MIT2024-07 Hector's Dolphin Acoustic Deterrence Devices in Trawl and Set Net Fisheries

Measurements of Sound Propagation At-Sea in New Zealand's Coastal Waters

JASCO Applied Sciences (Australia) Pty Ltd

21 August 2026

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P002091-001
Document 04323
Version 2.0 FINAL

Suggested citation:

Warren, V.E., S.C. Connell, and C.R. McPherson. 2026. MIT2024-07 Hector's Dolphin Acoustic Deterrence Devices in Trawl and Set Net Fisheries: Measurements of Sound Propagation At-Sea in New Zealand's Coastal Waters. Document 04323, Version 2.0 FINAL. Technical report by JASCO Applied Sciences for Department of Conservation, Te Papa Atawhai.

Report approved by:

Version	*Role*	*Name*	*Date*
2.0	Project Manager	James Tanner	21 August 2026
2.0	Senior Scientific Reviewer	Craig McPherson	21 August 2026

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Contents

Figures

Tables

Executive Summary

Two types of acoustic devices are regularly utilised in New Zealand waters to alert marine mammals to the presence of fishing gear, and/or to deter them from areas of risk or potential feeding opportunities. The two devices are the Netguard Dolphin Pinger (60 – 120 kHz model) and the STM Dolphin Deterrent Device (DDD) (DDD03H model). In 2025, JASCO Applied Sciences (Australia) (JASCO) undertook a measurement and modelling study (Warren et al. 2025) for Seafood New Zealand and the New Zealand Department of Conservation to verify the source characteristics and calculate underwater sound propagation associated with the two acoustic devices. This study reports on at-sea measurement trials conducted in April 2026 off the coast of Timaru, New Zealand that aimed to test the modelled assumptions (Warren et al. 2025) in a real world scenario by measuring the propagation of sound emitted by the devices and comparing it to the modelled outputs.

Four Netguard Pingers (with 60 m spacing) were mounted to the float-line of a bottom-mounted set net, and in a separate trial, two STM DDDs were suspended at 3 m above the seabed, 30 m apart to approximate their positions when mounted on the wing-ends of a trawl net. Acoustic measurements were undertaken using both static and mobile receivers to consider whether the propagation environment varied over time (temporal variability) and to examine how sound propagated over distance and depth (spatial variability). The static receiver was a baseplate JASCO Autonomous Multichannel Acoustic Recorder (AMAR) that was deployed onto the seabed. The mobile receiver was a JASCO Ocean Sound Meter-2 (OSM2) with a cabled hydrophone that was dipped from a vessel to near-surface, mid-water, and near-bottom depths. Recording bandwidths were 10 – 256,000 Hz for both receivers. Measurements were undertaken during calm weather, with wind speeds below 10 knots and wave heights of less than 0.1 m (Sea State 1). Nonetheless, significant drift in vessel location occurred during the mobile measurements. Careful notes and GPS positions were taken for each mobile measurement. For the static receiver, and for each dip obtained with the mobile receiver, average and maximum 1-s SPL values across the recording period were obtained, as well as an 'average maximum' value, which considered peaks in sound level in the acoustic data series, with each peak in SPL assumed to be driven by emissions of the Pingers or DDDs.

The results of the measurement trials are outlined in the sub-sections below. The overall aims of the study were to verify the modelled predictions, assess the effectiveness of the acoustic devices around an active fishing operation, and to identify any additional factors to consider for the effective use of the devices in operational settings.

Netguard Pinger results

Overall, the ambient noise environment across all frequency bands remained approximately consistent across the measurement period, as recorded by the static receiver. There were no notable trends in level across the recording period, such as might be caused by tidal movement or the arrival of another sound source (biological, geological or anthropogenic). Analysis focused on the 63 kHz-centred decidecade frequency band for the Netguard Pingers as this is the band that 'pings' are emitted in. The maximum received levels in the 63 kHz-centred decidecade frequency band, and to a lesser extent, the average maximum received level in the band, were higher at closer distances to the nearest Netguard Pinger which aids in confirming that the intended sound sources (the Netguard Pingers) were driving the value of the 63 kHz-centred decidecade frequency band, and external sound sources did not unduly influence the results.

Overall, the Netguard Pingers functioned as intended, and the entire net region was ensonified by the 'pings' emitted by the four devices. This achieves the primary aim of attaching Pingers to set nets, which is to provide an alert system to marine mammals to raise awareness of an object of potential risk. The Pinger spacing applied (60 m) was more than adequate in this environment to avoid 'gaps' in the sound field along the length of the net.

The real-world underwater environment was more conducive to sound propagation than the environment applied within the modelling, with higher received levels recorded at all horizontal distances than were predicted by the modelling. The better real-world propagation could have been a result of different sediment properties (the model considered pure sand), bathymetric features (the model considered a perfectly flat seafloor), or sound speed profile parameters in the water column (the model considered a profile for the Timaru area for the month of July as a conservative choice).

Within the modelling study, the environment with the longest propagation had a range to detectability of a Netguard Pinger of 60 m for Hector’s and Māui dolphins. Within this measurement study, the real-world underwater environment was more conducive to sound propagation than the environment applied within the modelling and the detectability threshold relevant to Netguard Pinger emissions was found to be exceeded at approximately 60 to 120 m. Whilst this was the case for this specific location, the conducive propagation environment is unlikely to be present at all locations in the New Zealand marine environment. Therefore, it is not recommended that the results from this trial should be extrapolated to other locations around New Zealand, or considered to be the norm for this location given the calm sea conditions. Nonetheless, the results from this measurement trial and the original modelling study could be considered in combination to produce future recommendations for spacing of Netguard Pingers on set nets.

While underwater noise measurements and modelling can speak to the temporal and spatial propagation of the sound fields emitted by the acoustic devices, to be confident that the devices function as effective bycatch mitigation tools, the responses of marine mammals to the emitted sounds must be confirmed. This is identified as an area in need of future research as there is limited understanding of the behaviour of free-ranging marine mammals in New Zealand, let alone in relation to active fisheries operations. Animal-mounted telemetry tags that record fine-scale movement, in combination with passive acoustic monitoring equipment at fishery sites, could form a basis for initial investigations on the performance of Pingers as a bycatch mitigation tool.

STM DDD results

During the measurements of the STM DDDs, the ambient noise environment across all frequency bands remained approximately consistent across the measurement period, as recorded by the static receiver. Analysis for the STM DDDs focused on the 25 kHz-centred decidecade frequency band, which was the band with the longest modelled propagation and is a local maxima within the source spectra. Towards the beginning of the measurements, a passing vessel contributed sound energy below 3000 Nonetheless, the maximum received levels in the 25 kHz-centred decidecade frequency band, and to a lesser extent, the average maximum received level in the band, were higher at closer distances to the STM DDDs which aids in confirming that the DDDs were the primary driver of the level of the 25 kHz-centred decidecade frequency band in the underwater environment.

