8	140.7	140.6	145.9	151.3	150.9	155.9	156.7	160.0	160.0	163.8	167.1	158.5	153.8	161.9
75%	118.0	117.9	118.8	124.9	132.8	137.8	144.3	149.1	143.3	147.7	152.3	156.2	156.0	157.7	161.7	156.1	151.2	151.0
Median	115.1	115.0	116.3	119.6	127.0	130.8	136.7	142.4	139.9	144.7	148.5	150.7	151.7	153.1	157.2	148.6	146.4	148.6
25%	112.3	112.6	112.5	115.1	119.4	122.6	126.6	135.7	133.3	137.4	141.4	144.7	143.4	141.3	146.5	144.7	140.4	142.9
5%	105.0	106.0	106.7	105.9	107.1	109.6	112.9	128.9	126.7	131.4	133.6	138.3	136.1	135.2	139.8	140.5	136.6	140.2
Minimum	101.1	97.1	97.1	97.0	99.7	102.5	106.1	126.3	114.1	129.8	122.8	133.3	132.1	131.5	136.4	135.4	134.5	138.2

Table 8. Broadband source level measurements for the Netguard Pinger and STM Dolphin Deterrent Device along the 0-degree and 90-degree azimuth respectively. Levels in SPL (dB re 1µPa), back-propagated to 1 m from source. Broadband across emission frequencies.

Percentile	Netguard Pinger (dB re 1µPa)	STM DDD (dB re 1µPa)
Maximum	147.8	173.6
95%	146.7	171.2
75%	145.7	165.9
Median	142.1	161.2
25%	138.5	152.9
5%	128.1	147.4
Minimum	126.5	143.8

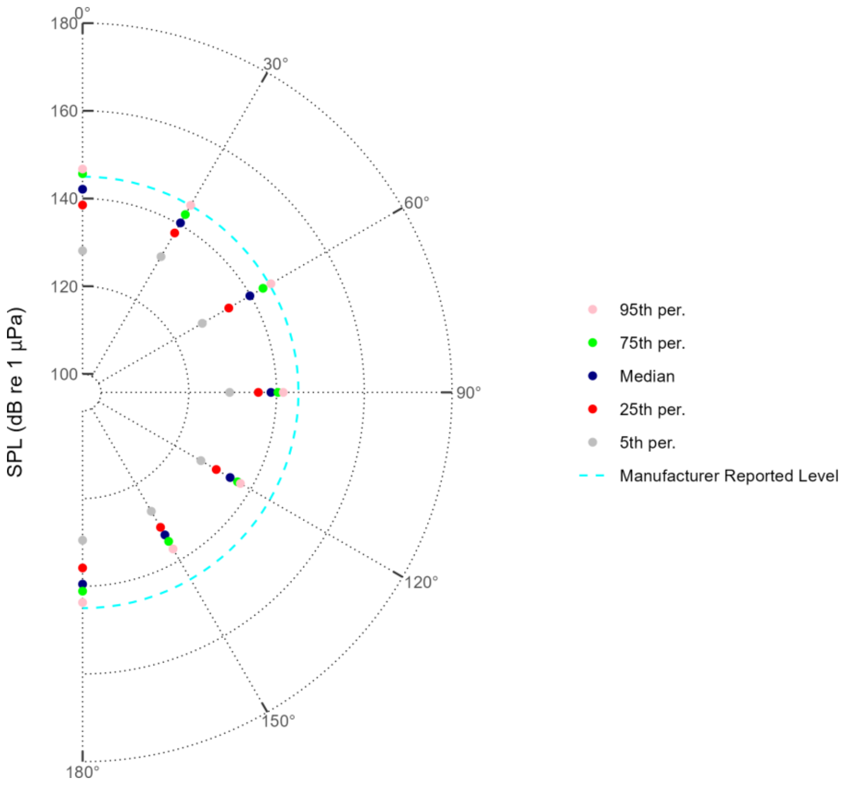


Figure 11. Measured source level for the Netguard Dolphin Pinger, showing 5th, 25th, 75th and 95th percentile levels along with median level. The manufacturers reported source level of 145 dB re 1 µPa is presented also.

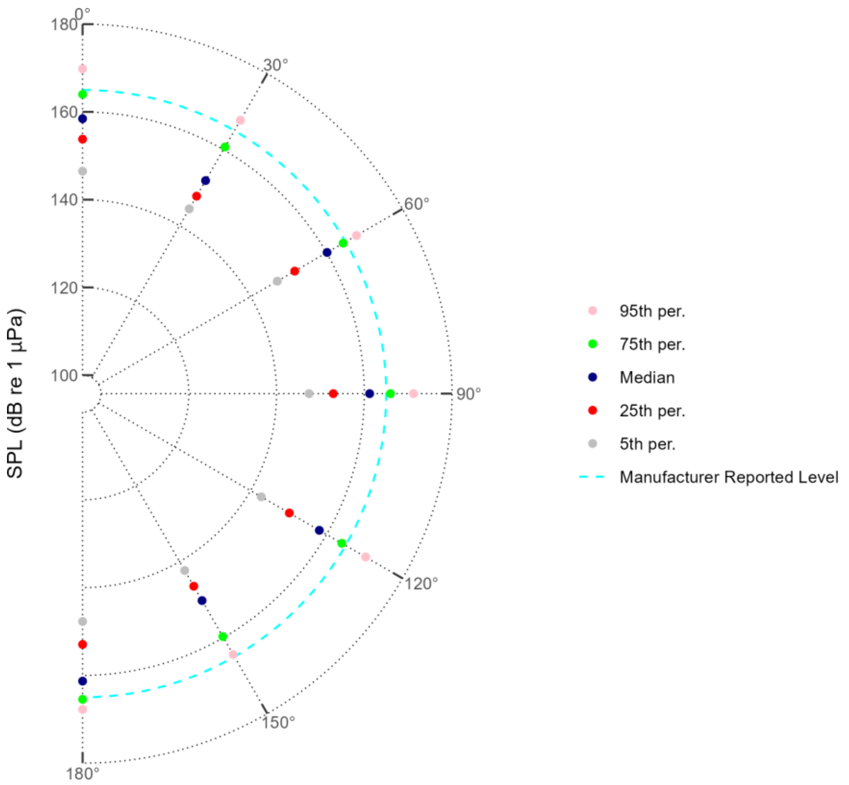


Figure 12. Measured source level for the STM Dolphin Deterrent Device, showing 5th, 25th, 75th and 95th percentile levels along with median level. The manufacturers reported source level of 165 dB re 1 µPa is presented also.

Table 9. Summary of signal and inter-signal silent durations, and derived operating time (time active, %).

Device	Mean Signal Duration (s)	Mean Silent Inter-Signal Duration (s)	Time Active (%)
Netguard Pinger	0.332 [1]	3.975 [1]	7.71
STM DDD	12.22 [1]	40.0 [2]	23.4

[1] Measured using PAMlab
[2] From STM DDD user manual

3.2. Modelling Results

The maximum-over-depth sound fields for the modelled scenarios are presented below in two formats: as tables of distances to sound levels and, where the distances are long enough, as contour maps showing the directivity and range to various sound levels. Single source modelling results are presented in Section 3.2.1 and multi-source modelling results are presented in Section 3.2.2.

Estimated underwater acoustic levels for non-impulsive noise sources are presented as sound pressure levels (SPL, L_p), and as accumulated sound exposure levels (SEL, L_E), as appropriate for different noise effect criteria. The SPL metric is the root-mean-square pressure level over a stated frequency band over a specified time window; a time window of 1 s was used. To evaluate the potential for accumulated sound exposure levels (SEL), the duration of the SEL accumulation was defined as integrated over a 10-minute, 1-hour and 24-hour period. The SEL is a cumulative metric that reflects the dosimetric impact of noise levels within a given time period based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The corresponding SEL radii represent an unlikely worst-case scenario. More realistically, marine mammals would not stay in the same location for long periods. Therefore, a reported radius for SEL criteria does not mean that marine fauna travelling within this radius of the source will be injured, but rather that an animal could be exposed to the sound level associated with impairment if it remained within the ensonified region for the stated time period.

Detectability results for the devices are provided in Section 3.3.

3.2.1. Single Source Modelling

3.2.1.1. Tabulated Results – Netguard Pinger

Tables 10 to 13 present the maximum horizontal distances to specific SPL contours for a single static modelled Netguard Pinger. The SPL footprints represent instantaneous sound fields and do not depend on time accumulation. The marine mammal behavioural response threshold of 120 dB re 1 µPa (NOAA 2024) is marked within each table.

Tables 14 to 17 present the maximum horizontal distances to very high-frequency cetacean TTS and PTS contours (NMFS, 2024) for a single static modelled Netguard Pinger for varying time accumulation (10 minutes, 1 hour, and 24 hours).

Table 10. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to sound pressure level (SPL) from the modelled Netguard Pinger in 10 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
130	–	–	–	–	–	–	–	–
120[a]	16	11	18	15	16	11	14	11
110	87	51	86	47	52	36	50	36
100	291	141	292	129	149	111	141	115

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 11. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to sound pressure level (SPL) from the modelled Netguard Pinger in 25 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
130	–	–	–	–	–	–	–	–
120[a]	16	11	16	15	15	11	11	11
110	60	36	57	46	51	35	43	36
100	219	138	202	127	148	116	135	113

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 12. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to sound pressure level (SPL) from the modelled Netguard Pinger in 50 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
130	–	–	–	–	–	–	–	–
120[a]	15	11	15	15	15	11	11	11
110	51	35	47	45	50	35	39	35
100	169	129	163	123	147	115	133	107

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 13. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to sound pressure level (SPL) from the modelled Netguard Pinger in 100 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
130	–	–	–	–	–	–	–	–
120[a]	15	11	15	15	15	11	11	11
110	50	35	46	45	47	35	35	34
100	148	115	132	123	146	115	115	106

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 14. *SEL₂₄ₕ*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds for VHF cetaceans based on NMFS (2024) from the modelled Netguard Pinger in 10 m water depth, along with ensonified area (km²).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
TTS – 161 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	7	\	7	\	10	\	7	\	7	\	7	\	7	\	7	\

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km²).

Table 15. *SEL24h*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on NMFS (2024) from the modelled Netguard Pinger in 25 m water depth, along with ensonified area (km^2).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
TTS – 161 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km^2).

Table 16. *SEL24h*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on NMFS (2024) from the modelled Netguard Pinger in 50 m water depth, along with ensonified area (km^2).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
TTS – 161 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km^2).

Table 17. *SEL_{24h}*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on NMFS (2024) from the modelled Netguard Pinger in 100 m water depth, along with ensonified area (km²).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
TTS – 161 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km²).

3.2.1.2. Tabulated Results – STM DDD

Tables 18 to 21 present the maximum horizontal distances to specific SPL contours for a single static modelled STM DDD. The SPL footprints represent instantaneous sound fields and do not depend on time accumulation. The marine mammal behavioural response threshold of 120 dB re 1 µPa (NOAA 2024) is marked within each table.

Tables 22 to 25 present the maximum horizontal distances to very high-frequency cetacean TTS and PTS contours (NMFS, 2024) for a single static modelled STM DDD for varying time accumulation (10 minutes, 1 hour, and 24 hours).

Table 18. *SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in metres) to sound pressure level (SPL) from the modelled STM DDD in 10 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
150	–	–	–	–	–	–	–	–
140	14	10	15	11	11	10	11	10
130	67	40	65	40	40	30	41	30
120[a]	209	110	210	105	110	89	113	93
110	486	227	481	227	252	206	252	210
100	994	432	991	439	753	397	515	415

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 19. *SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in metres) to sound pressure level (SPL) from the modelled STM DDD in 25 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
150	–	–	–	–	–	–	–	–
140	11	10	14	11	11	10	10	10
130	41	30	45	39	40	29	36	30
120[a]	152	105	151	105	108	87	110	093
110	368	224	367	227	232	186	238	208
100	855	428	779	426	739	373	453	394

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 20. *SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in metres) to sound pressure level (SPL) from the modelled STM DDD in 50 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
150	–	–	–	–	–	–	–	–
140	11	10	11	11	11	10	10	10
130	40	29	41	039	39	29	30	30
120[a]	127	89	122	102	108	86	99	84
110	305	224	304	223	231	185	233	203
100	797	425	644	435	731	368	451	405

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 21. *SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in metres) to sound pressure level (SPL) from the modelled STM DDD in 100 m water depth.

SPL (L_p; dB re 1 µPa)	Sand Seabed				Mud Seabed			
	Near Surface		Near Seafloor		Near Surface		Near Seafloor	
	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4	Sea State 0	Sea State 4
	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
150	–	–	–	–	–	–	–	–
140	11	10	11	11	11	10	11	11
130	39	29	42	41	39	29	30	30
120[a]	108	87	109	106	106	86	91	85
110	260	204	257	226	229	184	227	197
100	766	412	556	455	730	367	462	411

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 22. *SEL*$_{24h}$: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL$_{24h}$ PTS and TTS thresholds for VHF cetaceans based on NMFS (2024) from the modelled STM DDD in 10 m water depth, along with ensonified area (km^2).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	10	\	7	\	11	0.001	10	\	10	\	7	\	7	\	7	\
TTS – 161 dB re 1 µPa²·s																
10 min	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\
1 hr	27	0.002	18	0.001	25	0.002	21	0.001	21	0.002	15	0.001	18	0.001	15	0.001
24 hr	191	0.115	92	0.027	191	0.115	89	0.025	91	0.026	70	0.015	97	0.030	78	0.020

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km^2).

Table 23. *SEL₂₄ₕ*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds for VHF cetaceans based on NMFS (2024) from the modelled STM DDD in 25 m water depth, along with ensonified area (km^2).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	10	\	7	\	10	\	10	\	10	\	7	\	7	\	7	\
TTS – 161 dB re 1 µPa²·s																
10 min	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\
1 hr	21	0.002	15	0.001	21	0.002	20	0.001	21	0.001	15	0.001	16	0.001	15	0.001
24 hr	129	0.052	86	0.023	127	0.051	89	0.025	90	0.025	70	0.015	93	0.028	76	0.018

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km^2).

Table 24. *SEL₂₄ₕ*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds for VHF cetaceans based on NMFS (2024) from the modelled STM DDD in 50 m water depth, along with ensonified area (km^2).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	10	\	7	\	10	\	10	\	10	\	7	\	7	\	7	\
TTS – 161 dB re 1 µPa²·s																
10 min	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\
1 hr	21	0.001	15	0.001	21	0.001	21	0.001	20	0.001	15	0.001	16	0.001	15	0.001
24 hr	103	0.033	71	0.016	100	0.032	87	0.024	88	0.024	70	0.015	82	0.022	71	0.016

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km^2).

Table 25. *SEL_{24h}*: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds for VHF cetaceans based on NMFS (2024) from the modelled STM DDD in 100 m water depth, along with ensonified area (km²).

Operation Time	Sand Seabed								Mud Seabed							
	Near Surface				Near Seafloor				Near Surface				Near Seafloor			
	Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4		Sea State 0		Sea State 4	
	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
PTS – 181 dB re 1 µPa²·s																
10 min	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1 hr	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
24 hr	10	\	7	\	10	\	10	\	10	\	7	\	7	\	7	\
TTS – 161 dB re 1 µPa²·s																
10 min	7	\	7	\	7	\	7	\	7	\	7	\	7	\	7	\
1 hr	20	0.001	15	0.001	21	0.001	21	0.001	20	0.001	15	0.001	15	0.001	15	0.001
24 hr	89	0.025	70	0.015	93	0.028	89	0.025	87	0.024	68	0.015	72	0.017	70	0.015

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km²).

3.2.1.3. Sound Field Maps

Maps of the estimated threshold contours of interest for SPL are presented for the modelled scenarios. Results are grouped by device and water depth. Maps for SEL contours are not shown for single site modelling as ranges to thresholds are too small to be displayed graphically, or were not exceeded within the modelling resolution.