In order to compare to modelled results, the 25 kHz-centred decidecade frequency band were corrected to an estimate of the broadband received level. As with the Netguard Pinger measurements, the real-world underwater environment was more conducive to sound propagation than the environment applied within the modelling, with higher received levels recorded than were predicted by the modelling.

The original work conducted by Warren et al. (2025) verified the sound source characteristics of the STM DDDs, and this measurement study has validated the overall outputs of the modelling study in terms of the propagation of sound, albeit with less transmission loss affecting propagation than was expected from the modelled scenarios. The sound source characteristics and verified modelling approach could now be used in future modelling work to consider the ensonified areas arising from multiple DDD sources, such as might occur across a fleet of fishing vessels operating in a specific area. Such modelling could contribute to management-level decision-making by quantifying acute and cumulative noise exposure that would be experienced by local marine mammal species, potentially allowing for a balance to be struck between adequate deterrence from risk areas and excessive noise pollution within the habitat. Further research to understand how free-ranging marine mammals respond to the DDD sound source would also be valuable, to ensure the devices function as effective bycatch mitigation tools.

1. Introduction

In 2025, JASCO Applied Sciences (Australia) (JASCO) undertook a measurement and modelling study (Warren et al. 2025) for Seafood New Zealand and the New Zealand Department of Conservation to verify the source characteristics and calculate underwater sound propagation associated with two acoustic devices that are regularly utilised in New Zealand waters to alert marine mammals to the presence of fishing gear, and/or to deter them from areas of risk or potential feeding opportunities. The two devices were the Netguard Dolphin Pinger (60 – 120 kHz model); and the STM Dolphin Deterrent Device (DDD) (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 that emits a more complex signal with greater randomness 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).

Within the modelling study (Warren et al. 2025), sound propagation was considered for single static devices for an array of water depths (10, 25, 50, and 100m), seabed sediments (sand or mud), sea-state conditions (sea state 0 or sea state 4), and deployment depths (near the surface or near the seafloor). The study also considered examples of typical multi-source deployments. For the Netguard Pinger, the multi-source scenario considered nine Netguard Pingers, 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. For the STM DDD, the 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. The multi-source scenario details were provided by Seafood New Zealand and intended to represent realistic device deployment scenarios.

This report presents results from underwater measurements of the two device types in a real-world coastal New Zealand marine environment, and compares the measured propagation of the devices against the modelled results obtained by Warren et al. (2025). Measurements were obtained as part of the Conservation Services Programme Annual Plan 2024/25[1] project MIT2024-07 for which the objectives were:

- To assess the effectiveness of viable acoustic devices in each class/category (set net and trawl) in the marine environment around an active fishing operation, and test against modelled predictions.
- To identify any additional factors to consider for effective use in operational settings as well as recommendations for future research.

For this real-world study, measurements were undertaken off the coast of Timaru, New Zealand, using both static and mobile receivers. It was not possible to replicate the exact environmental conditions applied within the modelled scenarios (which considered a theoretical environment, with a perfectly flat seabed, for example), however the real-world measurement locations aimed to match to modelled parameters where possible.

The design of the measurement study is summarised in Section 2.1, and specific details of the mooring hardware and analysis methodology are provided in Sections 2.2 and 2.3, respectively. Results from the measurement trials are reported in Section 3, along with comparisons against modelled results from Warren et al. (2025). All findings are then discussed in Section 4, along with some considerations for effective use of the devices in operational settings and future research recommendations.

[1] https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/plans-and-submissions/202425/final-csp-annual-plan-2024-25.pdf

2. Methods

At-sea measurements were undertaken off the coast of Timaru, off the east coast of the South Island of New Zealand. Mooring deployments/retrievals and mobile measurements were conducted from two local Timaru-based vessels. The vessels were an 11.5 m-long inshore trawler, and a 15 m-long inshore trawler/set netter.

2.1. Measurement Methodology

The measurement methodology for both device types combined one static receiver deployed on the seabed, and one mobile receiver that was dipped from the vessel to sample the sound field at different depths and distances. The aim of the static receiver was to monitor the sound of the devices and the ambient environment across the course of the measurement period to provide insight into whether the propagation environment varied over time (temporal variability). Measurements undertaken using the mobile receiver increased the number of sampling locations and was aimed at providing an understanding of potentially variable sound propagation within the environment (spatial variability).

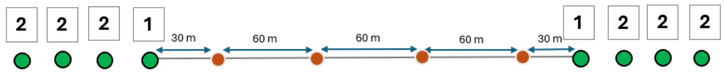
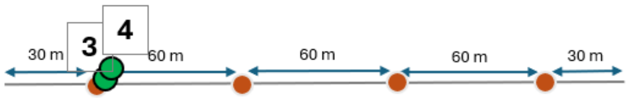
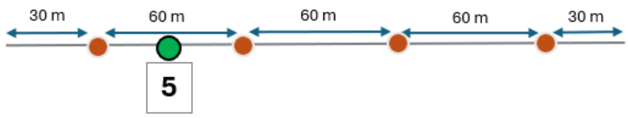
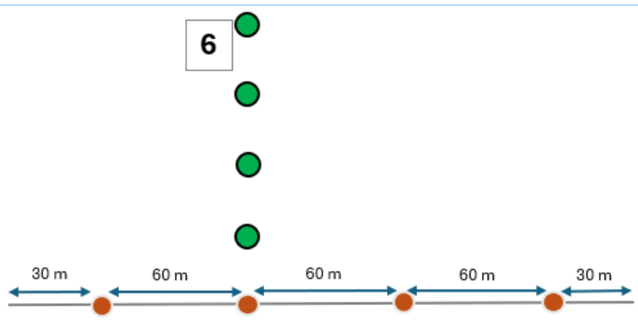
2.1.1. Netguard Pinger

Netguard Pingers were deployed as per their typical deployment methodology; mounted to the float-line of a bottom-mounted set net. While the modelling study by Warren et al. (2025) considered three set nets, for the at-sea measurement trial, measurements were undertaking around one set net to maximise the return on the sampling effort. This was feasible as the modelled sound fields around each net were not shown to overlap significantly between adjacent nets (with 2km spacing). A 250 m long set net was utilised in this study, which is typical of fishers in the Timaru area. This is not identical to the modelled multi-source scenario which considered 600 m long set nets. Furthermore, unlike the modelled scenario which considered 200 m spacing, Netguard Pingers were spaced at 60 m intervals along the set net during the real-world measurements, based on the recommended spacing that was obtained by Warren et al. (2025). Accordingly, for these trials, four pingers were required on the 250 m net.

On the day of the Netguard Pinger measurements, the study site was reached and a visual scan for marine mammals was undertaken (further details provided below). As no marine mammals were sighted, the set net was deployed with the four Netguard Pingers already attached which activated when they made contact with the seawater. The static receiver was then deployed close to one of the Pinger locations. Mobile measurements were undertaken around the net area at near-surface (2 m depth), mid-water (20 m depth) and near-seafloor (38 m depth) depths, as per Table 1. Each dip was intended to occur for 5 minutes in duration, to capture 60 pings.

Upon completion of the mobile measurements, the static receiver and set net were retrieved. Prior to retrieving the set net, ten minutes were spent actively scanning the area visually to check for marine mammals. The Operations Plan provided provision to delay net hauling if marine mammals were sighted in the area (further details provided below).

Table 1. Program of mobile dips undertaken for the Netguard Pinger. Each dip was obtained at near-surface (2 m depth), mid-water (20 m depth) and near-seafloor (38 m depth) in 40m water depth. In each diagram, OSM2 dip locations = green dots, Pinger locations = orange dots. Illustrated locations are indicative only.

<table>
<tr><th>Dip ID</th><th>Description</th><th>Distance to closest Netguard Pinger (m)</th><th>Diagram</th></tr>
<tr><td>1</td><td>Each end of set net</td><td>30</td><td rowspan="2">
</td></tr>
<tr><td>2</td><td>Beyond each end of set net</td><td>45, 60, 75</td></tr>
<tr><td>3</td><td>As close as possible to a Pinger</td><td><10</td><td rowspan="2">
</td></tr>
<tr><td>4</td><td>10 m from a Pinger</td><td>10</td></tr>
<tr><td>5</td><td>Half-way between two Pingers</td><td>30</td><td>
</td></tr>
<tr><td>6</td><td>Perpendicular from a Pinger</td><td>20, 40, 60, 80</td><td>
</td></tr>
</table>

The Netguard Pingers were deployed on a commercial set net in order to obtain the most accurate representation of their typical real-world usage and any relationships in their relative positioning to each other when mounted on a net that could not be captured had they been attached to standalone bottom-mounted moorings. Nonetheless, set nets do present a bycatch hazard for marine mammals. The following precautions were taken to minimise risk to free-ranging marine mammals during the measurement trials:

- Netguard Pinger measurements were undertaken at a location outside of the Set Net Closure area.
- Prior to the commencement of any deployment activities, active visual scanning for marine mammals was undertaken for a minimum of ten minutes once on site to ensure that none were in the region that could potentially be disturbed or put at risk by activities. Marine mammals were not sighted at either the Pinger or DDD study sites, but the Operations Plan provided provision to relocate and re-scan a new site if marine mammals were encountered.

- Trials were undertaken on calm weather days to enable visual scanning for marine mammals to be as effective as possible.
- The set net was deployed for the length of time required to undertake the measurements, and no longer.
- Netguard Pingers were mounted on the net with conservative spacing of 60 m derived from the modelling study by Warren et al. (2025), as opposed to the manufacturer's recommendation of 200 m.
- Ten minutes of active visual scanning for marine mammals was undertaken prior to retrieving the set net to mitigate potential risks that could be incurred while the net was hauled onto the vessel. This period of net movement has the potential to increase bycatch risk if marine mammals are interacting with the net. The Operations Plan provided provision to delay net hauling if marine mammals were sighted in the area; marine mammals were not sighted, therefore this was not required to be implemented.

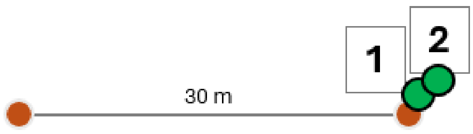
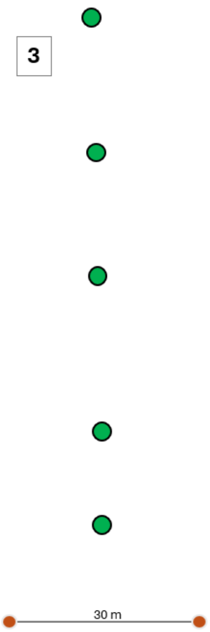
2.1.2. STM DDD

The modelling study conducted by Warren et al. (2025), considered single static STM DDDs, as well as two STM DDD's mounted at each wing-end of a trawl net, 30 m apart, moving along a straight track, to simulate a trawl net being pulled behind a vessel.

For this at-sea measurement trial, measurements were conducted around two static STM DDDs moored from the seabed and located 30 m apart. This static simplification allowed the measurements to be taken more accurately and was more logistically feasible than undertaking moving measurements of the devices situated on a moving trawl net.

On the day of the STM DDD measurements, the study site was reached and a visual scan for marine mammals was undertaken (further details provided in Section 2.1.1). As no marine mammals were sighted, the DDD mooring was deployed with the two STM DDDs already attached which activated when they made contact with the seawater. The static receiver was then deployed close to one of the DDD locations. Mobile measurements were then undertaken around the DDD mooring at near-surface (2 m depth), mid-water (12.5 m depth) and near-seafloor (23 m depth) depths, as per Table 2. Each dip was intended to occur for 10 minutes in duration, to capture ~10 emissions. Upon completion of the mobile measurements, the static receiver and DDD mooring were retrieved.

Table 2. Program of mobile dips undertaken for the STM DDD. Each dip was obtained at near-surface (2 m depth), mid-water (12.5 m depth) and near-seafloor (23 m depth) in 25 m water depth. In each diagram, OSM2 dip locations = green dots, DDD locations = orange dots. Illustrated locations are indicative only.

Dip ID	Description	Distance to closest STM DDD (m)	Diagram
1	As close as possible to a DDD	<10	
2	10 m from a DDD	10	
3	Perpendicular from the centre of the two DDDs	50, 100, 200, 300, 400	
4	Parallel from the DDD line	50, 100, 200, 300, 400	

2.2. Mooring Hardware

The following sub-sections expand on the different acoustic measurement devices and the mooring methods utilised for the Netguard Pingers and STM DDDs.

2.2.1. Static Receiver

Underwater sound was recorded with an Autonomous Multichannel Acoustic Recorder (AMAR, JASCO) (Figure 1). The AMAR was fitted with an M36 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa sensitivity). The AMAR hydrophone was protected by a hydrophone cage, which was covered with an open-cell foam to minimize non-acoustic noise caused by water flowing over the hydrophone transducer; this noise is often referred to as 'flow noise'. The AMAR recorded continuously at 512,000 samples per second (512 ksps) for a recording bandwidth of 10 Hz to 256,000 Hz. Acoustic data were stored on internal solid-state flash memory. The AMAR was calibrated before and after deployment. Appendix A describes the calibration procedure.

The AMAR was deployed on the seabed with a groundline, anchor and surface float, and was located close to one of the acoustic devices. Its position was marked via GPS, and the distance to each acoustic device could therefore be calculated.