3.2.1.3.1. Netguard Pinger

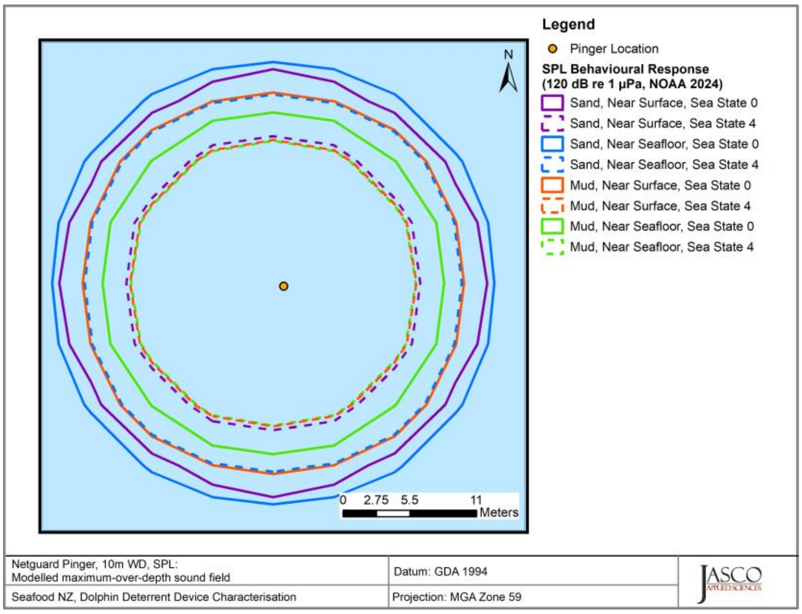


Figure 13. *Netguard Pinger in 10 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

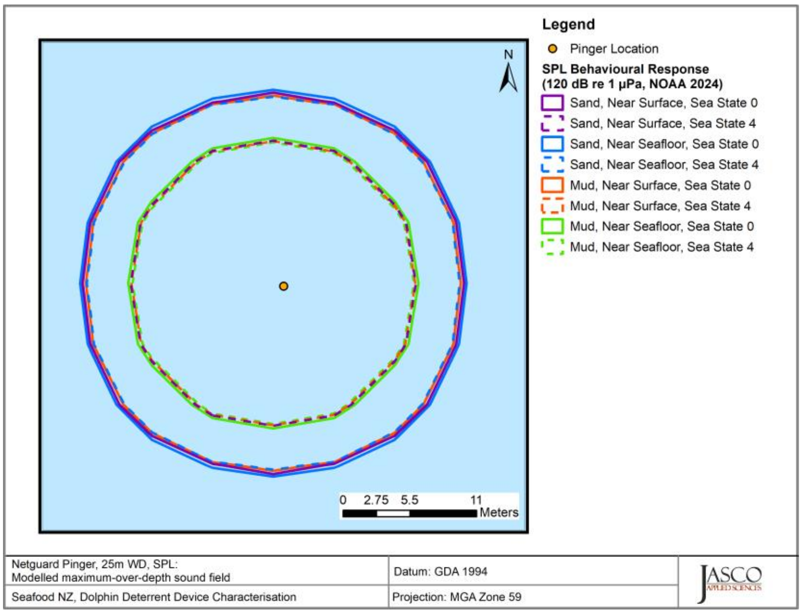


Figure 14. *Netguard Pinger in 25 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

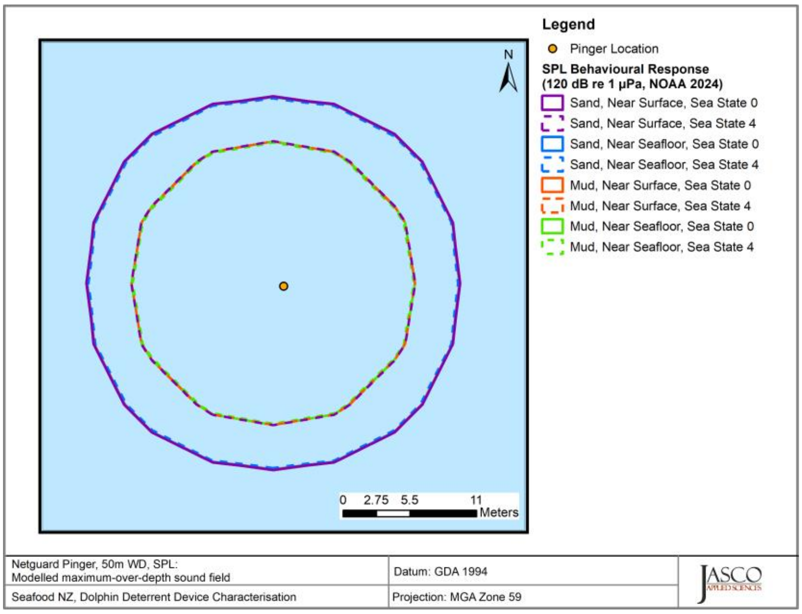


Figure 15. *Netguard Pinger in 50 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

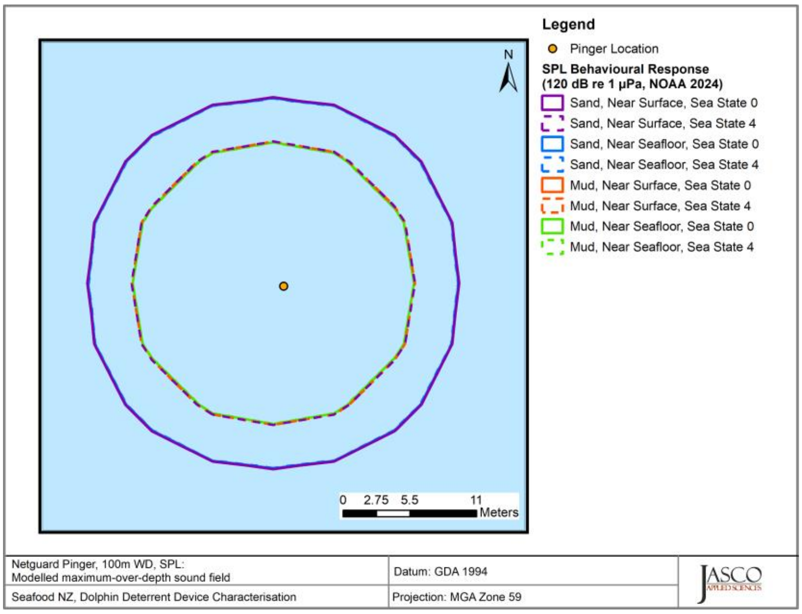


Figure 16. *Netguard Pinger in 100 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

3.2.1.3.2. STM DDD

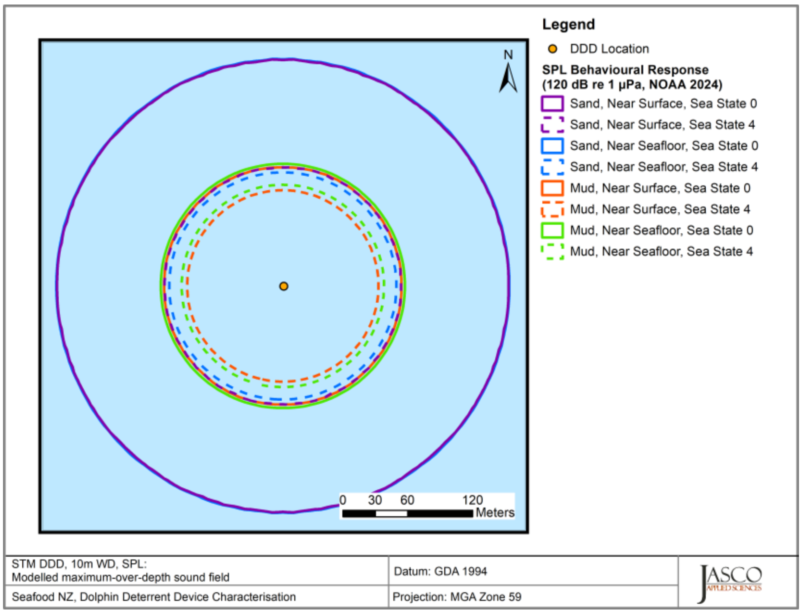


Figure 17. *STM DDD in 10 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

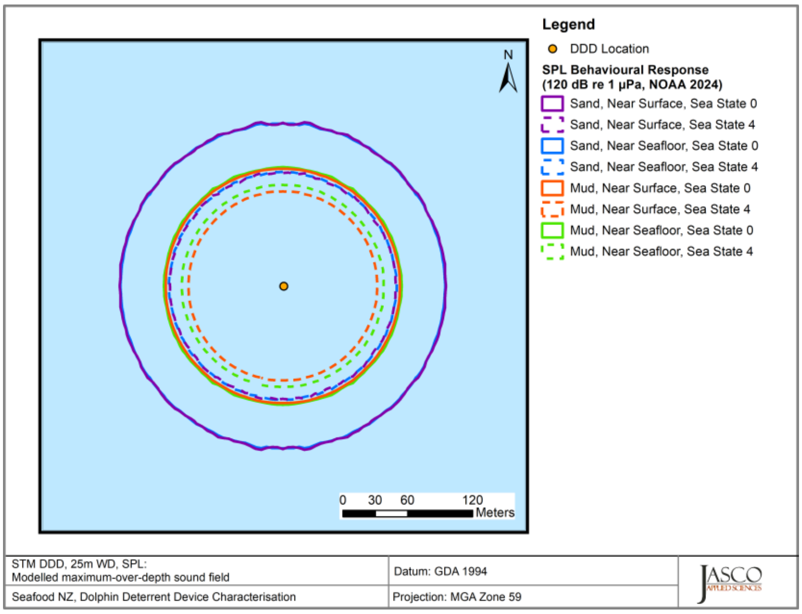


Figure 18. *STM DDD in 25 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

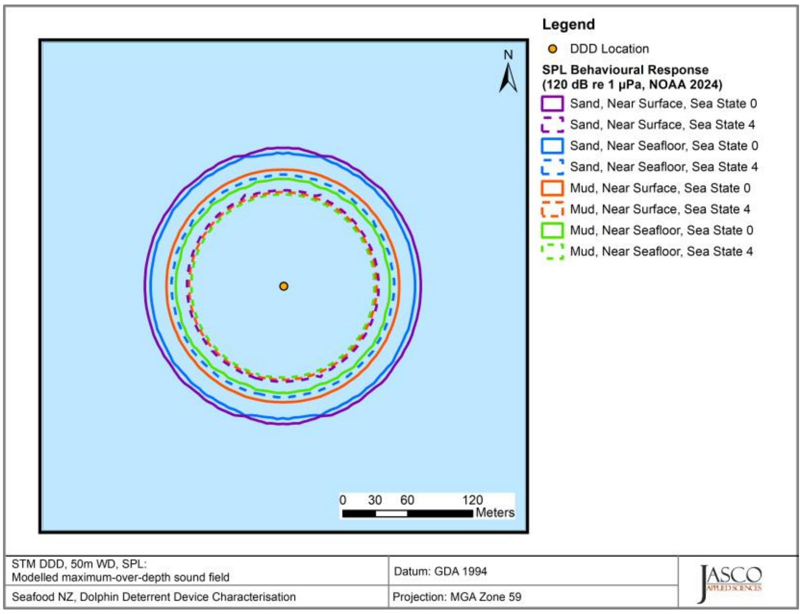


Figure 19. *STM DDD in 50 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

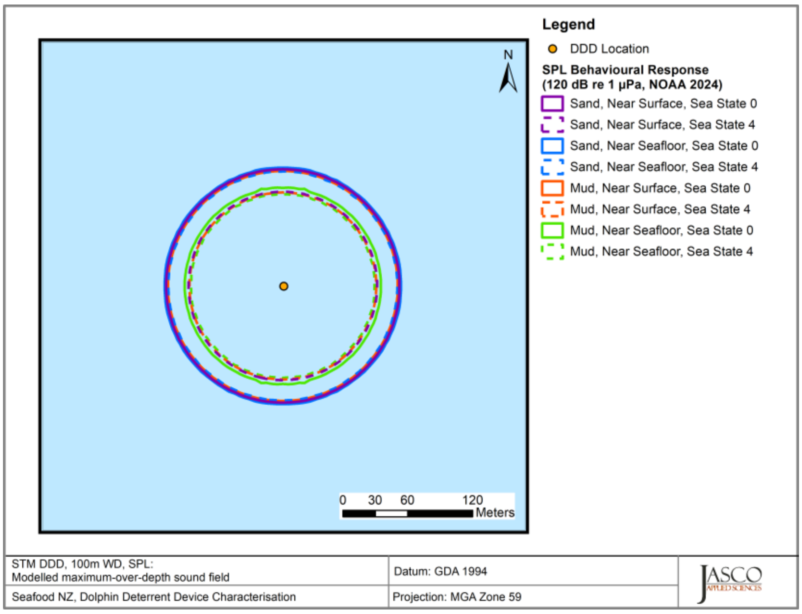


Figure 20. *STM DDD in 100 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

3.2.2. Multi-Source Modelling Results

In addition to single-source modelling, this study also considered two examples of typical multi-source deployments. Nine Netguard Pingers were modelled within one scenario, three each on three static bottom-mounted set nets. Each modelled set net was 600 m long with 200 m spacing between pingers along each net, with 2 km spacing between the set nets. The second multi-source scenario consisted of two STM DDD's mounted at each wing-end of a trawl net. The two devices were modelled 30 m apart, moving along a straight track to simulate a trawl net being pulled behind a vessel.

Both scenarios were modelled in typical environmental conditions: the modelled set net scenario was undertaken in 50 m water depth over a mud seabed; while the trawling scenario was undertaken in

25 m water depth over a sand seabed. Both scenarios considered sea states of 0 and the devices were modelled near to the sea floor.

3.2.2.1. Tabulated Results

Table 26 presents the maximum horizontal distances to specific SPL contours for the multi-source modelling scenarios of nine static Netguard Pingers on three set nets, and two STM DDDs mounted at either end of a 30 m trawl net opening. The SPL footprints represent instantaneous sound fields and do not depend on time accumulation. The marine mammal behavioural response threshold of 120 dB re 1 µPa (NOAA 2024) is marked within each table.

Table 27 presents the maximum horizontal distances to very high-frequency cetacean TTS and PTS contours (NMFS, 2024) for the multi-source modelling scenarios, over 24 hour periods. During the modelled 24 hours, the Netguard Pingers are modelled as static sources with a soak time of 18 hours, while the STM DDDs move at 2.2 knots along a straight transit path for a total of 10 hours.

Table 26. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to sound pressure level (SPL) from the modelled multi-source scenarios.

	Nine Netguard Pingers, 3 each on three set nets	Two STM DDDs, one at each wing end of a 30m trawl net
SPL (L_p; dB re 1 µPa)	R_{max} (m)	R_{max} (m)
150	–	–
140	–	29
130	–	74
120[a]	11	203
110	41	464
100	332	976

[a] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

Table 27. SEL_{24h}: Maximum (R_{max}) horizontal distances (in metres) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on NMFS (2024) from the modelled multi-source scenarios, along with ensonified area (km^2).

	Nine Netguard Pingers, 3 each on three set nets		Two STM DDDs, one at each wing end of a 30m trawl net	
Operation Time	R_{max} (m)	Area (km^2)	R_{max} (m)	Area (km^2)
PTS – 181 dB re 1 µPa²·s				
24 hr	–	–	–	–
TTS – 161 dB re 1 µPa²·s				
24 hr	7	0.0011	–	–

A dash indicates the level was not reached within the limits of the modelled resolution (5 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.00008 km^2).

3.2.2.2. Sound Field Maps

Maps of the estimated threshold contours of interest for SPL are presented for the modelled scenarios (Figures 21 and 22). Maps are also included for very high-frequency cetacean weighted SEL contours (Figures 23 and 24); NMFS (2024) criteria are highlighted where they are exceeded.