Figure 1. The baseplate JASCO AMAR utilised as the static recorder.

2.2.2. Mobile Receiver

Mobile measurements were conducted with a field-calibrated Ocean Sound Meter-2 (OSM2; manufactured by JASCO Applied Sciences). The OSM2 was connected to a field laptop on the vessel, and to a cabled hydrophone which was dipped from the vessel at varying distances and depths around the acoustic devices. The start and end positions of each dip were marked via GPS, and the distance to each acoustic device could therefore be calculated for each measurement dip.

The OSM2 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.

2.2.3. Netguard Pinger Mooring

Based on recommended conservative 60 m spacing obtained from the modelling report by Warren et al. (2025), four Netguard Pingers were mounted on a 250 m setnet as per Figure 2, with 1 to 2 m leeway within the spacing. Pingers were mounted on the float-line of the net, 2.38 m above the seabed.

Pingers were lashed directly to the net with thin line, as per the manufacturer's recommended instructions. The pingers were in no way shrouded or insulated with any other materials or floatation items. Each pinger location was marked at the surface with a surface-buoy clipped alongside the pinger on the float-line of the net. New batteries were placed in the pingers for the purposes of the trial.

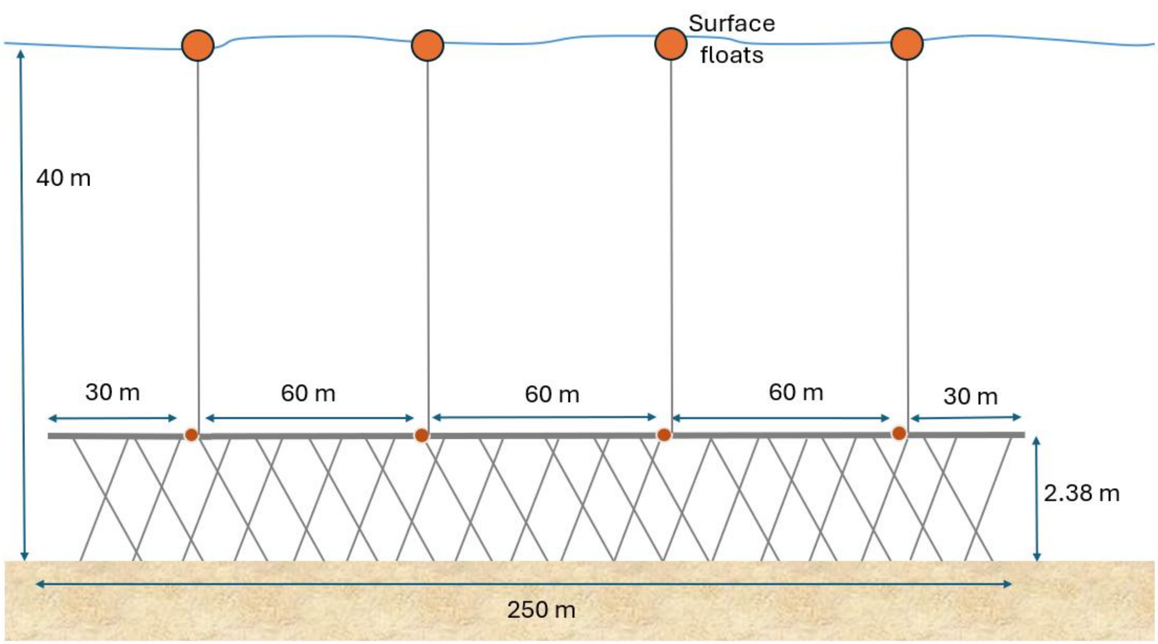


Figure 2. Cross-section/vertical view of the Netguard Pinger locations (small red circles) on the float line of the set net.

Figure 3. Netguard Pingers attached to the float-line of a 250 m set net, prior to deployment, showing that the devices were lashed securely to the float-line, without any shrouding or insulation, as per manufacturer instructions.

2.2.4. STM DDD Mooring

The trial utilised two static STM DDDs moored from the seabed and located 30 m apart. Figure 4 provides a diagram of the mooring design for the STM DDDs.

The DDDs were lashed to surface lines at 3 m above the seafloor, to mimic the height of a trawl net headline. The DDDs were in no way shrouded or insulated with any other materials or floatation items. The DDDs were fully charged for the trial.

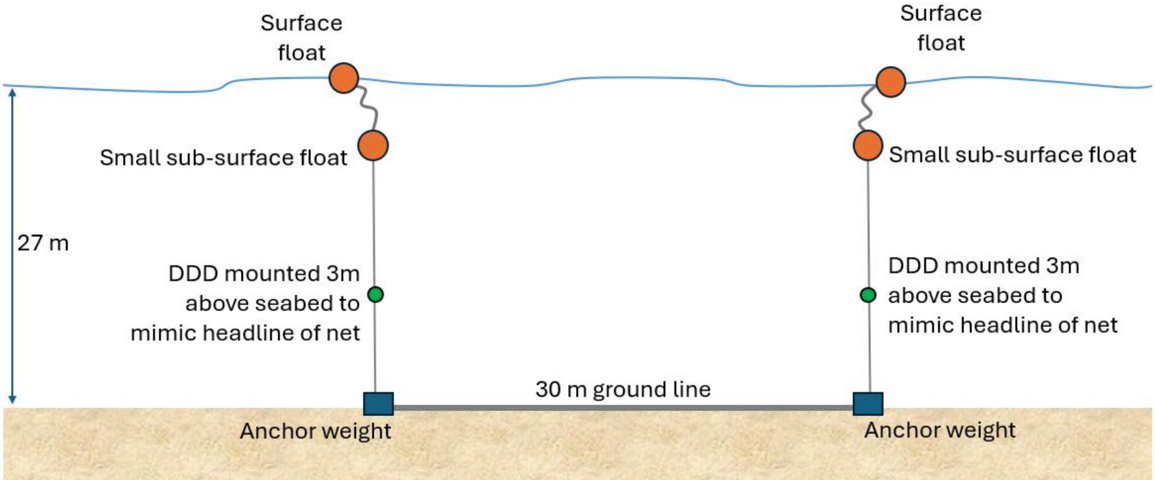


Figure 4. Cross-section/vertical view of the STM DDD mooring. DDDs indicated by small green circles.

2.3. Analysis Methodology

Approximately 61 GB of acoustic data were collected during the at-sea measurements. 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 sound levels over a fixed time window (1 second for this study).

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 measurement instrument (either the AMAR or the OSM2). Appendix A provides details on calibration procedures. Summaries of sound statistics were computed for each 1-second period.

The first stage of the sound level analysis involved computing the sound pressure level (SPL) for each second of data. SPL analysis was performed by averaging 120 fast-Fourier transforms (FFTs) that each included 1-second of data with a 50% overlap that use the Hann window to reduce spectral leakage. The 1-second data were stored as power spectral densities and summed over frequency to calculate decidecade-band SPL. Appendix B.3 lists the frequencies of the decidecade band levels (decidecade bands are similar to 1/3-octave-bands.)

The decidecade analysis sums as many frequencies as contained in the recorded bandwidth and reduces them to a manageable set of up to 45 bands that approximate the critical bandwidths of mammal hearing. The decade bands further summarise the sound levels into four frequency bands for manageability. Appendices B.2 and B.3 contain detailed descriptions of the acoustic metrics and decidecade analysis, respectively.

2.3.1. Static Receiver Data

The aim of the static receiver was to monitor the sound of the devices and the ambient environment across the course of the measurement period to provide insight into whether the propagation environment varied over time (temporal variability). In Section 3, the sound levels from the full deployment periods of the static receivers are presented as:

- **Band-level plots**: These strip charts show the averaged received SPL as a function of time within a given frequency band. Figures show the total sound levels (across the entire recorded bandwidth from 10–256,000 Hz) and the levels in the decade bands centred at 50 Hz (8.9–89.1 Hz), 500 Hz (89.1–891.3 Hz), 5000 Hz (891.3–8,913 Hz), and all higher frequency data (8,913–256,000 Hz). The final band contains all sound relevant to the Netguard Pinger (which produces sound between 60,000 – 70,000 Hz, Figure 5), and most of the sound relevant to the STM DDD (which produces broadband sound across all measured frequencies (Figure 5).
- **Long-term Spectral Averages (LTSAs)**: These colour plots show power spectral density levels as a function of time (*x* axis) and frequency (*y* axis). The frequency axis uses a logarithmic scale, which provides equal vertical space for each decade increase in frequency and equally shows the contributions of low- and high-frequency sound sources. The LTSAs are excellent summaries of the temporal and frequency variability in the data.
- **Decidecade box-and-whisker plots**: The 'boxes' in these figures represent the middle 50% of the range of SPL, so that the bottom of the box is the sound level 25th percentile (L_{25}) of the recorded levels, the bar in the middle of the box is the median (L_{50}), and the top of the box is the level that exceeded 75% of the data (L_{75}). The whiskers indicate the maximum and minimum ranges of the data.
- **Spectral density level percentiles**: While the decidecade box-and-whisker plots represent the histogram of each band's sound pressure levels, the power spectral density data have too many frequency bins for a similar presentation. Instead, coloured lines represent the L_5, L_{25}, L_{50}, L_{75}, and

L_{95} percentiles of the histograms, as well as the mean level. Shading underneath these lines indicate the relative probability distribution. It is common to compare the power spectral densities to the results from Wenz (1962), which documented the variability of ambient spectral levels off the US Pacific coast as a function of frequency of measurements for a range of weather, vessel traffic, and geologic conditions (see Appendix B.1). The Wenz levels are only appropriate for approximate comparisons because those data were collected in deep water and low-frequency sound levels have generally increased since the 1960's (Andrew et al. 2011).

Analysis was also conducted on the received levels of the sounds emitted by the acoustic devices. Based on the source characterisation study by Warren et al. (2025), analysis focused on the 63 kHz-centred decidecade frequency band for the Netguard Pingers, which produce sound within this band, and the 25 kHz-centred decidecade frequency band for the STM DDDs, which was the band with the longest modelled propagation and is a local maxima within the source spectra (Figure 5). The 1-second resolution sound pressure levels (SPLs) for the given decidecade band (as explained in Section 2.3) were assessed for the minimum, average and maximum value across the recording period. Maximum values were assumed to be associated with device emissions, and minimum values were associated with background ambient noise levels. Average values were calculating by converting decibel values to linear space, taking the mean, and converting back to log space. In addition, an 'average maximum' value was also calculated, which was the average value of 'peak' heights in the data series, with peaks assumed to be driven primarily by the acoustic device emissions. Figures 13 and 25 in Sections 3.1.1.1 and 3.2.1.1 provide visualisations of the data to aid understanding of these peaks.

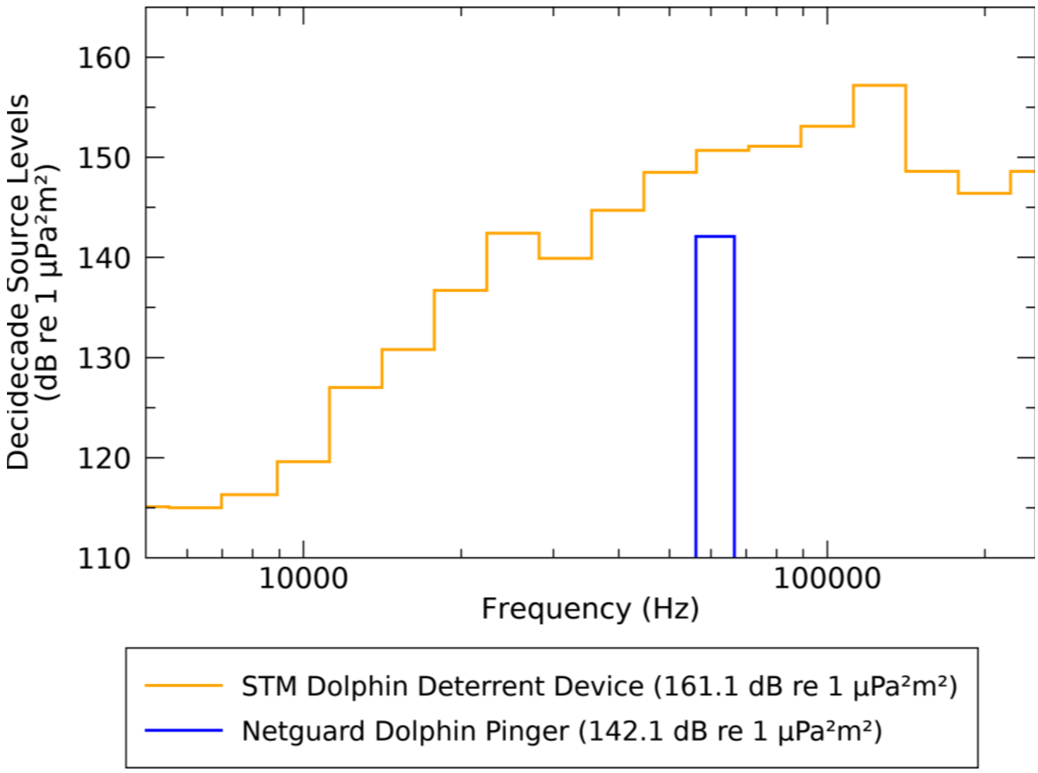


Figure 5. Monopole source level (MSL) spectra (in decidecade frequency-band) for median source levels for the STM DDD and the Netguard Pinger, from Warren et al. (2025).