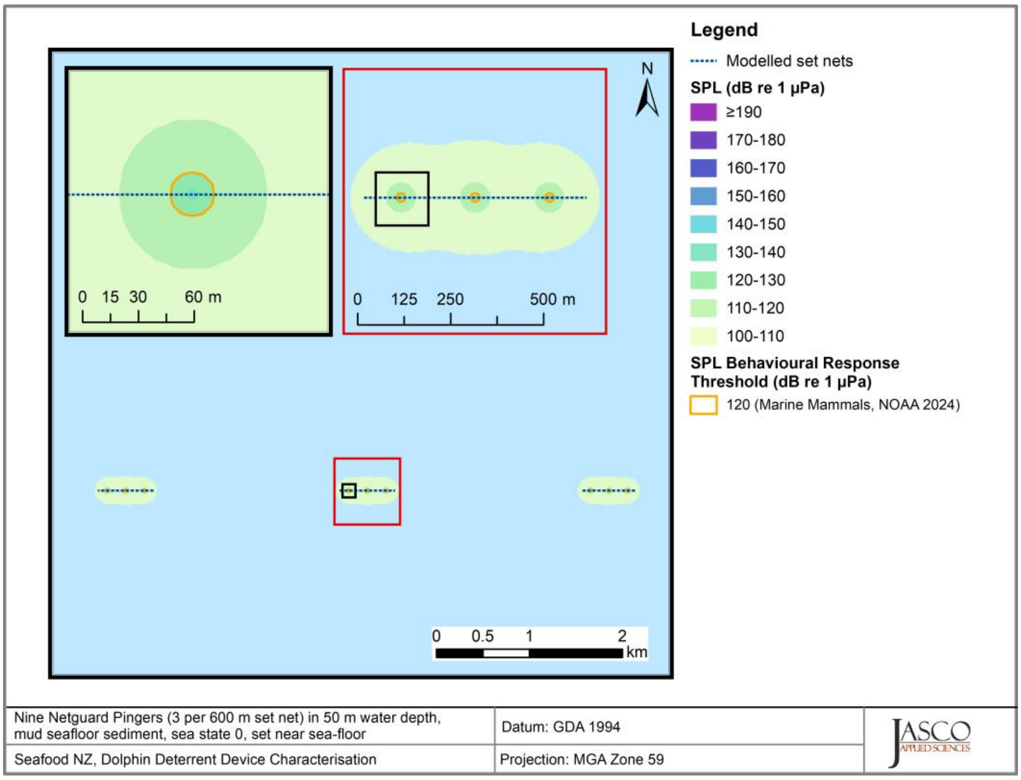


Figure 21. *Nine Netguard Pingers set across three set nets in 50 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

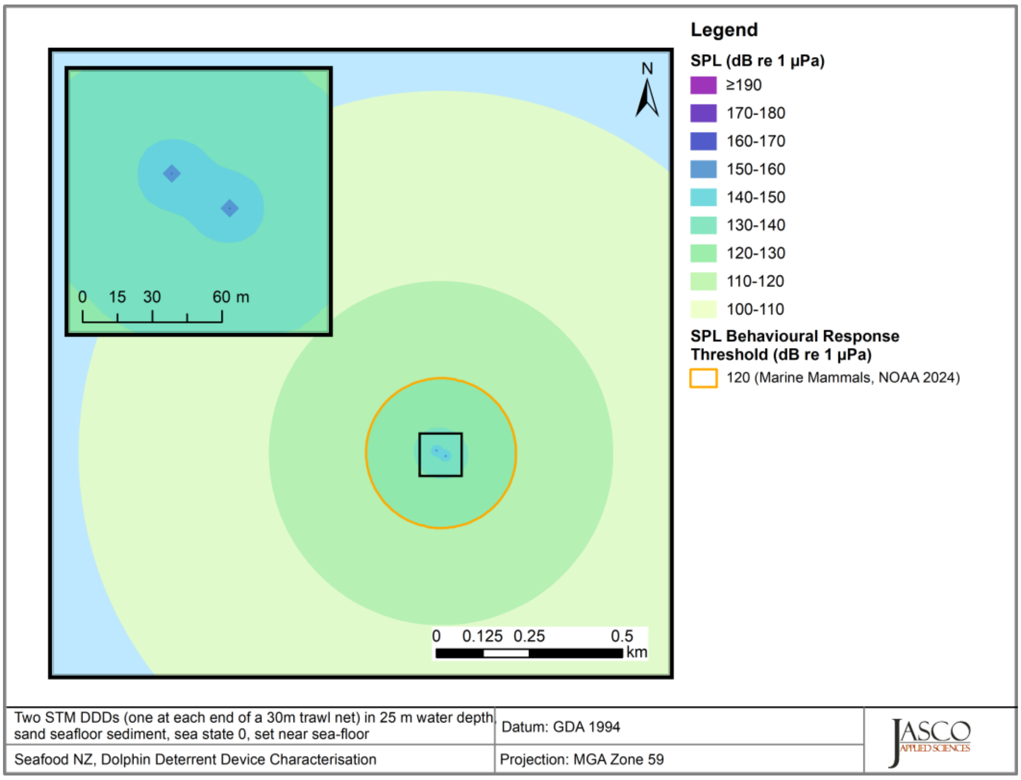


Figure 22. Two *STM DDDs, one at each wing-end of a 30 m trawl net opening, in 25 m water depth, SPL*: Sound level contour map showing the isopleths for behavioural response threshold for marine mammals.

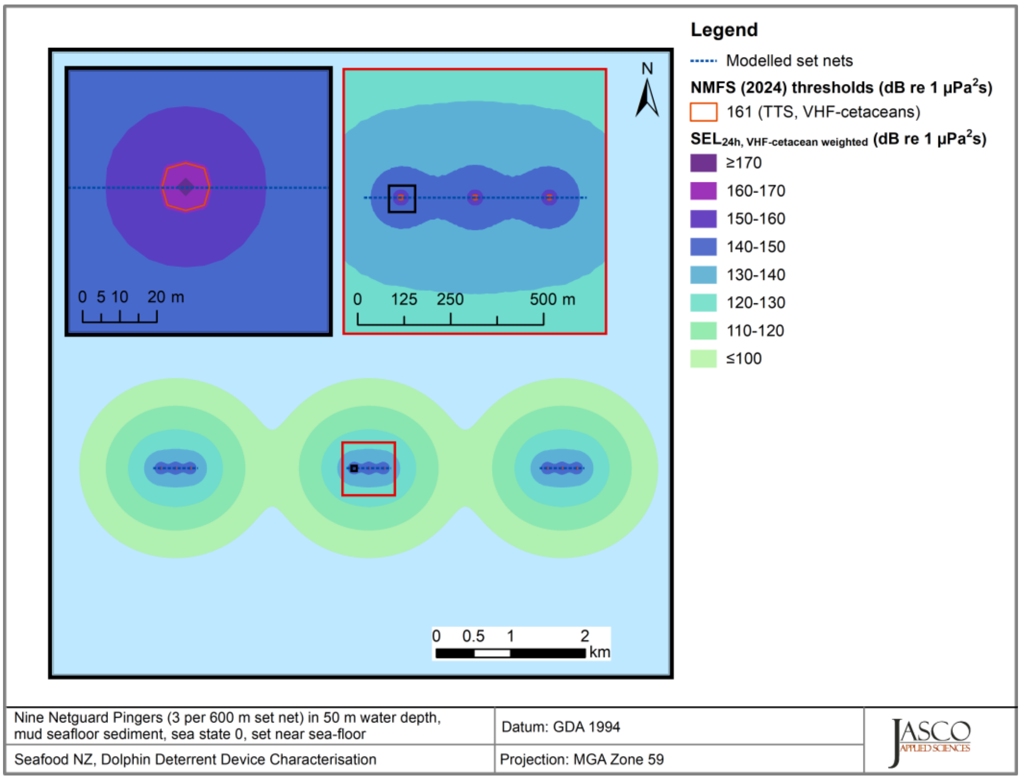


Figure 23. *Nine Netguard Pingers set across three set nets in 50 m water depth, 18 hours soak time, VHF-cetacean cSEL$_{24h}$*: Sound level contour map showing the isopleth for TTS onset in VHF-cetaceans.

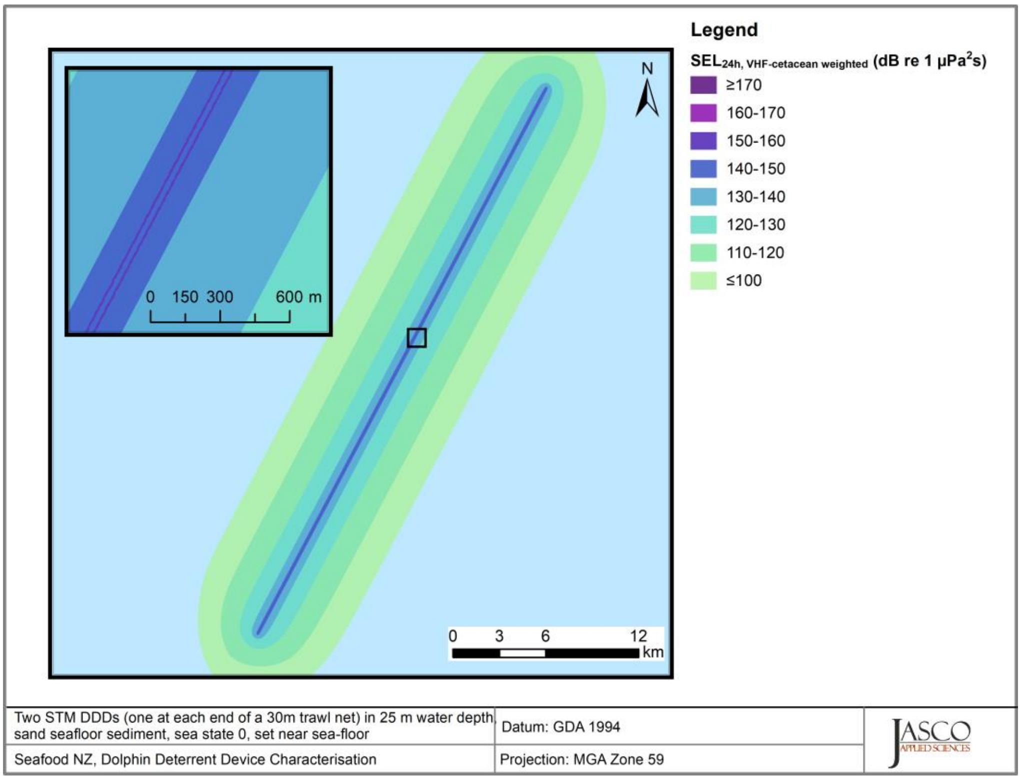


Figure 24. Two *STM DDDs, one at each wing-end of a 30 m trawl net opening, in 25 m water depth, for a total of 10 hours trawl time, VHF-cetacean weighted cSEL$_{24h}$*: Sound level contour map.

3.3. Detectability Results

For the consideration of the distances at which single devices are likely to be audible to Hector’s and Māui dolphins in a typical ambient environment, this study took into account ambient sound level in an exemplar location, the most relevant critical ratio values, and the audiogram for very high-frequency cetaceans (refer to Section 2.3 for full details). The aim of the analysis was to determine whether the maximum range of detectability of the devices is most likely to be limited by the animal’s hearing abilities or by the level of ambient noise (i.e. are the devices outside of the dolphins most sensitive hearing range, or is the ambient noise level likely to be so loud that the devices can only be heard in very close proximity).

Tables 28 and 29 present the median ambient noise levels from the Queen Charlotte Sound / Tōtaranui data in the frequency range of each device, as well as the critical ratio added to each ambient noise level (i.e. the minimum level at which signals from the device are distinguishable from background noise by the dolphins). Critical ratio values were obtained from Erbe et al. (2016). The corresponding audiogram measurement for each frequency is also presented, which corresponds to the quietest sound level a very high-frequency cetacean would be able to hear at each frequency. The median ambient noise levels and audiogram for very high-frequency cetaceans are presented in Figure 25.

Table 28. Audiogram and ambient-noise-plus-critical ratio (CR) levels used to determine detectability threshold for the Netguard Dolphin Pinger.

Decidecade Band Centre-Frequency (kHz)	Critical Ratio (from Erbe *et al.* 2016)	Median Ambient Level (dB re 1 µPa)	Detectability Threshold (Ambient + CR)	Audiogram (dB re 1 µPa)
63	34	78.8	112.8	55.8

Table 29. Audiogram and ambient-noise-plus-critical ratio (CR) levels used to determine detectability threshold for the STM DDD.

Decidecade Band Centre-Frequency (kHz)	Critical Ratio (from Erbe *et al.* 2016)	Median Ambient Level (dB re 1 µPa)	Detectability Threshold (Ambient + CR)	Audiogram (dB re 1 µPa)
25	27	76.2	103.2	57.9
50	29	78.3	107.3	56.2
126	37	78.5	115.5	55.2

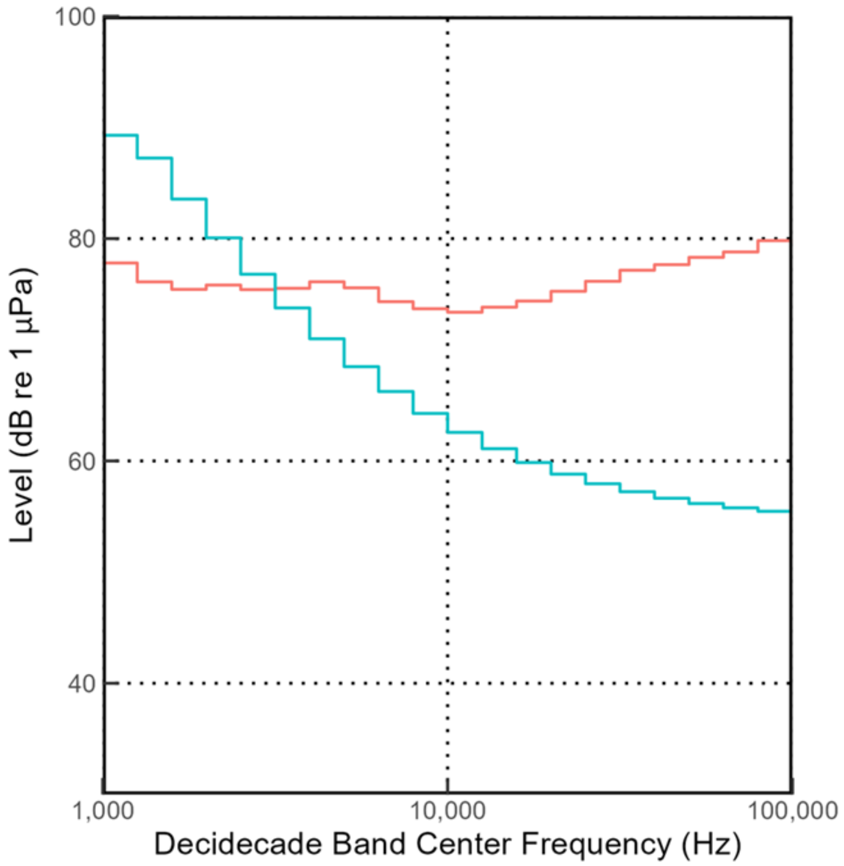


Figure 25. Median ambient noise level in Queen Charlotte Sound / Tōtaranui (red line) and the audiogram for very high-frequency cetaceans obtained from NMFS (2024) (blue line).

For both devices, over all considered frequencies, the sum of the ambient level and critical ratio exceeded the corresponding audiogram values and hence ambient sound would be the limiting factor for detectability, not the dolphins ability to hear the output of either device.

Tables 30 and 31 present the source level of each of the two devices corresponding to the considered frequencies, and the associated range to the detectability threshold for both the longest and shortest propagating scenarios from the single source modelling.

Table 30. Furthest and shortest detection ranges for the Netguard Dolphin Pinger for Hector's and Māui dolphins.

Decidecade Band Centre-Frequency (kHz)	Source Level (dB re 1 µPa)	Median Ambient Level + CR (dB re 1 µPa)	Transmission Loss	Scenario	Range (m)
63	142.1	112.8	29.3	Furthest propagating; Near seafloor, sand seafloor, water depth 10m, sea state 0	60
63	142.1	112.8	29.3	Shortest propagating; Near surface, mud seafloor, water depth 100m, sea state 4	30

Table 31. Furthest and shortest detection ranges for the STM DDD for Hector's and Māui dolphins.

Decidecade Band Centre-Frequency (kHz)	Source Level (dB re 1 µPa)	Median Ambient Level + CR (dB re 1 µPa)	Transmission Loss	Scenario	Range (m)
25	142.4	103.2	39.2	Furthest propagating; Near seafloor, sand seafloor, water depth 10m, sea state 0	375
50	148.5	107.3	41.2	Furthest propagating; Near seafloor, sand seafloor, water depth 10m, sea state 0	315
126	157.2	115.5	41.8	Furthest propagating; Near seafloor, sand seafloor, water depth 10m, sea state 0	195
25	142.4	103.2	39.2	Shortest propagating; Near surface, mud seafloor, water depth 100m, sea state 4	105
50	148.5	107.3	41.2	Shortest propagating; Near surface, mud seafloor, water depth 100m, sea state 4	110
126	157.2	115.5	41.8	Shortest propagating; Near surface, mud seafloor, water depth 100m, sea state 4	95

Detectability within the multi-source modelling scenarios was also considered. In the multi-source scenario for the Netguard Pinger, nine static pingers were considered, deployed across three set nets near the seafloor in 50 m water depth over mud sediment. Considering the typical ambient sound environment outlined above, the maximum distance for Hector's and Māui dolphin audibility of each of the nine devices was 30 m, comparable to the shortest propagating environment considered in Table 30.

For the STM DDD multi-source scenario of two DDDs, one deployed at each wing-end of a 30 m trawl net in 25 m water depth over a sand seabed, the maximum distance for Hector's and Māui dolphin audibility of the devices was 345 m (detection range for the 25 kHz centred decidecade band).

4. Discussion

This study measured underwater sound levels associated with two types of dolphin acoustic device; the Netguard Dolphin Pinger and the STM Dolphin Deterrent Device. These two marine mammal acoustic deterrent devices are regularly utilised in New Zealand waters to deter Hector's and Māui dolphins away from fishing activities. Both of these small dolphin species are threatened by fisheries interactions. The measured sound levels of the devices were used as source levels to compute maximum radii (R_{max}) within which PTS, TTS and behavioural response effects occur. In addition, the maximum ranges that Hector's and Māui dolphins would be able to hear each device in typical ambient noise conditions was also calculated. Confirming the technical specifications of the devices improves the understanding of the true extent of potential dolphin displacement around commercial fishing activities while using these devices, and helps provide recommendations for the most effective use of the devices. Acoustic modelling enabled an assessment to be undertaken in a controlled environment allowing for direct comparisons that would not have been feasible within a real-world measurement study.

4.1. Measurement

The source levels of three STM DDDs and three Netguard Dolphin Pingers were measured and analysed in this study. The median source level for the Netguard Pinger was 142.1 dB re 1 µPa and for the STM DDD was 161.1 dB re 1 µPa (10 Hz – 256 kHz). The STM DDD was louder than the Netguard Pinger, as expected from the manufacturer specifications and intended applications for the devices, and all signals from either device were near the levels specified by the manufacturers. This study confirms the acoustic metric applicable to the source level of each device (SPL, dB re 1µPa), an aspect which is not always reported by the manufacturers. Neither device displayed strong directionality, indicating acoustic emissions were broadly dispersed from each device, rather than focused along a specific output direction.

The signals emitted by the Netguard Pinger were consistent, with short tonal emissions characterized by a narrow frequency band and both uniform duration signals and inter-signal silences. Emissions were centred around the 63 kHz decidecade band, with no notable energy emitted in any other frequency band.

The signals emitted by the STM DDD were over a much wider frequency band (from 5 kHz to 256 kHz, the limit of the recordings), for random durations (ranging between approximately 5 and 20 s), and with varying inter-signal silent intervals. Manufacturer specifications state that the STM DDD produces signals up to 500 kHz. The device measurements were completed using the JASCO OSM-2 at 512 ksps, the maximum sampling limit of the device, meaning that the highest frequency that could be measured was 256 kHz. Accordingly, some minor aliasing was evident in the recordings, see Figure 10 for example, but the aliasing was mitigated by extremely effective on-device anti-aliasing filtering, reducing the effect and constraining it to above 240 kHz. A local maximum at 126 kHz is observed within the measured frequency range (Figure 5), and the broadband level across the measured range is close to that reported by the manufacturer, so we assume that the level does not exceed this maximum at higher frequencies and that most of the sound energy emitted by the device was measured. Moreover, the peak of the hearing response curve for very high-frequency cetaceans, such as Hector's and Māui dolphins, is in the 10 to 50 kHz range (Appendix A.4.1) and these species have reduced sensitivity to extremely high frequency sound (the generalised upper limit of their hearing is at 165 kHz (Table A-1)) and are therefore unlikely to be able to perceive the highest frequencies emitted by the STM DDD.

The emissions made by the Netguard Pinger and the STM DDD fall within the key hearing sensitivity range of very high-frequency cetaceans, such as Hector's and Māui dolphins, and will be detectable.

4.2. Acoustic Modelling

This study modelled the sound fields produced by single static devices within an array of environmental conditions, as well as two example scenarios illustrating the sound fields associated with typical deployment arrangements for the two device types.

The Netguard Pinger, a lower-level acoustic device, is commonly deployed on bottom-mounted set nets to warn marine mammals of the presence of the net that may otherwise be unnoticed, potentially leading to bycatch scenarios. In this study, nine Netguard Pingers were modelled across three 600 m-long set nets with 200 m spacing and 18 hours soak time. The STM DDD is a louder device, often deployed with the intention of encouraging marine mammals away from an area of potential danger (e.g. a moving trawl net). Here, two STM DDDs (one on either wing-end of a 30 m trawl net opening) were modelled transiting along a trawling track at 2.2 knots for a total period of 10 hours (a combination of two 5-hour trawls).

In the single source scenarios, the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) was exceeded by a single STM DDD to a maximum range of 210 m, whilst the maximum range to the same criterion for a single Netguard Pinger was 18 m. In the modelling environment that resulted in the longest propagation distances, the accumulated SEL_{24h} criteria for TTS for very high-frequency cetaceans occurred within 191 m of a single static STM DDD and within 10 m of a single static Netguard Pinger. In this modelling environment, the accumulated SEL_{24h} criteria for PTS for very high-frequency cetaceans was exceeded within 11 m of the STM DDD. The PTS threshold was not exceeded for the Netguard Pinger.

In the multi-source scenarios (which were conducted with respect to typical use environments rather than maximum or minimum propagation distances), the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) was exceeded up to a maximum range of 203 m by the two STM DDDs, and up to 11 m by each of the nine Netguard Pingers. Only the Netguard Pinger multi-source scenario exceeded any of the NMFS (2024) criteria, with TTS occurring within 7 m of each of the nine Netguard Pingers if a very high-frequency cetacean such as a Hector's or Māui dolphin stays within this radius for a full 24 hour period.

As the multi-source Netguard Pinger modelling comprised static moored devices, the results from this scenario are similar to the equivalent results from the single device modelling scenarios. The main configuration difference is that the soak time of the set nets considered in the multiple source scenario was 18 hours, as opposed to the full 24 hours modelled in the single source scenarios.

Conversely, the single and multi-source scenarios modelled for the STM DDD provide relatively contrasting results because the single source modelling considered devices that were static for 24 hours while the multi-source modelling considered devices that were constantly moving for 10 hours. Accordingly, the accumulated sound footprint of the moving DDDs is spread along the modelled tracklines and is not concentrated into a specific location; this explains the lack of PTS or TTS exceedance zones within the multi-source scenario. Moreover, the multi-source scenario considers 14 hours of silence within the 24-hour modelled period when the trawl is not active, whereas the single source modelling considered the devices to be active (with a duty cycle of 23.4%) across the full 24-hour period. The NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) illustrates the impact of mounting two DDDs on the trawl net as opposed to one (as per the single source modelling); in the multi-source modelling this criterion is exceeded in a radius up to 203 m (measured from the mid-point between the two devices, Table 26), whereas a single STM DDD in the equivalent environment exceeded this criterion up to 151 m (Table 19).

Synthetic, perfectly flat bathymetry was used for the acoustic modelling, with a separate bathymetry for each water depth. Sound travelling in shallower water can often propagate further than sound in deeper water for short and intermediate ranges as the sound energy is better guided by the seafloor and sea surface, hence leading to cylindrical spreading and longer ranges to thresholds. However, increased interactions with the sea surface and seafloor results in higher losses for long ranges. In deeper water, spherical spreading will be dominant, and while a similar volume of water will be exposed above threshold, ranges to thresholds will be shorter as the sound energy is able to spread vertically as well as horizontally.

The modelling was conducted for both sand and mud seabed sediments to allow for comparison. A sand seafloor is more reflective than a mud seafloor, and hence more of the sound energy stays within the water column and ranges to thresholds were further. Similarly, a flat sea surface (corresponding to sea state 0) is more reflective than a rough sea surface (corresponding to sea state 4), and hence ranges to thresholds were further for sea state 0.

The sound speed profile used in the modelling (Appendix B.1.2) was based on conditions off the coast of Timaru, New Zealand and was derived from data from the U.S. Naval Oceanographic Office's Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009). The month of July was chosen based on an analysis of the temperature, salinity and sound speed profiles extracted from this database, which suggested that July would result in the most conservative ranges to the considered thresholds. Accordingly, had an SSP from a different month been applied within the modelling, the resulting ranges to considered criteria would likely have been shorter.

In addition to the use of a conservative SSP, the modelled results are based on other inherent assumptions. For example, the flat bathymetry, basic seabed sediments (sand or mud) and constant propagation environments provide simplifications of real-world complexity. Furthermore, within the detectability assessment, the ambient noise spectrum is assumed to be typical of other environments inhabited by Hector's and Māui dolphins, and the hearing threshold and critical ratio are based on another species within the same hearing group (Harbour porpoises, *Phocoena phocoena*) due to a lack of more specific information. The overall aim of the modelling was to provide an unbiased assessment that is largely representative of environments inhabited by Hector's and Māui dolphins. Specific other environments could be modelled to ensure certainty.

SEL_{10min}, SEL_{1h}, and SEL_{24h} are cumulative metrics that reflect the dosimetric impact of noise levels within 10 min, 1 hour, and 24 hours respectively, based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The corresponding radii represent a worst–case scenario, decreasing in likelihood with increased integration time. More realistically, marine mammals would not stay in the same location (or at a similar range to the source) for 10 min/1 hour/24 hours. Therefore, a reported radii for SEL_{10min}, SEL_{1h}, and SEL_{24h} metrics do not mean that marine fauna travelling within this radius of the source will be injured, but rather than an animal could be exposed to the sound level associated with impairment if it remained in that location for the given time period. SEL_{10min} and SEL_{1hr} are likely to be more relevant metrics for marine mammals moving around an active fishery activity than SEL_{24hr}.

During the characterisation measurements, the Netguard Pinger was recorded to emit signals approximately 7.71% of the time, as compared to the STM DDD that emitted signals 23.4% of the time. Within a given time period, the STM DDD emits a greater amount of sound energy compared to the Netguard Pinger, further increasing the ranges to accumulated sound exposure thresholds beyond the fact that the STM DDD features a higher source level.

With regard to the highest frequencies emitted by the STM DDD that were not able to be measured or modelled in this assessment, it should be noted that sound tends to experience greater loss due to absorption at very high frequencies resulting in poorer propagation, and sound at frequencies higher than 256 kHz would contribute little to either the ranges to SPL behavioural threshold or cumulative SEL injurious thresholds as it exceeds the frequencies that Hector's and Māui dolphins are most sensitive to (Appendix A.4).

4.3. Recommendations

Detectability of both the Netguard Pinger and the STM DDD are limited by ambient noise, not the hearing abilities of Hector's and Māui dolphins, as shown in Tables 28 and 29. The Netguard Pinger was modelled as being detectable between 30 m and 60 m from the source (corresponding to shortest and furthest propagating environmental scenarios), and the STM DDD as being detectable between 95 m (shortest propagating scenario, hardest frequency to detect) and 375 m (further propagating scenario, easiest frequency to detect). Generally, for higher frequency sounds, detectability is reduced due to both elevated ambient noise level, increased critical ratio, and high frequencies being attenuated more due to absorption while propagating.

Marine mammal pingers and acoustic deterrent devices are commonly deployed during fishing activities in New Zealand to alert marine mammals to the presence of fishing gear, and/or to deter them from areas of risk or depredation opportunities. The measured and modelled devices allow an examination of the most appropriate deployment spacing for the considered devices. Deployment on static linear set nets is relatively straightforward to estimate, and thus has been considered here for recommendations on device placement. The trawl fishery scenario is more complex, and will require considerations of specific vessels and device placement location within the water column, thus specific spacing recommendations are not presented.

For bottom-mounted set nets, it is pertinent to understand how best to space the devices to maximise acoustic coverage, without introducing unnecessary sound emitters into the marine environment. Here we consider recommendations for spacing the devices along a horizontal stretch of net to ensure that a dolphin approaching the net from a perpendicular angle is exposed to at least one sound emission to make it aware of the potential danger posed by the net. The detectability of the devices is based on the results provided in Section 3.3, which considers detectability within a typical ambient noise environment from the Queen Charlotte Sound / Tōtaranui.

Using the approach detailed in Erbe et al. (2011), and Erbe and McPherson (2012), assuming that a dolphin swims directly towards a set net from a perpendicular direction, the maximum device spacing must be set such that once a dolphin is within detectability range of the device, at least one signal must occur before the dolphin reaches the net. This maximum device spacing, *d* in metres, is given by

$$d = 2\sqrt{r^2 - v^2T^2} \tag{4-1}$$

where *r* is the range to detectability threshold, *v* is the speed of the dolphin, and *T* is the inter-signal silent duration (reported in Section 3.1). The swimming speeds of Hector's and Māui dolphins have not been reported, however captive Commerson's dolphins (*Cephalorhynchus commersonii*) and wild Heaviside's dolphins (*Cephalorhynchus heavisidii*) (species within the *Cephalorhynchus* genus along with Hector's and Māui dolphins) have been studied revealing average swim speeds up to 1.3 ms^{-1} (Elwen et al. 2006, Shpak et al. 2009). Hence, for the Netguard Pinger, with a dolphin swim speed of 1.3 ms^{-1}, a minimum range to detectability threshold of 30 m (Table 30) and inter-signal duration of 3.75 s (Table 9), maximum pinger separation is recommended as 60 m (rounded from 59.2 m). For the STM DDD, a minimum range to detectability threshold of 95 m (Table 31) and inter-signal duration of 40 s (Table 9) gives a maximum recommended device separation of 160 m, if these devices were to be deployed on a set net. Environmental conditions that correspond to longer sound propagation, and hence longer ranges to detectability thresholds, would correspond to longer maximum recommended device separation, as would dolphins swimming slower or the devices emitting sound more frequently.

Within the multi-source modelling for the Netguard Pinger, devices were modelled at 200 m spacing along each of the three set nets which was considered representative of a typical real-world deployment. The results of the modelling suggested that within this scenario the maximum detectable distance was 30 m from each pinger. As the modelled spacing of devices was 200 m, this implies that some areas of each net would not be ensonified. We understand that 200 m spacing is recommended by the manufacturer of the pingers; the results presented here are based on the measured source level of the tested pingers which was lower than that stated by the manufacturer (assuming the same metric is appropriate) and results in the assessment that 200 m spacing is too generous in a typical ambient environment.

With regard to deploying and spacing the Netguard Pinger and STM DDD in real-world applications, it is important to consider the motive and intended consequences of the devices. The purpose of the Netguard Pinger is not acoustic injury, nor strong behavioural responses. The purpose of deploying pingers is to indicate to a marine mammal that an area contains a potentially risky component, for example a static set net, that might otherwise be undetected. The sound level produced by a pinger does not need to be particularly loud as the marine mammals do not need to be scared away from the area, merely warned to pay more attention. Accordingly, there is no need to use a louder sound source for this purpose, which would have the potential to cause excess noise and unnecessary habitat displacement or exclusion.

The STM DDD on the other hand, is intended to be a louder device that is used to encourage marine mammals to move away from dynamic, high-risk activities in order to avoid potential danger. Nonetheless, excess noise should still be avoided. This study shows that the maximum horizontal distance to the marine mammal behavioural response threshold for a single DDD is 151 m, and for two DDDs mounted 30 m apart in an equivalent environment the maximum horizontal distance to the same criterion is 203 m; therefore, for most purposes, a single DDD is likely to be sufficient.

In order for acoustic devices to be effective, they should be deployed in an unimpeded manner (i.e. tied tightly to the fishing equipment at equal interval spacing). Pingers and other acoustic devices should not be shrouded or insulated by other materials as this could impede their effectiveness. Similarly, batteries within the devices should be consistently maintained in order to ensure the device is working at its optimum; depleted batteries may lead to differences in sound emissions.

4.4. Conclusion

JASCO Applied Sciences (JASCO) performed a measurement and modelling study of underwater sound levels associated with two devices that are regularly utilised in New Zealand waters: the Netguard Dolphin Pinger (60 – 120 kHz model); and the STM Dolphin Deterrent Device (DDD) (DDD03H model). Confirming the technical specifications also improves the understanding of the true extent of potential dolphin displacement around commercial fishing activities while using these devices, and aids in recommendations for how to deploy the devices most effectively.