2.3.2. Mobile Receiver Data

The aim of the mobile measurements was to provide an understanding of potentially variable sound propagation across the study region (spatial variability).

As per the static receiver analysis (Section 2.3.1), for each dip period, the 1-second resolution sound pressure levels (SPLs) for the given decidecade band (63 kHz-centred decidecade frequency band for the Netguard Pinger analysis, and the 25 kHz-centred decidecade frequency band for the STM DDD) were assessed. As the aim of the mobile measurements was to focus on spatial variability in the received levels of the acoustic device emissions, the average, maximum and average maximum values are presented. These results are considered in light of the dip depth and horizontal and slant distances to the closest acoustic device.

2.3.3. Comparison to Modelled Results

The received levels recorded in this measurement study were considered in light of the modelled results obtained by Warren et al. (2025) for the most similar environmental conditions. Warren et al. (2025) presented propagation distances to specific sound levels based on median source levels for the two device types (142.1 dB re 1 μPa^2m^2 for the Netguard Pinger, and 161.1 dB re 1 μPa^2m^2 for the STM DDD, per Figure 5), however the analysis conducted on the at-sea measurements focused on maximum received levels. Therefore, in order to directly compare the at-sea measurement results with the modelled results, the measured levels were adjusted to match the median values recorded during the source characterisation study (Table 8 in Warren et al. (2025)) and the at-sea measurement results were shifted -5.7 dB for the Netguard Pinger (the maximum source level was 147.8 dB re 1 μPa^2m^2 compared to a median source level of 142.1 dB re 1 μPa^2m^2 (which is shown in Figure 5)), and -12.4 dB for the STM DDD (the maximum source level was 173.6 dB re 1 μPa^2m^2 compared to a median source level of 161.2 dB re 1 μPa^2m^2 (which is shown in Figure 5)).

The modelled results presented a ‘maximum-over-depth’ value, which is a horizontal range from the acoustic source where at least one depth point within the water column exceeded the relevant received level. The modelled range results therefore incorporate depth-variation in sound propagation from the source, but this also means that the depth-specific measurements made within this at-sea study cannot all be directly compared to the modelled results, especially in the case of near-surface measurements where the slant distance between the acoustic device and the dipped receiver can be substantially different from the horizontal range. These considerations are discussed in context with the measurement results in Sections 3.1.2 and 3.2.2. 50th percentile (median) and 90th percentile best fit curves were calculated for the data using a spreading loss equation with an absorption term.

It should be noted that the modelled results for the STM DDD considered the propagation ranges of the broadband sound source (5,012 – 251,189 Hz), whereas this measurement study focused on 25,000 Hz-centred decidecade frequency band levels (22,281 – 28,050 Hz). This simplification was intended to avoid capturing external noise sources in the environment that may occur within other frequency bands, while providing a reliable measure that is correlated to the overall broadband sound emitted by the DDDs. The broadband source level of the STM DDDs was 18.7 dB higher than the level of the 25,000 Hz-centred decidecade frequency band (refer to Figure 5 and Warren et al. (2025)), and this correction factor has been applied to the measured data from the STM DDD, in addition to the conversion from maximum to median level outlined above, to enable a comparison with modelled results.

The modelling study conducted by Warren et al. (2025) also included estimates for the ranges at which Hector’s and Māui dolphins would be able to acoustically detect each device within typical ambient noise conditions. The analysis considered audiograms for very-high frequency cetaceans from NMFS (2024) and critical ratios from Erbe et al. (2016). Full details of the methods are provided by Warren et al. (2025). Within this measurement study, the average ambient levels were influenced by the acoustic devices given that these were deployed before, and retrieved after, the recording devices were deployed. As such, this study also considers the distance to frequency-band-specific critical ratio level for Hector’s and Māui dolphins in relation to the measured ambient noise level obtained from the Queen Charlotte Sound / Tōtaranui as 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).

In general, the reported received levels are presented in terms of sound pressure level (SPL), representing the average instantaneous acoustic level (across 1 second, for this analysis). The evaluation of a cumulative sound field can also be considered by accounting for the number of seconds of operation during an accumulation period. Here, measurement results were converted to sound exposure level (SEL) for given time periods by considering the duration of the desired time period and the proportion of time the devices were emitting sound. As per the modelling study by Warren et al. (2025), SEL was assessed over 10 minutes, 1 hour and 24 hours. 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 (7.71% for the Netguard Pingers, and 23.4% for the STM DDDs). SEL results were then decreased by the hearing ability of Hector's and Māui dolphins within the specified frequency band (63 kHz for Netguard Pingers, and broadband (5,012 – 251,189 Hz) for STM DDD measurements with broadband correction (+18.7 dB)) based on parameters provided in Accomando et al. (2025). The resulting SEL values were compared to frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Accomando et al. (2025) for the onset of permanent threshold shift (PTS)/auditory injury (AUD INJ) and temporary threshold shift (TTS) in marine mammals for non-impulsive sound sources, as per the modelling study by Warren et al. (2025) (which compared against identical thresholds presented within NMFS (2024)). For the SEL evaluations, the 50th percentile curve fit to the maximum received SPL levels were considered, as these were expected to be most representative of the closest device than the average maximum SPL values, and therefore assumed to be most similar to the single-device scenarios undertaken in the modelling study. Results from the SEL evaluations are also presented in relation to the propagation of median source levels, per the conversion outlined at the beginning of this Section.

3. Results

STM DDD measurements were made on 27 April 2026 (local time) and Netguard Pinger measurements were made on 28 April 2026 (local time). Both days featured extremely favourable sea conditions for undertaking measurements, with wind speeds below 10 knots and wave heights of less than 0.1 m (Sea State 1).

Figure 6 displays a map of the Netguard Pinger and STM DDD measurement locations off the coast of Timaru, along with insets showing the device arrangements and the static receiver location at each site. Netguard Pinger measurements were undertaken at a location outside of the Set Net Closure area.

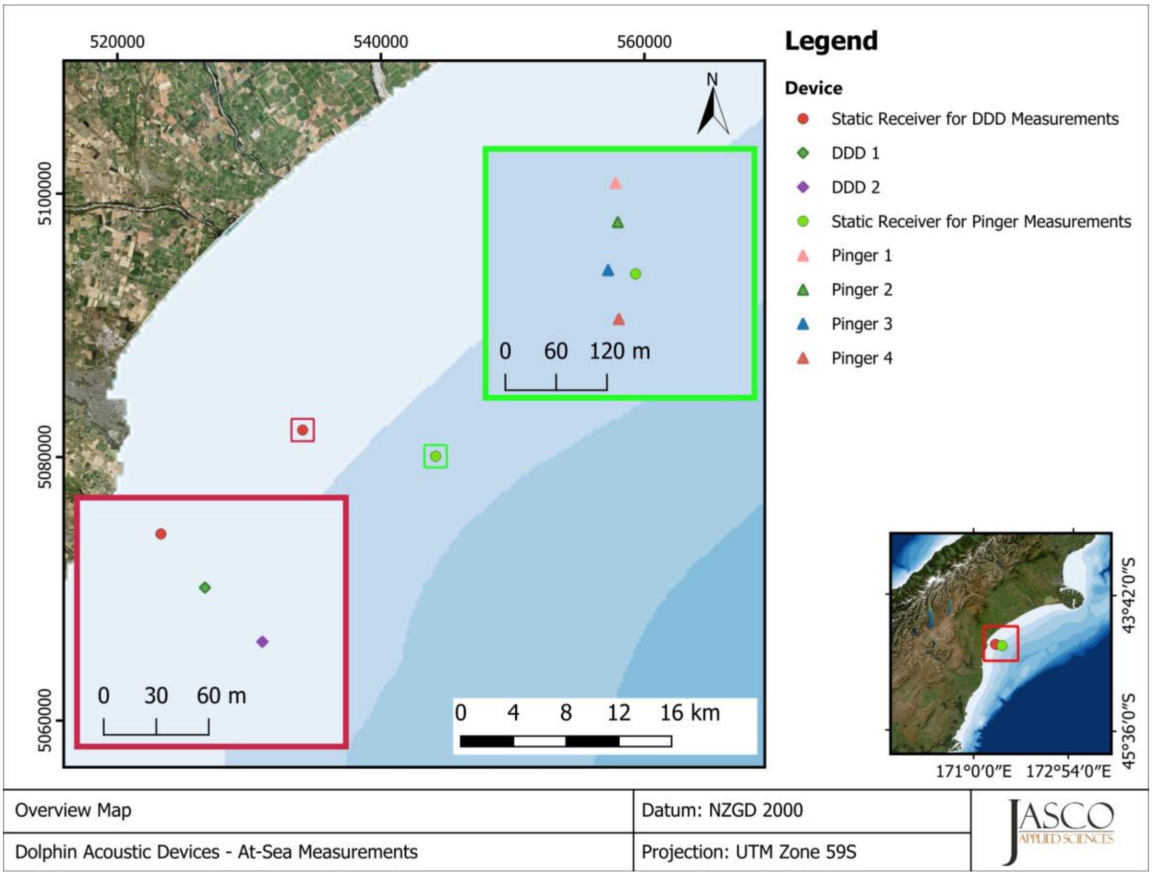


Figure 6. Overview map of the Netguard Pinger and STM DDD measurement locations, and the layout of the acoustic devices and static receiver (AMAR) at each site.

Despite calm weather conditions, significant drifting of the vessel and surface markers occurred during both measurement days, which was notable when trying to achieve very fine resolution distance measurements. GPS positions were taken at every event, including the location of each acoustic device, each static receiver, and the location of each OSM2 dip start and end. Nonetheless, due to the drift encountered, mobile OSM2 measurement results with the fine scale planned in Section 2.1 were not all feasible. In the following sections, results from the mobile receiver are presented with an average distance to the closest acoustic device, based on the distance at the start and end of the measurement period.

No marine mammals were sighted during either the Netguard Pinger or STM DDD measurement activities. Albatross were sighted on the water nearby during the DDD trials, likely attracted by the sight of the fishing vessel.

3.1. Netguard Pinger

3.1.1. Measurement Results

3.1.1.1. Static Receiver

The static AMAR recorder was situated closest to Pinger 3 (Table 3, Figure 6). The water depth at the study site was 40 m, and the hydrophone was mounted approximately 60 cm above the seabed on a baseplate mooring (Section 2.2.1). The Netguard Pingers were mounted on the float-line of the net at 2.38 m, therefore the hydrophone was located approximately 1.8 m lower in the water column than the Pingers.

Table 3. Static recorder, Netguard Pinger: AMAR depth and horizontal distance to each Netguard Pinger

Water depth (m)	Hydrophone depth (m)	Horizontal distance from Pinger 1 (m)	Horizontal distance from Pinger 2 (m)	Horizontal distance from Pinger 3 (m)	Horizontal distance from Pinger 4 (m)
40	39.4	110	65	33	57

Figure 7 presents the full data period recorded by the static receiver as a band-level plot (top panel) and a long-term spectral average (LTSA) spectrogram (bottom panel). Both panels provide an overview of the sound variability in time and frequency, as well as the presence and level of contributions from different sources. Short-term events appear as vertical stripes on the spectrogram and spikes on the band level plots. Long-term events appear in the spectrograms as horizontal bands of colour. Raised levels at the start and end of the recording are related to deployment and retrieval activities, the ~6 broadband ‘spikes’ during the recording period are related to the study vessel manoeuvring for mobile measurements, and the horizontal line at ~63 kHz (bottom panel) is due to emissions from the Netguard Pingers, with harmonics of the emissions evident at ~130 and ~200 kHz. Other than these notable features, the ambient noise environment is generally quiet.

Overall, the ambient noise environment across all frequency bands remained consistent across the measurement period (Figure 7, top panel), besides the features mentioned above. There were no notable trends in level across the recording, such as might be caused by tidal movement or the arrival of another sound source (biological, geological or anthropogenic).

Figure 8 presents the full data period recorded by the static receiver as a percentile figure showing box-and-whisker plots by decidecade frequency band (top panel) and power spectral density (PSD) by percentile (bottom panel) across the whole recording period. In both panels, the raised sound pressure level at ~63 kHz is due to emissions from the Netguard Pingers, with harmonics evident at ~130 and ~200 kHz.