The results of this measurement study provide decidecade-band source level measurements across three of each type of device allowing for a statistical distribution of source levels. The median was 142.1 dB re 1 µPa for the Netguard Pinger and 161.1 dB re 1 µPa for the STM DDD (10 Hz – 256 kHz). Although similar to, they are not directly comparable to the manufacturer-reported source levels, as the latter are presented without specifying the frequency domain, statistical measures used, or whether the reported levels reflect a design target or the actual performance of manufactured units.

Modelling the devices enables a robust comparison to be completed as all conditions can be controlled. The maximum distance to the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) was 210 m, which was associated with a single static STM DDD modelled over a sand seabed, with the device near the seafloor, sea state 0 (Table 32). The maximum range to the same criterion for a single static Netguard Pinger was 18 m (sand seabed, device near the seafloor, sea state 0) (Table 32). The maximum distance for accumulated SEL_{24h} scenarios for TTS for very high-frequency cetaceans was 191 m for a single static STM DDD and 10 m for a single static Netguard Pinger (sand seabed, device near the seafloor, sea state 0). The maximum distance for accumulated SEL_{24h} criteria for PTS for very high-frequency cetaceans was 11 m for the STM DDD (sand seabed, device near the seafloor, sea state 0). The PTS threshold was not exceeded for the Netguard Pinger.

Table 32. Summary of modelling results: Summary of maximum (R_{max}) horizontal distances (in metres), from modelled scenarios, to the marine mammal behavioural response criterion of 120 dB re 1 μPa (SPL) and frequency-weighted VHF-cetacean SEL_{24h} TTS and PTS thresholds (161 and 181 dB re 1 μPa²·s, respectively). Ensonified areas are also provided for TTS and PTS thresholds.

Device	Description	Marine Mammal Behavioural Response - SPL [a]	VHF-cetacean TTS - SEL_{24h} [b]		VHF-cetacean PTS - SEL_{24h} [b]	
		R_{max} (m)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
Netguard Pinger	Sand seabed, device near seafloor, sea state 0	18	10	/	–	–
STM DDD	Sand seabed, device near seafloor, sea state 0	210	191	0.115	11	0.001

Noise exposure criteria: [a] NOAA (2024) and [b] NMFS (2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

In addition to single-source modelling, this study also considered two examples of typical multi-source deployments. Nine Netguard Pingers were modelled within one scenario, three each on three static 600-m long bottom-mounted set nets. An 18-hour soak time was considered. The second multi-source scenario consisted of two STM DDD's mounted at each wing-end of a trawl net. The two devices were modelled 30 m apart, moving along a straight track at 2.2 knots for 10 hours, to simulate a trawl net being pulled behind a vessel for two five-hour trawls. Distances to the marine mammal behavioural response, TTS and PTS criteria are summarised in Table 33.

Table 33. Summary of multi-source modelling results: Summary of maximum (R_{max}) horizontal distances (in metres), from modelled devices to the marine mammal behavioural response criterion of 120 dB re 1 μPa (SPL) and frequency-weighted VHF-cetacean SEL_{24h} TTS and PTS thresholds (161 and 181 dB re 1 μPa²·s, respectively). Ensonified areas (in km²) are also provided for TTS and PTS thresholds.

Scenario Description	Environment	Marine Mammal Behavioural Response - SPL [a]	VHF-cetacean TTS - SEL_{24h} [b]		VHF-cetacean PTS - SEL_{24h} [b]	
		R_{max} (m)	R_{max} (m)	Area (km²)	R_{max} (m)	Area (km²)
Nine Netguard Pingers, 3 each on 3 static set nets	50 m water depth, mud seabed, device near seafloor, sea state 0	11	7	0.0011	–	/
Two STM DDDs, one at each end of a 30 m trawl net, trawling for 10 hours at 2.2 knots	25 m water depth, sand seabed, device near seafloor, sea state 0	203	–	/	–	/

Noise exposure criteria: [a] NOAA (2024) and [b] NMFS (2024).
A dash indicates the level was not reached within the limits of the modelled resolution (5 m).

With regard to trawl fishery activities, this study showed that the maximum horizontal distance to the marine mammal behavioural response zone for a single DDD is 151 m, and for two DDDs mounted 30 m apart in an equivalent environment the maximum horizontal distance to the same criterion is 203 m; therefore, for most purposes, a single DDD is likely to be sufficient.

Furthermore, the maximum distance at which an animal is able to hear and distinguish the sound of a device within a typical underwater noise environment was also considered. The Netguard Pinger was modelled as being detectable between 30 m and 60 m from the source (corresponding to shortest and furthest propagating environmental scenarios), and the STM DDD as being detectable between 95 m (shortest propagating scenario, hardest frequency to detect) and 375 m (further propagating scenario, easiest frequency to detect). Within the multi-source modelling, which was conducted for typical deployment conditions rather than maximum propagation conditions, the maximum audibility distance for Hector's and Māui dolphins was 30 m from each of the Netguard Pingers and up to 345 m for the two STM DDDs mounted 30 m apart on a trawl net.

Based on the detectability of the devices and other factors, such as the average swim speed of the dolphins, maximum separation spacing for the Netguard Pinger on static set nets is recommended as 60 m in a typical ambient environment. If the STM DDD is deployed for this purpose, the maximum separation spacing is recommended as 160 m. These spacings are pertinent to conservative modelling scenario results (i.e. not the modelling scenarios that resulted in the longest propagation ranges), but it should be noted that in reality the shortest detection ranges could be influenced by external variables, such as anthropogenic noise masking the sound of the device, which would result in a need to space the devices more closely together.

Glossary

Unless otherwise stated in an entry, these definitions are consistent with ISO 18405 (2017).

Light blue text indicates related terms that might be in this glossary. Dark blue text indicates clickable links to related terms in this glossary

1/3-octave

One third of an octave. A 1/3-octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec).

1/3-octave-band

Frequency band whose bandwidth is one 1/3 octave. The bandwidth of a 1/3-octave-band increases with increasing centre frequency.

absorption

The conversion of sound energy to heat energy. Specifically, the reduction of sound pressure amplitude due to particle motion energy converting to heat in the propagation medium.

acoustic impedance

The ratio of the sound pressure in a medium to the volume flow rate of the medium through a specified surface due to the sound wave. It is a measure of how well sound propagates through a particular medium.

acoustic noise

Sound that interferes with an acoustic process.

ambient sound

Sound that would be present in the absence of a specified activity (ISO 18405:2017). It is usually a composite of sound from many sources near and far, e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation

The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium. Attenuation depends on frequency—higher frequency sounds are attenuated faster than lower frequency sounds.

audiogram

A graph or table of hearing threshold as a function of frequency that describes the hearing sensitivity of an animal over its hearing range.

auditory frequency weighting

The process of applying an auditory frequency-weighting function. An example for marine mammals are the auditory frequency-weighting functions published by Southall et al. (2007).

auditory frequency-weighting function

Frequency-weighting function describing a compensatory approach accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.

azimuth

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also known as bearing.

background noise

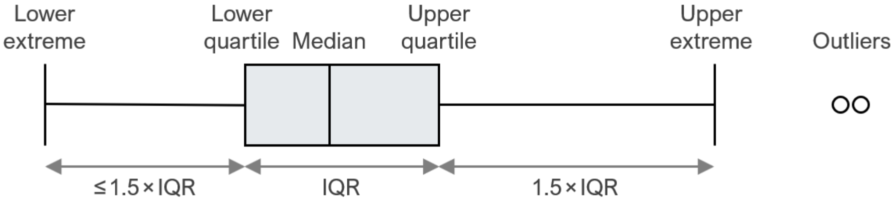
Combination of ambient sound, acoustic self-noise, and, where applicable, sonar reverberation (ISO 18405:2017) that is detected, measured, or recorded with a signal.

bandwidth

A range within a continuous band of frequencies. Unit: hertz (Hz).

box-and-whisker plot

A statistical data plot that illustrates the centre, spread, and overall range of data as a visual 5-number summary. The box is the interquartile range (IQR), which shows the middle 50 % of the data—from the lower quartile (25th percentile) to the upper quartile (75th percentiles). The line inside the box is the median (50th percentile). The whiskers show the lower and upper extremes excluding outliers, which are data points that fall more than 1.5 × IQR beyond the upper or lower quartiles.



boxcar averaging

A signal smoothing technique that returns the averages of consecutive segments of a specified width.

broadband level

The total level measured over a specified frequency range. If the frequency range is unspecified, the term refers to the entire measured frequency range.

broadside direction

Perpendicular to the travel direction of a source. Compare with endfire direction.

cetacean

Member of the order Cetacea. Cetaceans are aquatic mammals and include whales, dolphins, and porpoises.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called a longitudinal wave. In seismology/geophysics, it's called a primary wave or P-wave. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

conductivity-temperature-depth (CTD)

Measurement data of the ocean's conductivity, temperature, and depth; used to compute sound speed profiles and salinity.

confined explosives

Explosives detonated within a substrate, including ice, as opposed to unconfined explosives that are detonated in open water, or not within a substrate.

continuous sound

A sound whose sound pressure level remains above the background noise during the observation period and may gradually vary in intensity with time, e.g., sound from a marine vessel.

critical band

The auditory bandwidth within which background noise strongly contributes to masking of a single tone. Unit: hertz (Hz).

critical ratio level

The difference between the sound pressure level of a masked tone, which is barely audible, and the spectral density level of the background noise at similar frequencies, referenced to 1 Hz. Unit: decibel (dB).

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006). For example, one decade up from 1000 Hz is 10,000 Hz, and one decade down is 100 Hz.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Especially suited to quantify variables with a large dynamic range.

decidecade

One tenth of a decade. Approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct), and for this reason sometimes referred to as a 1/3 octave.

decidecade band

Frequency band whose bandwidth is one decidecade. The bandwidth of a decidecade band increases with increasing centre frequency.

delphinid

Member of the family of oceanic dolphins (Delphinidae), composed of approximately 35 extant species, including dolphins, porpoises, and killer whales.

duty cycle

The percentage of time during which an intermittently activated acoustic monitoring system is recording sound. For example, recording 30 min of every hour is a 50 % duty cycle.

endfire direction

Aligned with the travel direction of a source. Compare with broadside direction.

energy source level

A property of a sound source equal to the sound exposure level measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^2 m^2 s.

energy spectral density

Ratio of energy (time-integrated square of a specified field variable) to bandwidth in a specified frequency band from f_1 to f_2. In equation form, the energy spectral density E_f is given by:

$E_f = 2\int_{f_1}^{f_2} |X(f)|^2 \, \mathrm{d}f / (f_2 - f_1)$ where $X(f)$ is the Fourier transform of the field variable $x(t)$:
$X(f) = \int_{-\infty}^{+\infty} x(t) \exp(-2\pi i f t) \, \mathrm{d}t$.

The field variable $x(t)$ is a scalar quantity, such as sound pressure. It can also be the magnitude or a specified component of a vector quantity such as sound particle displacement, velocity, or acceleration. The unit of energy spectral density depends on the nature of x, as follows:

- If x = sound pressure: Pa^2 s/Hz
- If x = sound particle displacement: m^2 s/Hz
- If x = sound particle velocity: $(\mathrm{m/s})^2$ s/Hz
- If x = sound particle acceleration: $(\mathrm{m/s}^2)^2$ s/Hz

The factor of two on the right side of the equation for E_f is needed to express a spectrum that is symmetric about f = 0, in terms of positive frequencies only. See entry 3.1.3.9 of ISO 18405 (2017).

energy spectral density level

The level ($L_{E,f}$) of the energy spectral density (E_f) in a stated frequency band and time window. Defined as: $L_{E,f} = 10\log_{10}(E_f/E_{f,0})$. Unit: decibel (dB). As with energy spectral density, energy spectral density level can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement). The reference value ($E_{f,0}$) for energy spectral density level depends on the nature of the field variable.

energy spectral density source level

A property of a sound source equal to the energy spectral density level of the sound pressure measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 $\mu\mathrm{Pa}^2\,\mathrm{m}^2$ s/Hz.

ensonified

Exposed to sound.

equal-loudness-level contour

Curve that shows, as a function of frequency, the sound pressure level required to produce a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI S1.1-2013).

far field

The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears to radiate from a single point.

Fourier transform, Fourier synthesis

A mathematical technique which, although it has varied applications, is referenced in a physical data acquisition context as a method used in the process of deriving a spectrum estimate from time-series data (or the reverse process, termed the inverse Fourier transform). A computationally efficient numerical algorithm for computing the Fourier transform is known as the fast Fourier transform (FFT).

frequency

The rate of oscillation of a periodic function measured in cycles per unit time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

frequency weighting

The process of applying a frequency-weighting function.

frequency-weighting function

The squared magnitude of the sound pressure transfer function (ISO 18405:2017). For sound of a given frequency, the frequency-weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

- *Auditory frequency-weighting function*: compensatory frequency-weighting function accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.
- *System frequency-weighting function*: frequency-weighting function describing the sensitivity of an acoustic recording system, which typically consists of a hydrophone, one or more amplifiers, and an analog-to-digital converter.

functional hearing group

Category of animal species when classified according to their hearing sensitivity, hearing anatomy, and susceptibility to sound. For marine mammals, initial groupings were proposed by Southall et al. (2007), and revised groupings are developed as new research/data becomes available. Revised groupings proposed by Southall et al. (2019) include low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, phocid carnivores in water, other carnivores in water, and sirenians. Example hearing groups for fish include species for which the swim bladder is involved in hearing, species for which the swim bladder is not involved in hearing, and species without a swim bladder (Popper et al. 2014). See also auditory frequency-weighting functions, which are often applied to these groups.

geoacoustic

Relating to the acoustic properties of the seabed.

harmonic

A sinusoidal sound component that has a frequency that is an integer multiple of the frequency of a sound to which it is related. For a sound with a fundamental frequency of f, the harmonics have frequencies of $2f$, $3f$, $4f$, etc.

hearing threshold

For a given species or functional hearing group, the sound level for a given signal that is barely audible (i.e., that would be barely audible for a given individual in the presence of specified background noise during a specific percentage of experimental trials).

hertz (Hz)

Unit of frequency defined as one cycle per second. Often expressed in multiples such as kilohertz (1 kHz = 1000 Hz).

high-frequency (HF) cetaceans

See functional hearing group. The mid- and high-frequency cetaceans groups proposed by Southall et al. (2007) were renamed high- and very-high-frequency cetaceans, respectively, by Southall et al. (2019).

hydrophone

An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

hydrostatic pressure

The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

intermittent sound

A sound whose level abruptly drops below the background noise level multiple times during an observation period.

impulsive sound

Qualitative term meaning sounds that are typically transient, brief (less than 1 s), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Sources of impulsive sound include, among others, explosives, seismic airguns, and impact pile drivers.

isopleth

A line drawn on a map through all points having the same value of some specified quantity (e.g., sound pressure level isopleth).

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. For example, a value of sound pressure level with reference to 1 µPa^2 can be written in the form *x* dB re 1 µPa^2.

manual analysis

Human examination of acoustic data via visual review of spectrograms and/or aural inspection of data.

manual detection

The output of manual analysis as recorded in an annotation.

masking

Obscuring of sounds of interest by other sounds at similar frequencies.

median

The 50th percentile of a statistical distribution.

monopole source level (MSL)

A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point source (monopole). Often used to quantify source levels of vessels or industrial operations from measurements. See also radiated noise level.

M-weighting

A set of auditory frequency-weighting functions proposed by Southall et al. (2007).

***N* percent exceedance level**

The sound level exceeded *N* % of the time during a specified time interval. See also percentile level.

non-impulsive sound

Sound that is not an impulsive sound. Not necessarily a continuous sound.

octave

The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete

Member of Odontoceti, a suborder of cetaceans. These whales, dolphins, and porpoises have teeth (rather than baleen plates). Their skulls are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

parabolic equation method

A computationally efficient solution to the acoustic wave equation that is used to model propagation loss. The parabolic equation approximation omits effects of backscattered sound (which are negligible for most ocean-acoustic propagation problems), simplifying the computation of propagation loss.

peak sound pressure level (PK), zero-to-peak sound pressure level

The level (L_{pk}) of the squared maximum magnitude of the sound pressure (p_{pk}^2) in a stated frequency band and time window. Defined as $L_{pk} = 10\log_{10}(p_{\mathrm{pk}}^2/p_0^2) = 20\log_{10}(p_{\mathrm{pk}}/p_0)$. Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa^2.

peak-to-peak sound pressure

The difference between the maximum and minimum sound pressure over a specified frequency band and time window. Unit: pascal (Pa).

percentile level

The sound level not exceeded *N* % of the time during a specified time interval. The *N*th percentile level is equal to the (100−*N*) % exceedance level. See also N percent exceedance level.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. Considered auditory injury. Compare with temporary threshold shift.

point source

A source that radiates sound as if from a single point.

power spectral density

Generic term, formally defined as power in a unit frequency band. Unit: watt per hertz (W/Hz). The term is sometimes loosely used to refer to the spectral density of other parameters such as squared sound pressure. Ratio of energy spectral density, E_f, to time duration, Δt, in a specified temporal observation window. In equation form, the power spectral density P_f is given by $P_f = E_f/\Delta t$. Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement).

power spectral density level

The level ($L_{P,f}$) of the power spectral density (P_f) in a stated frequency band and time window. Defined as: $L_{P,f} = 10\log_{10}(P_f/P_{f,0})$. Unit: decibel (dB).

As with power spectral density, power spectral density level can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement). The reference value ($P_{f,0}$) for power spectral density level depends on the nature of the field variable.

power spectral density source level

A property of a sound source equal to the power spectral density level of the sound pressure measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa² m²/Hz.

propagation loss (PL)

Difference between a source level (SL) and the level at a specified location, PL(x) = SL − L(x). Unit: decibel (dB). See also transmission loss.

radiated noise level (RNL)

A source level that has been calculated assuming sound pressure decays geometrically with distance from the source, with no influence of the sea-surface or seabed. Often used to quantify source levels of vessels or industrial operations from measurements. See also monopole source level.

received level

The level of a given field variable measured (or that would be measured) at a given location.

reference value

Standard value of a quantity used for calculating underwater sound level. The reference value depends on the quantity for which the level is being calculated:

Quantity	Reference value
Sound pressure	p_0^2 = 1 μPa² or p_0 = 1 μPa
Sound exposure	E_0 = 1 μPa² s
Sound particle displacement	δ_0^2 = 1 pm²
Sound particle velocity	u_0^2 = 1 nm²/s²
Sound particle acceleration	a_0^2 = 1 μm²/s⁴

sensation level

Difference between the sound pressure level and hearing threshold at a specified frequency. Unit: decibel (dB).

shear wave

A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called a secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium. In common meaning, a form of energy that propagates through media (e.g., water, air, ground) as pressure waves.

sound exposure

Time integral of squared sound pressure over a stated time interval in a stated frequency band. The time interval can be a specified time duration (e.g., 24 h) or from start to end of a specified event (e.g., a pile strike, an airgun pulse, a construction operation). Unit: pascal squared second (Pa² s). Symbol: E.

sound exposure level (SEL)

The level (L_E) of the sound exposure (E) in a stated frequency band and time window: L_E = 10log$_{10}$(E/E_0) (ISO 18405:2017). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 µPa^2 s.

sound exposure spectral density

Distribution as a function of frequency of the time-integrated squared sound pressure per unit bandwidth of a sound having a continuous spectrum (ISO 18405:2017). Unit: pascal squared second per hertz (Pa^2 s/Hz).

sound field

Region containing sound waves.

sound intensity

Product of the sound pressure and the sound particle velocity (ISO 18405:2017). The magnitude of the sound intensity is the sound energy flowing through a unit area perpendicular to the direction of propagation per unit time. Unit: watt per meter squared (W/m^2). Symbol: I.

sound particle acceleration

The rate of change of sound particle velocity. Unit: meter per second squared (m/s^2). Symbol: a.

sound particle motion

Movement caused by the action of sound of the smallest volume of a medium that represents its mean physical properties. Important for determining effects of underwater noise on fishes and invertebrates because their hearing organs sense particle motion rather than sound pressure.

sound particle displacement

Displacement of a material element caused by the action of sound, where a material element is the smallest element of the medium that represents the medium's mean density (ISO 18405:2017). Unit: meter (m). Symbol: δ.

sound particle velocity

The velocity of a particle in a material moving back and forth in the direction of the pressure wave. Unit: meter per second (m/s). Symbol: u.

sound pressure

The contribution to total pressure caused by the action of sound (ISO 18405:2017). Unit: pascal (Pa). Symbol: p.

sound pressure level (SPL), rms sound pressure level

The level (L_p) of the time-mean-square sound pressure (p^2_{rms}) in a stated frequency band and time window: L_p = 10log$_{10}$(p^2_{rms}/p^2_0) = 20log$_{10}$(p_{rms}/p_0), where rms is the abbreviation for root-mean-square. Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 µPa^2. SPL can also be expressed in terms of the root-mean-square (rms) with a reference value of p_0 = 1 µPa. The two definitions are equivalent.

sound speed profile

The speed of sound in the water column as a function of depth below the water surface.

soundscape

The characterization of the ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field (ISO 18405:2017).

source level (SL)

A property of a sound source equal to the sound pressure level measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^2 m^2.

spectrogram

A visual representation of acoustic amplitude over time and frequency. A spectrogram's resolution in the time and frequency domains should generally be stated as it determines the information content of the representation.

spectrum

Distribution of acoustic signal content over frequency, where the signal's content is represented by its power, energy, mean-square sound pressure, or sound exposure.

surface duct

The upper portion of a water column within which the gradient of the sound speed profile causes sound to refract upward and therefore reflect repeatedly off the surface resulting in relatively long-range sound propagation with little loss.

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity caused by noise exposure. Compare with permanent threshold shift.

thermocline

A depth interval near the ocean surface that experiences larger temperature gradients than the layers above and below it due to warming or cooling by heat conduction from the atmosphere and by warming from the sun.

transmission loss (TL)

The difference between a specified level at one location and that at a different location: $\mathrm{TL}(x_1,x_2) = L(x_1) - L(x_2)$ (ISO 18405:2017). Unit: decibel (dB). See also propagation loss.

unweighted

Term indicating that no frequency-weighting function is applied.

validated detection

The output of an automated detector that has been subsequently validated by a human during manual analysis.

very high-frequency (VHF) cetaceans

See functional hearing group.

wavelength

Distance over which a wave completes one cycle of oscillation. Unit: meter (m). Symbol: λ.

Literature Cited

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.1-2013. *American National Standard: Acoustical Terminology*. New York. https://webstore.ansi.org/Standards/ASA/ANSIASAS12013.

[DoC] Department of Commerce (US) and [NOAA] National Oceanic and Atmospheric Administration (US). 2018. 83 FR 63268: Takes of Marine Mammals Incidental to Specified Activities; Taking Marine Mammals Incidental to Geophysical Surveys in the Atlantic Ocean. *Federal Register* 83(235): 63268–63270. https://www.federalregister.gov/d/2018-26460.

[HESS] High Energy Seismic Survey. 1999. *High Energy Seismic Survey Review Process and Interim Operational Guidelines for Marine Surveys Offshore Southern California*. Prepared for the California State Lands Commission and the United States Minerals Management Service Pacific Outer Continental Shelf Region by the High Energy Seismic Survey Team, Camarillo, CA, USA. 98 p. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2001100103.xhtml.

[ISO] International Organization for Standardization. 2006. *ISO 80000-3:2006. Quantities and units — Part 3: Space and time*. https://www.iso.org/standard/31888.html.

[ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics — Terminology*. Geneva. https://www.iso.org/obp/ui/en/#!iso:std:62406:en.

[NMFS] National Marine Fisheries Service (US). 1998. *Acoustic Criteria Workshop*. Co-Chairs: Dr. Roger Gentry and Dr. Jeanette Thomas. 9-11 Sep 1998.

[NMFS] National Marine Fisheries Service (US). 2016. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55. 178 p.

[NMFS] National Marine Fisheries Service (US). 2018. *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59. 167 p. https://media.fisheries.noaa.gov/dam-migration/tech_memo_acoustic_guidance_(20)_(pdf)_508.pdf.

[NMFS] National Marine Fisheries Service (US). 2024. *2024 Update to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 3.0): Underwater and In-Air Criteria for Onset of Auditory Injury and Temporary Threshold Shifts*. Report by the US Department of Commerce and NOAA. NOAA Technical Memorandum NMFS-OPR-xx. https://www.fisheries.noaa.gov/s3/2024-05/NMSFAcousticGuidance-DraftTECHMEMOGuidance-3.0-FEB-24-OPR1.pdf.

[NOAA] National Oceanic and Atmospheric Administration (US). 2013. *Draft guidance for assessing the effects of anthropogenic sound on marine mammals: Acoustic threshold levels for onset of permanent and temporary threshold shifts*. National Oceanic and Atmospheric Administration, US Department of Commerce, and NMFS Office of Protected Resources, Silver Spring, MD, USA. 76 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2015. *Draft guidance for assessing the effects of anthropogenic sound on marine mammal hearing: Underwater acoustic threshold levels for onset of permanent and temporary threshold shifts*. NMFS Office of Protected Resources, Silver Spring, MD, USA. 180 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2016. *Document Containing Proposed Changes to the NOAA Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts*. National Oceanic and Atmospheric Administration and US Department of Commerce. 24 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2024. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (web page), 30 Jan 2024. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west.

[ONR] Office of Naval Research. 1998. *Workshop on the Effect of Anthropogenic Noise in the Marine Environment*. *ONR Workshop*, 10–12 Feb 1998. https://apps.dtic.mil/sti/tr/pdf/ADA640861.pdf.

Aerts, L.A.M., M. Blees, S.B. Blackwell, C.R. Greene, Jr., K.H. Kim, D.E. Hannay, and M.E. Austin. 2008. *Marine mammal monitoring and mitigation during BP Liberty OBC seismic survey in Foggy Island Bay, Beaufort Sea, July-August 2008: 90-day report*. Document P1011-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., Greeneridge Sciences Inc., and JASCO Applied Sciences for BP Exploration Alaska. 199 p. ftp://ftp.library.noaa.gov/noaa_documents.lib/NMFS/Auke%20Bay/AukeBayScans/Removable%20Disk/P1011-1.pdf.

Austin, M.E. and G.A. Warner. 2012. *Sound Source Acoustic Measurements for Apache's 2012 Cook Inlet Seismic Survey*. Version 2.0. Technical report by JASCO Applied Sciences for Fairweather LLC and Apache Corporation.

Austin, M.E. and L. Bailey. 2013. *Sound Source Verification: TGS Chukchi Sea Seismic Survey Program 2013*. Document 00706, Version 1.0. Technical report by JASCO Applied Sciences for TGS-NOPEC Geophysical Company.

Austin, M.E., A. McCrodan, C. O'Neill, Z. Li, and A.O. MacGillivray. 2013. *Marine mammal monitoring and mitigation during exploratory drilling by Shell in the Alaskan Chukchi and Beaufort Seas, July–November 2012: 90-Day Report*. *In*: Funk, D.W., C.M. Reiser, and W.R. Koski (eds.). Underwater Sound Measurements. LGL Rep. P1272D–1. Report from LGL Alaska Research Associates Inc. and JASCO Applied Sciences, for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 266 pp plus appendices.

Austin, M.E. 2014. Underwater noise emissions from drillships in the Arctic. *In*: Papadakis, J.S. and L. Bjørnø (eds.). *UA2014*. 22–27 Jun 2014, Rhodes, Greece. pp. 257–263.

Austin, M.E., H. Yurk, and R.A. Mills. 2015. *Acoustic Measurements and Animal Exclusion Zone Distance Verification for Furie's 2015 Kitchen Light Pile Driving Operations in Cook Inlet*. Version 2.0. Technical report by JASCO Applied Sciences for Jacobs LLC and Furie Alaska.

Austin, M.E. and Z. Li. 2016. *Marine Mammal Monitoring and Mitigation During Exploratory Drilling by Shell in the Alaskan Chukchi Sea, July–October 2015: Draft 90-day report*. *In*: Ireland, D.S. and L.N. Bisson (eds.). Underwater Sound Measurements. LGL Rep. P1363D. Report from LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. For Shell Gulf of Mexico Inc, National Marine Fisheries Service, and US Fish and Wildlife Service. 188 pp + appendices.

Austin, M.E., D.E. Hannay, and K.C. Bröker. 2018. Acoustic characterization of exploration drilling in the Chukchi and Beaufort seas. *Journal of the Acoustical Society of America* 144: 115–123. https://doi.org/10.1121/1.5044417

Beach Energy Limited. 2020. *Environment Plan: Artisan-1 Exploration Well Drilling*. 544 p. https://docs.nopsema.gov.au/A764159.

Carnes, M.R. 2009. *Description and Evaluation of GDEM-V 3.0*. US Naval Research Laboratory, Stennis Space Center, MS. NRL Memorandum Report 7330-09-9165. 21 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/a494306.pdf.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93(4): 1736–1742. https://doi.org/10.1121/1.406739.

Collins, M.D., R.J. Cederberg, D.B. King, and S. Chin-Bing. 1996. Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* 100(1): 178–182. https://doi.org/10.1121/1.415921.

Constantine, R. 2023. *Cephalorhynchus hectori ssp. maui.* (web page).

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862–863. https://doi.org/10.1121/1.382038.

Delarue, J.J.-Y., C.R. McPherson, C.J. Whitt, E.E. Maxner, and K.A. Kowarski. 2017. Appendix B. Acoustic Monitoring in Queen Charlotte Sound: July 2016 to December 2016. *In* Goetz, K. and K. Hupman (eds.). *Passive Acoustic Monitoring in the greater Cook Strait region with particular focus on Queen Charlotte Sound / Tōtaranui*. NIWA Client Report No. 2017216WN for Marlborough District Council, June 2017. pp. 46–150. https://www.marlborough.govt.nz/repository/libraries/id:1w1mps0ir17q9sgxanf9/hierarchy/Documents/Environment/Coastal/Scientific%20Investigations%20List/Queen%20Charlotte%20Sound%20underwater%20soundscape.

Dunlop, R.A., M.J. Noad, R.D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2017. Determining the behavioural dose–response relationship of marine mammals to air gun noise and source proximity. *Journal of Experimental Biology* 220(16): 2878–2886. https://doi.org/10.1242/jeb.160192.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2018. A behavioural dose-response model for migrating humpback whales and seismic air gun noise. *Marine Pollution Bulletin* 133: 506–516. https://doi.org/10.1016/j.marpolbul.2018.06.009.

Ellison, W.T. and P.J. Stein. 1999. *SURTASS LFA High Frequency Marine Mammal Monitoring (HF/M3) Sonar: Sustem Description and Test & Evaluation*. Under US Navy Contract N66604-98-D-5725. http://www.surtass-lfa-eis.com/wp-content/uploads/2018/02/HF-M3-Ellison-Report-2-4a.pdf.

Ellison, W.T. and A.S. Frankel. 2012. A common sense approach to source metrics. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 433–438. https://doi.org/10.1007/978-1-4419-7311-5_98.

Elwen, S., M.A. Meyer, P.B. Best, P.G.H. Kotze, M. Thornton, and S. Swanson. 2006. Range and movements of female Heaviside's dolphins (Cephalorhynchus heavisidii), as determined by satellite-linked telemetry. *Journal of Mammalogy* 87(5): 866-877.

Erbe, C., C.R. McPherson, and A. Craven. 2011. *Acoustic Investigation of Bycatch Mitigation Pingers*. Report P001115-001-2. Technical Report by JASCO Applied Sciences for Australian Marine Mammal Centre. 89 p.

Erbe, C. and C.R. McPherson. 2012. Acoustic characterisation of bycatch mitigation pingers on shark control nets in Queensland, Australia. *Endangered Species Research* 19(2): 109–121. https://doi.org/10.3354/esr00467.

Erbe, C., C.J. Reichmuth, K. Cunningham, K. Lucke, and R.J. Dooling. 2016. Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin* 103(1): 15–38. https://doi.org/10.1016/j.marpolbul.2015.12.007.

Finneran, J.J. and C.E. Schlundt. 2010. Frequency-dependent and longitudinal changes in noise-induced hearing loss in a bottlenose dolphin (*Tursiops truncatus*). *Journal of the Acoustical Society of America* 128(2): 567–570. https://doi.org/10.1121/1.3458814.

Finneran, J.J. and A.K. Jenkins. 2012. *Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis*. SPAWAR Systems Center Pacific, San Diego, CA, USA. 64 p.

Finneran, J.J. 2015. *Auditory weighting functions and TTS/PTS exposure functions for cetaceans and marine carnivores*. Technical report by SSC Pacific, San Diego, CA, USA.

Finneran, J.J. 2016. *Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise*. Technical Report for Space and Naval Warfare Systems Center Pacific, San Diego, CA, USA. 49 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf.

Funk, D.W., D.E. Hannay, D.S. Ireland, R. Rodrigues, and W.R. Koski. 2008. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–November 2007: 90-day report*. LGL Report P969-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Research Ltd. for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 218 p. http://www-static.shell.com/static/usa/downloads/alaska/shell2007_90-d_final.pdf.

Goetz, K. and K. Hupman. 2017. *Passive Acoustic Monitoring in the greater Cook Strait region with particular focus on Queen Charlotte Sound / Tōtaranui*. National Institute of Water and Atmospheric Research Inc, Wellington. https://www.marlborough.govt.nz/repository/libraries/id:1w1mps0ir17q9sgxanf9/hierarchy/Documents/Environment/Coastal/Scientific%20Investigations%20List/Queen%20Charlotte%20Sound%20underwater%20soundscape.

Hannay, D.E. and R.G. Racca. 2005. *Acoustic Model Validation*. Document 0000-S-90-04-T-7006-00-E, Revision 02. Technical report by JASCO Research Ltd. for Sakhalin Energy Investment Company Ltd. 34 p.

Ireland, D.S., R. Rodrigues, D.W. Funk, W.R. Koski, and D.E. Hannay. 2009. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–October 2008: 90-Day Report*. Document P1049-1. 277 p.

Lucke, K., U. Siebert, P.A. Lepper, and M.-A. Blanchet. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *Journal of the Acoustical Society of America* 125(6): 4060–4070. https://doi.org/10.1121/1.3117443.

MacGillivray, A.O. 2018. Underwater noise from pile driving of conductor casing at a deep-water oil platform. *Journal of the Acoustical Society of America* 143(1): 450–459. https://doi.org/10.1121/1.5021554.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyak, and J.E. Bird. 1983. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior*. Report 5366. http://www.boem.gov/BOEM-Newsroom/Library/Publications/1983/rpt5366.aspx.

Malme, C.I., P.R. Miles, C.W. Clark, P.L. Tyack, and J.E. Bird. 1984. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Phase II: January 1984 Migration*. Report 5586. Report by Bolt Beranek and Newman Inc. for the US Department of the Interior, Minerals Management Service, Cambridge, MA, USA. https://www.boem.gov/sites/default/files/boem-newsroom/Library/Publications/1983/rpt5586.pdf.

Malme, C.I., B. Würsig, J.E. Bird, and P.L. Tyack. 1986. *Behavioral responses of gray whales to industrial noise: Feeding observations and predictive modeling*. Document 56. NOAA Outer Continental Shelf Environmental Assessment Program. Final Reports of Principal Investigators. 393–600 p.

Martin, S.B., K.C. Bröker, M.-N.R. Matthews, J.T. MacDonnell, and L. Bailey. 2015. Comparison of measured and modeled air-gun array sound levels in Baffin Bay, West Greenland. *OceanNoise 2015*. 11–15 May 2015, Barcelona, Spain.

Martin, S.B. and A.N. Popper. 2016. Short- and long-term monitoring of underwater sound levels in the Hudson River (New York, USA). *Journal of the Acoustical Society of America* 139(4): 1886–1897. https://doi.org/10.1121/1.4944876.

Martin, S.B., J.T. MacDonnell, and K.C. Bröker. 2017a. Cumulative sound exposure levels—Insights from seismic survey measurements. *Journal of the Acoustical Society of America* 141(5): 3603–3603. https://doi.org/10.1121/1.4987709.

Martin, S.B., M.-N.R. Matthews, J.T. MacDonnell, and K.C. Bröker. 2017b. Characteristics of seismic survey pulses and the ambient soundscape in Baffin Bay and Melville Bay, West Greenland. *Journal of the Acoustical Society of America* 142(6): 3331–3346. https://doi.org/10.1121/1.5014049.

Matthews, M.-N.R. and A.O. MacGillivray. 2013. Comparing modeled and measured sound levels from a seismic survey in the Canadian Beaufort Sea. *Proceedings of Meetings on Acoustics* 19(1): 1–8. https://doi.org/10.1121/1.4800553.

McCrodan, A., C.R. McPherson, and D.E. Hannay. 2011. *Sound Source Characterization (SSC) Measurements for Apache's 2011 Cook Inlet 2D Technology Test*. Version 3.0. Technical report by JASCO Applied Sciences for Fairweather LLC and Apache Corporation. 51 p.

McPherson, C.R. and G.A. Warner. 2012. *Sound Sources Characterization for the 2012 Simpson Lagoon OBC Seismic Survey 90-Day Report*. Document 00443, Version 2.0. Technical report by JASCO Applied Sciences for BP Exploration (Alaska) Inc.

McPherson, C.R., K. Lucke, B.J. Gaudet, S.B. Martin, and C.J. Whitt. 2018. *Pelican 3-D Seismic Survey Sound Source Characterisation*. Document 001583, Version 1.0. Technical report by JASCO Applied Sciences for RPS Energy Services Pty Ltd.

McPherson, C.R. and S.B. Martin. 2018. *Characterisation of Polarcus 2380 in^3 Airgun Array*. Document 001599, Version 1.0. Technical report by JASCO Applied Sciences for Polarcus Asia Pacific Pte Ltd.

Nedwell, J.R. and A.W.H. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25 Jun 1998, London, UK.

Nedwell, J.R., A.W.H. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, J.A.L. Spinks, and D. Howell. 2007. *A validation of the dB$_{ht}$ as a measure of the behavioural and auditory effects of underwater noise*. Document 534R1231 Report by Subacoustech Ltd. for Chevron Ltd, TotalFinaElf Exploration UK PLC, Department of Business, Enterprise and Regulatory Reform, Shell UK Exploration and Production Ltd, The Industry Technology Facilitator, Joint Nature Conservation Committee, and The UK Ministry of Defence. 74 p. https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-et-al-2007.pdf.

NOAA Fisheries. 2024. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (web page), 30 Jan 2024. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west.

O'Neill, C., D. Leary, and A. McCrodan. 2010. Sound Source Verification. (Chapter 3) *In* Blees, M.K., K.G. Hartin, D.S. Ireland, and D.E. Hannay (eds.). *Marine mammal monitoring and mitigation during open water seismic exploration by Statoil USA E&P Inc. in the Chukchi Sea, August-October 2010: 90-day report*. LGL Report P1112-1. Technical report by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. for Statoil USA E&P Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. pp. 1–34.

Payne, R. and D. Webb. 1971. Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences* 188: 110–141. https://doi.org/10.1111/j.1749-6632.1971.tb13093.x.

Popper, A.N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, et al. 2014. *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014. SpringerBriefs in Oceanography. ASA Press and Springer. https://doi.org/10.1007/978-3-319-06659-2.

Porter, M.B. and Y.C. Liu. 1994. Finite-element ray tracing. *In*: Lee, D. and M.H. Schultz (eds.). *International Conference on Theoretical and Computational Acoustics*. Volume 2. World Scientific Publishing Co. pp. 947–956.

Racca, R., A.N. Rutenko, K.C. Bröker, and M.E. Austin. 2012a. A line in the water - design and enactment of a closed loop, model based sound level boundary estimation strategy for mitigation of behavioural impacts from a seismic survey. *11th European Conference on Underwater Acoustics*. Volume 34(3), Edinburgh, UK.

Racca, R., A.N. Rutenko, K.C. Bröker, and G.A. Gailey. 2012b. Model based sound level estimation and in-field adjustment for real-time mitigation of behavioural impacts from a seismic survey and post-event evaluation of sound exposure for individual whales. *In*: McMinn, T. (ed.). *Acoustics 2012*. Fremantle, Australia. http://www.acoustics.asn.au/conference_proceedings/AAS2012/papers/p92.pdf.

Racca, R., M.E. Austin, A.N. Rutenko, and K.C. Bröker. 2015. Monitoring the gray whale sound exposure mitigation zone and estimating acoustic transmission during a 4-D seismic survey, Sakhalin Island, Russia. *Endangered Species Research* 29(2): 131–146. https://doi.org/10.3354/esr00703.

Reeves, R.R., S.M. Dawson, T.A. Jefferson, L. Karczmarski, K. Laidre, G. O'Corry-Crowe, L. Rojas-Bracho, E.R. Secchi, E. Slooten, et al. 2013. *Cephalorhynchus hectori.* (web page). The IUCN Red List of Threatened Species.

Shpak, O.V., O.I. Lyamin, P.R. Manger, J.M. Siegel, and L.M. Mukhametov. 2009. States of Rest and Activity in the Commerson's Dolphin Cephalorhynchus commersonii. *Journal of Evolutionary Biochemistry and Physiology* 45(1): 97-104.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33(4): 411–521. https://doi.org/10.1578/AM.33.4.2007.411.

Southall, B.L., D.P. Nowaceck, P.J.O. Miller, and P.L. Tyack. 2016. Experimental field studies to measure behavioral responses of cetaceans to sonar. *Endangered Species Research* 31: 293–315. https://doi.org/10.3354/esr00764.

Southall, B.L., J.J. Finneran, C.J. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals* 45(2): 125–232. https://doi.org/10.1578/AM.45.2.2019.125.

Teague, W.J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *Journal of Geophysical Research* 95(C5): 7167–7183. https://doi.org/10.1029/JC095iC05p07167.

Warner, G.A., C. Erbe, and D.E. Hannay. 2010. Underwater Sound Measurements. (Chapter 3) *In* Reiser, C.M., D.W. Funk, R. Rodrigues, and D.E. Hannay (eds.). *Marine Mammal Monitoring and Mitigation during Open Water Shallow Hazards and Site Clearance Surveys by Shell Offshore Inc. in the Alaskan Chukchi Sea, July-October 2009: 90-Day Report*. LGL Report P1112-1. Report by LGL Alaska Research Associates Inc. and JASCO Applied Sciences for Shell Offshore Inc., National Marine Fisheries Service (US), and Fish and Wildlife Service (US). pp. 1–54.

Warner, G.A., M.E. Austin, and A.O. MacGillivray. 2017. Hydroacoustic measurements and modeling of pile driving operations in Ketchikan, Alaska [Abstract]. *Journal of the Acoustical Society of America* 141(5): 3992. https://doi.org/10.1121/1.4989141.

Warren, V.E., J.J.-Y. Delarue, J. McEachern, S.B. Martin, and C.R. McPherson. 2023. Novel technologies to mitigate the risk of dolphin capture in inshore trawl fisheries: field implementation and data analysis. *New Zealand Aquatic Environment and Biodiversity Report* (325): 46.

Wood, J.D., B.L. Southall, and D.J. Tollit. 2012. *PG&E offshore 3-D Seismic Survey Project Environmental Impact Report–Marine Mammal Technical Draft Report*. Report by SMRU Ltd. 121 p. https://www.coastal.ca.gov/energy/seismic/mm-technical-report-EIR.pdf.

Zhang, Z.Y. and C.T. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* 98(6): 3391–3396. https://doi.org/10.1121/1.413789.

Zykov, M.M. and J.T. MacDonnell. 2013. *Sound Source Characterizations for the Collaborative Baseline Survey Offshore Massachusetts Final Report: Side Scan Sonar, Sub-Bottom Profiler, and the R/V Small Research Vessel experimental*. Document 00413, Version 2.0. Technical report by JASCO Applied Sciences for Fugro GeoServices, Inc. and US Bureau of Ocean Energy Management.

Appendix A. Acoustic Metrics

This section describes in detail the acoustic metrics, impact criteria, and frequency weighting relevant to the modelling study.

A.1. Pressure Related Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially pulsed sound such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate sound and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow International Organization for Standardization definitions and symbols for sound metrics (e.g., ISO 2017, ANSI S1.1-2013).

The sound pressure level (SPL or L_p; dB re 1 μPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that SPL always refers to an rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt/p_0^2\right)\text{ dB} \tag{A-1}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying SPL function.

The sound exposure level (SEL or L_E; dB re 1 μPa^2·s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)\,dt/T_0 p_0^2\right)\text{ dB} \tag{A-2}$$

where T_0 is a reference time interval of 1 s. SEL continues to increase with time when non-zero pressure signals are present. It is a dose-type measurement, so the integration time applied must be carefully considered for its relevance to impact to the exposed recipients.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to pulsed sounds, SEL can be calculated by summing the SEL of the N individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right)\text{ dB}\,. \tag{A-3}$$

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LFC,24h}$; Appendix A.4). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should also be specified.

A.2. Decidecade Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analysing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are one tenth of a decade wide. A decidecade is sometimes referred to as a "1/3 octave" because one tenth of a decade is approximately equal to one third of an octave. Each decade represents a factor 10 in sound frequency. Each octave represents a factor 2 in sound frequency. The centre frequency of the ith band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}}\ \mathrm{kHz} \tag{A-4}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith decade band are defined as:

$$f_{lo,i} = 10^{\frac{-1}{20}} f_c(i) \quad \text{and} \quad f_{hi,i} = 10^{\frac{1}{20}} f_c(i) \tag{A-5}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1). The acoustic modelling spans from band 10 (f_c (10) = 10 Hz) to band 44 ($f_c(44)$ = 25 kHz).

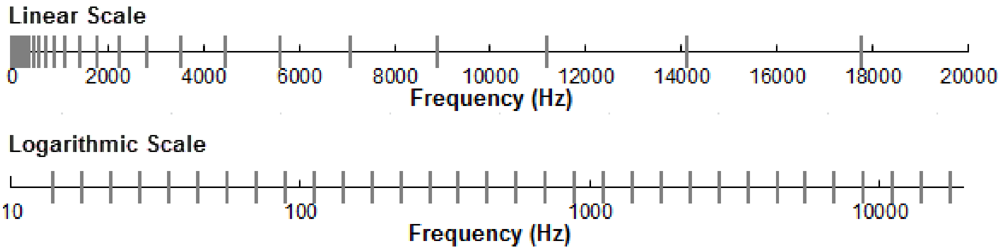


Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{lo,i}$ and $f_{hi,i}$:

$$L_{p,i} = 10\, log_{10} \int_{f_{lo,i}}^{f_{hi,i}} S(f)\, \mathrm{d}f\ \ \mathrm{dB} \tag{A-6}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}}\ \mathrm{dB} \tag{A-7}$$

Figure A-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient sound signal. Because the decidecade bands are wider than 1 Hz, the decidecade band SPL is higher than the spectral levels at higher frequencies. Acoustic modelling of decidecade bands requires less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

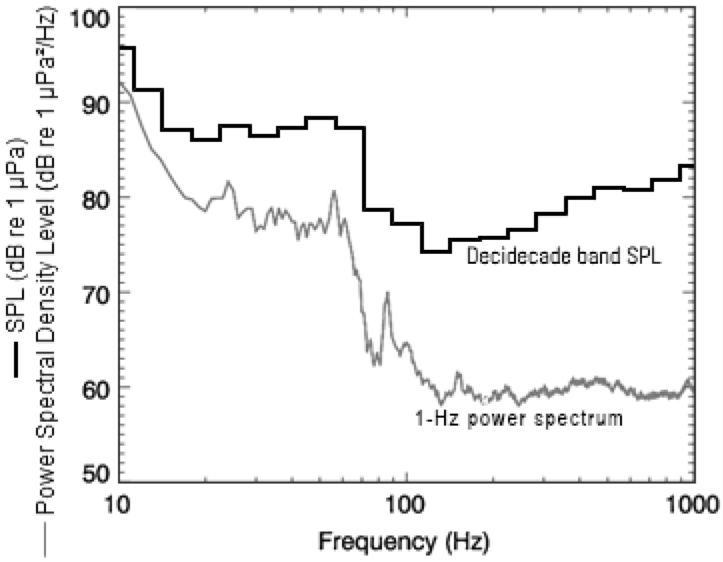


Figure A-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum.

A.3. Marine Mammal Noise Effect Criteria

It has been long recognised that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggest that communication distances of fin whales are reduced by shipping sounds. Subsequently, similar concerns arose regarding effects of other underwater noise sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater noise sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for auditory injury, impairment, and disturbance. The following sections summarise the recent development of thresholds; however, this field remains an active research topic.

A.3.1. Injury and Hearing Sensitivity Changes

In recognition of shortcomings of the SPL-only based auditory injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual auditory injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and Pinnipeds in Water (PINN). These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for humans; see Appendix A.4). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.’s (2007) thresholds, suggesting lower PTS and TTS values for LF and HF cetaceans while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbour porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HF cetaceans of 179 dB re 1 µPa^2·s. Because there were no data available for baleen whales, Wood et al. (2012) based their recommendations for LF cetaceans on results obtained from MF cetacean studies. In particular they referenced the Finneran and Schlundt (2010) research, which found mid-frequency cetaceans are more sensitive to non-impulsive sound exposure than Southall et al. (2007) assumed. Wood et al. (2012) thus recommended a more conservative TTS-onset level for LF cetaceans of 192 dB re 1 µPa^2·s.

As of present, a definitive approach is still not apparent. There is consensus in the research community that an SEL-based method is preferable, either separately or in addition to an SPL-based approach to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalised technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016). The guidance describes auditory injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2024 (NMFS 2024).

A.3.2. Behavioural Response

Numerous studies on marine mammal behavioural responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioural reactions. However, it is recognised that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison and Frankel 2012, Southall et al. 2016).

NMFS currently uses a step function (all-or-none) threshold of 120 dB re 1 µPa SPL (unweighted) for non-impulsive sounds to assess and regulate noise-induced behavioural impacts on marine mammals (NOAA 2024). The 120 dB re 1 µPa threshold is associated with continuous sources and was derived based on studies examining behavioural responses to drilling and dredging (NOAA 2018), referring to Malme et al. (1983), Malme et al. (1984), and Malme et al. (1986), which were considered in Southall et al. (2007). Malme et al. (1986) found that playback of drillship noise did not produce clear evidence of disturbance or avoidance for levels below 110 dB re 1 µPa (SPL), possible avoidance occurred for exposure levels approaching 119 dB re 1 µPa. Malme et al. (1984) determined that measurable reactions usually consisted of rather subtle short-term changes in speed and/or heading of the whale(s) under observation. It has been shown that both received level and proximity of the sound source is a contributing factor in eliciting behavioural reactions in humpback whales (Dunlop et al. 2017, Dunlop et al. 2018).

A.4. Marine Mammal Frequency Weighting

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal’s sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

A.4.1. Marine Mammal Frequency Weighting Functions

In 2015, a US Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. The new frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \quad \text{(A-8)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA’s technical guidance that assesses acoustic impacts on marine mammals (NMFS 2018). NOAA’s 2018 updates did not affect the parameters of the weighting functions or the threshold values. NMFS revised the parameters of the weighting functions and thresholds in 2024 (NMFS 2024), largely based on a revised report from Finneran (2024) containing revised auditory weighting functions that incorporated new relevant data on the effects of noise on marine mammal hearing. The terminology for mid- and high-frequency cetaceans was changed to high- and very high-frequency cetaceans (VHF cetaceans).

Table A-1 lists the generalised hearing range for VHF cetaceans, Table A-2 lists the frequency-weighting parameters, and Figure A-3 shows the resulting frequency-weighting curve.

Table A-1. Marine Mammal Hearing Group (NMFS 2024).

Hearing group	Generalised Hearing Range
Very high-frequency cetaceans (true porpoises, *Kogia*, river dolphins, *Cephalorhynchus* spp., *Lagenorhynchus cruciger* and *L. australis*)	200 Hz to 165 kHz

* Represents the generalised hearing range for the entire group as a composite (i.e., all species within the group), where individual species’ hearing ranges are typically not as broad. Generalised hearing range chosen based on ~65 dB threshold from normalized composite audiogram.

Table A-2. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2024).

Hearing group	a	b	flo (Hz)	fhi (Hz)	C (dB)
Very high-frequency cetaceans (true porpoises, *Kogia*, river dolphins, *Cephalorhynchus* spp., *Lagenorhynchus cruciger* and *L. australis*)	2.23	5	5,930	186,000	0.91

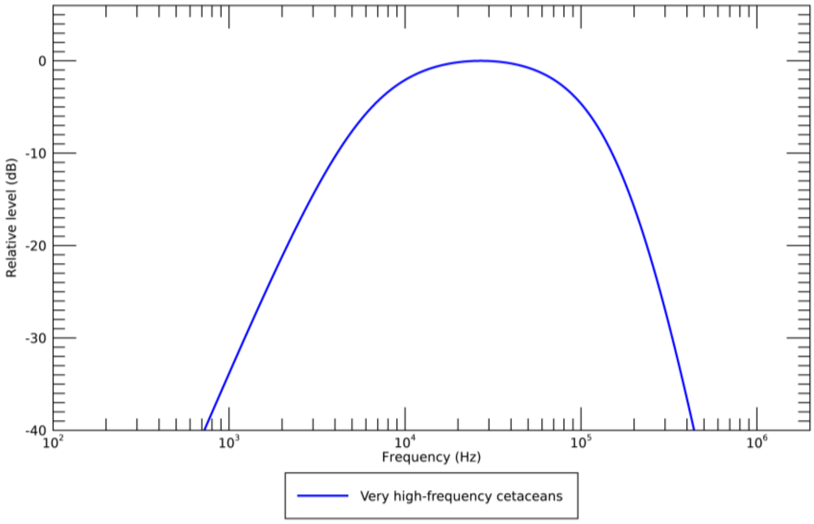


Figure A-3. Auditory weighting function for the very high-frequency cetacean functional marine mammal hearing group as recommended by NMFS (2024).

Appendix B. Methods and Parameters

B.1. Environmental Parameters

B.1.1. Bathymetry

Bathymetry throughout the modelled area was represented by synthetic, flat bathymetry files created at the four specified depths (10, 25, 50 and 100 m) at an arbitrary location. These bathymetric data were generated to represent generic conditions for the purpose of this study.

B.1.2. Sound Speed Profile

Three locations – near shore, coastal shelf, and edge of coastal shelf – were chosen off the coast of Timaru, New Zealand to provide a composite, representative sound speed profile. The sound speed profile was derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep). The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

Mean monthly sound speed profiles were derived from the GDEM profiles in the locality of the modelled sites. Sound speed profiles with an increase in speed with depth are often most favourable to longer-range sound propagation as they refracted more sound energy towards the surface, which is typically more reflective than seafloor interactions. As such, July was selected for sound propagation modelling to ensure precautionary estimates of distances to received sound level thresholds. Figure B-1 shows the resulting profile, which was used as input to the sound propagation modelling.

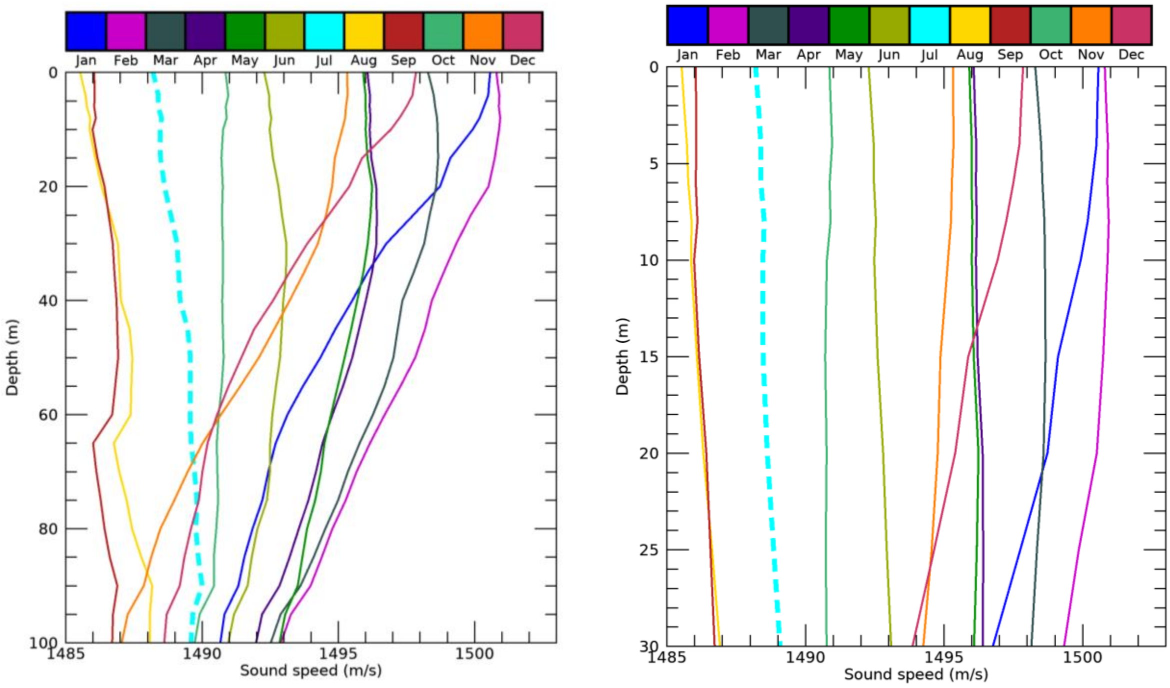


Figure B-1. Sound speed profiles for all months, with the applied month (July) displayed as a dotted line : full profile (left) and top 30 m (right) Profiles are calculated from temperature and salinity profiles from Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

B.1.3. Geoacoustics

Two modelled geoacoustic profiles were designed to represent a generic mud and generic sand seabed. Table B-1 and B-2 present the geoacoustic profile used for the mud and sand seabeds, respectively.

Table B-1. Geoacoustic profile for mud sediment. Each parameter varies linearly within the stated range.

Depth below seafloor (m)	Predicted lithology	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–1	Mud	1.63	1491.5–1525.1	0.04–0.20	103.2	3.65
1–5			1525.1–1556.5	0.20–0.34		
5–10			1556.5–1576.7	0.34–0.42		
10–30			1576.7–1621.0	0.42–0.60		
30–100			1621.0–1695.5	0.60–0.86		

Table B-2. Geoacoustic profile for sand sediment. Each parameter varies linearly within the stated range.

Depth below seafloor (m)	Predicted lithology	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–1	Medium Sand	2.07	1675.1–1787.7	0.12–0.55	389.9	3.65
1–5			1787.7–1903.2	0.55–0.92		
5–10			1903.2–1981.2	0.92–1.13		
10–30			1981.2–2160.3	1.13–1.53		
30–100			2160.3–2475.3	1.53–2.04		

B.2. Sound Propagation Models

B.2.1. Propagation Loss

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic energy source level (ESL), expressed in dB re 1 μPa^2·s m^2, and propagation loss (PL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 μPa^2·s by:

$$\mathrm{RL} = \mathrm{SL} - \mathrm{PL}. \tag{B-1}$$

B.2.2. MONM-BELLHOP

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). While other models may be more accurate for steep-angle propagation in high-shear environment, MONM is well suited for effective longer-range estimation. This model computes sound propagation at frequencies of 10 Hz to 1.6 kHz via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). MONM computes sound propagation at frequencies > 1.6 kHz via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM computes acoustic fields in three dimensions by modelling propagation loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ number of planes (Figure B-2).

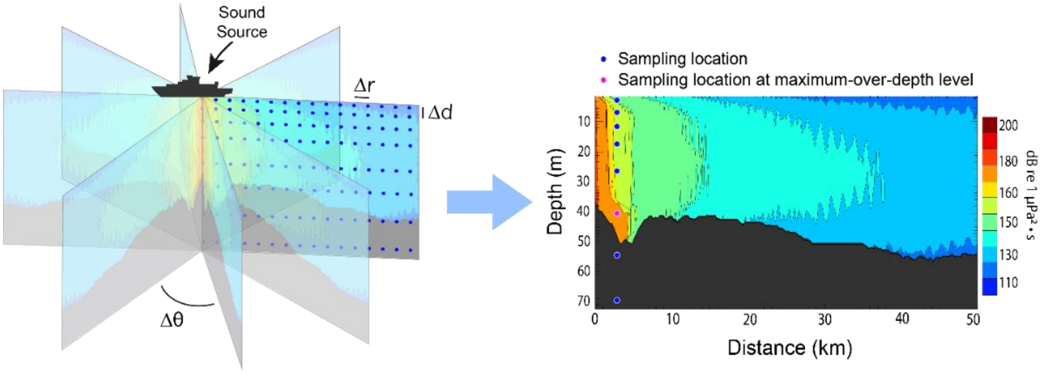


Figure B-2. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic propagation loss at the centre frequencies of decidecade bands. Sufficiently many decidecade frequency-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the propagation loss is modelled within each of the N vertical planes as a function of depth and range from the source. The decidecade received per-second SEL are computed by subtracting the band propagation loss values from the directional source level in that frequency band. Composite broadband received per-second SEL are then computed by summing the received decidecade levels.

The received 1-s SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received per-second SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received per-second SEL. These maximum-over-depth per-second SEL are presented as colour contours around the source.

B.3. Estimating Range to Thresholds Levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: 1) R_{max}, the maximum range to the given sound level over all azimuths, and 2) $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure B-3).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure B-3(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure B-3(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

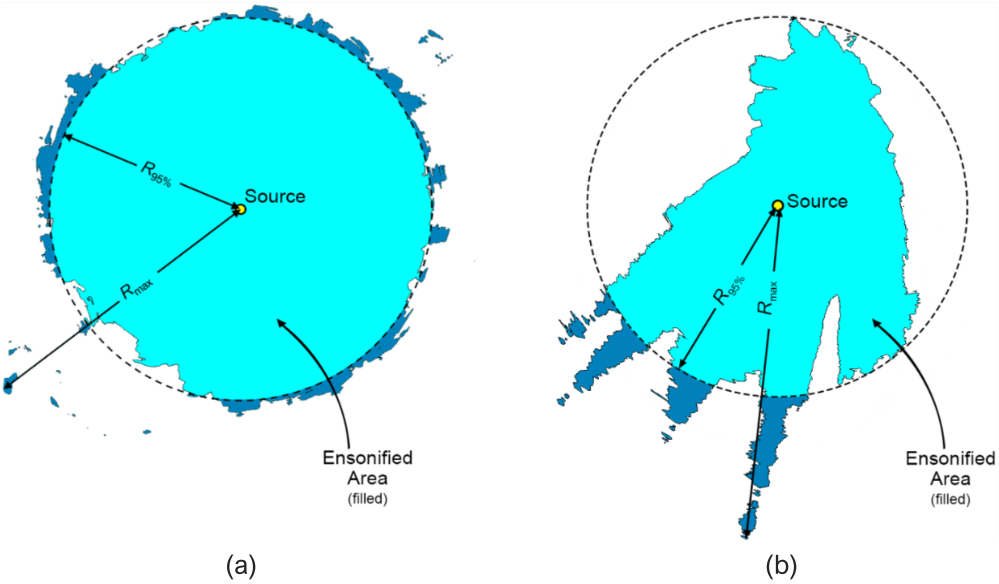


Figure B-3. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

B.4. Estimating Sound Fields from Moving Sources

During transit, new sound energy is constantly being introduced to the environment. The noise footprint for the transiting STM DDDs considered in this report were estimated by modelling the 1-s maximum over depth SEL footprints for the DDD at one location, and by translating and summing these footprints along the transit route. The modelled locations along the tracks were spaced uniformly, with an approximate step of $\Delta s \approx 5$ m.

The SEL sound field at any given point along the track is dependent upon the time duration within each 5 m segment of the track and the proportion of time that the device is active (P). When the track segment spacing is fixed, the duration of exposure depends upon the speed of movement during each segment of the transit. The 1-s SEL footprint at each location along the track (i) was therefore scaled based on the speed of trawling (2.2 knots) following:

$$\mathrm{SEL}_i = \mathrm{SEL}_{1s} + 10\log_{10}\left(P.\frac{\Delta s}{v}\right) . \qquad \text{(B-2)}$$

where v represents the vessel speed in m/s.

The present method acceptably reflects large-scale sound propagation features, primarily dependent on water depth, which dominate the cumulative field and is thus considered to provide a meaningful estimate of the SEL_{24h} field.

B.5. Model Validation Information

Predictions from JASCO's propagation models (MONM, FWRAM, and VSTACK) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including programs in the United States and Canadian Arctic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al.

2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities that have included internal validation of the modelling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016, Austin et al. 2018, Beach Energy Limited 2020).