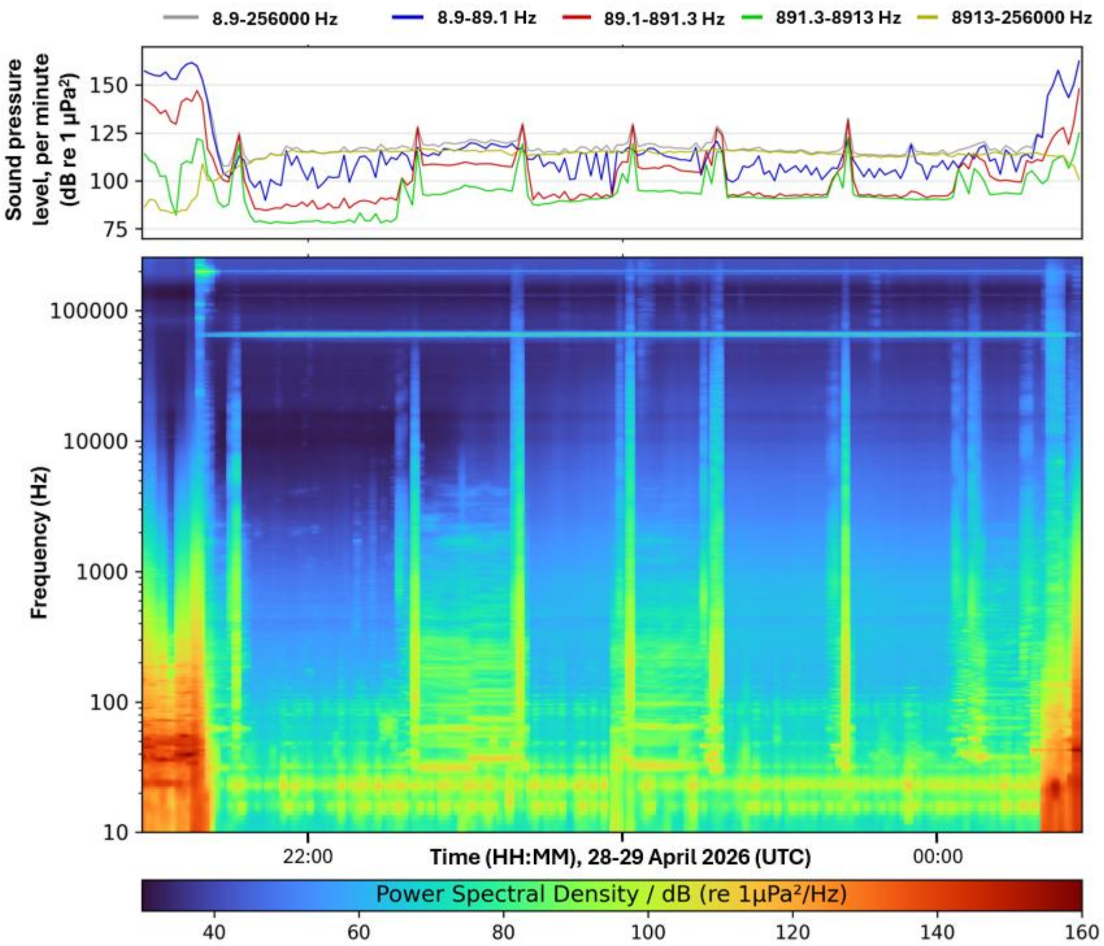


Figure 7. Netguard Pinger, static receiver: In-band sound pressure level (SPL) plot (top panel) and long-term spectral average (LTSA) spectrogram (bottom panel) of data recorded on the static receiver for the Netguard Pinger measurement. Raised levels at the start and end of the recording are related to deployment and retrieval activities, the ~6 broadband ‘spikes’ during the recording period are related to the study vessel manoeuvring for mobile measurements, and the horizontal line at ~63,000 Hz (bottom panel) is due to emissions from the Netguard Pingers.

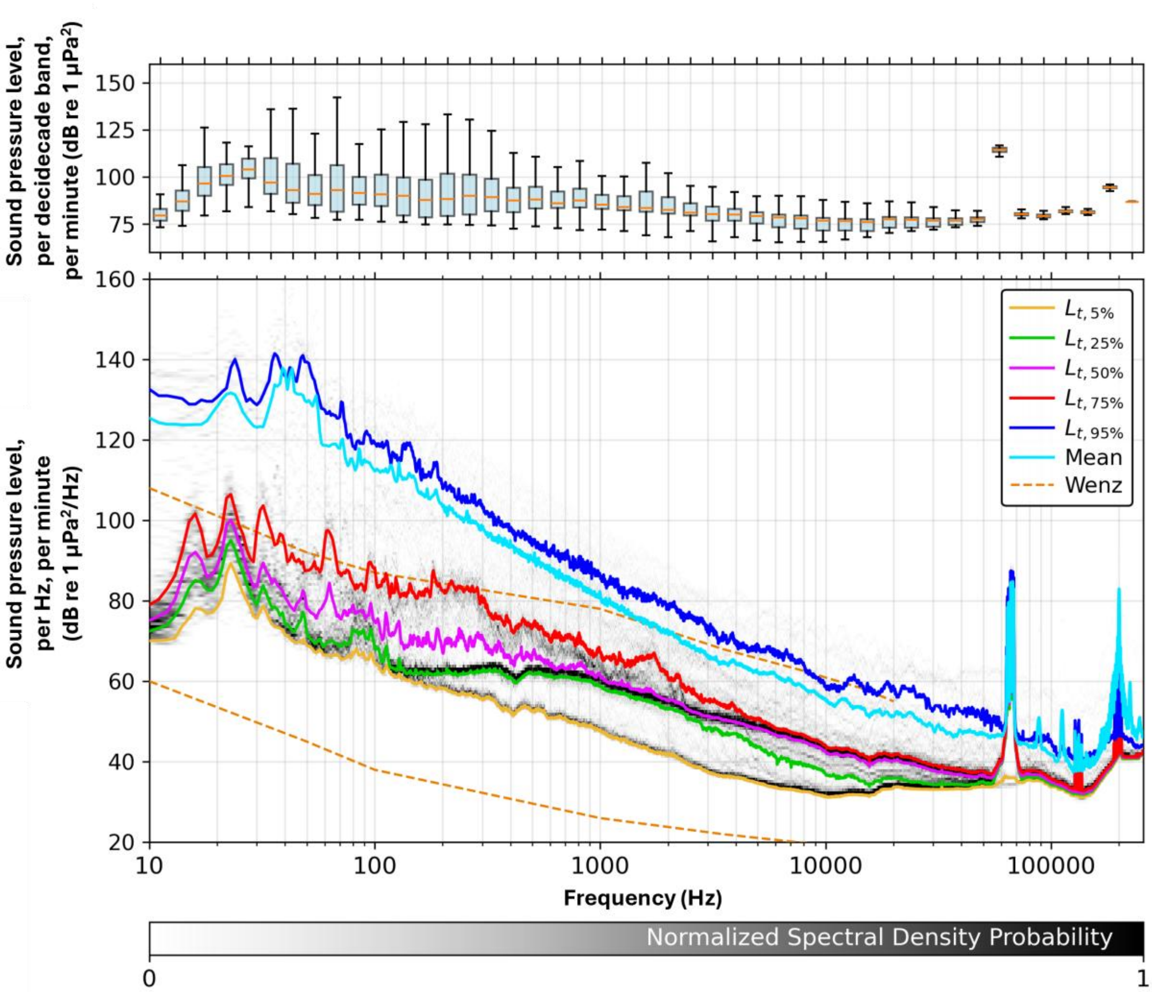


Figure 8. Netguard Pinger, static receiver: Percentiles and mean of decidecade band sound pressure level (SPL) (top panel) and percentiles and probability density (grayscale) of 1 min power spectral density levels (bottom panel) compared to the limits of prevailing noise (Wenz 1962) for data recorded on the static receiver for the Netguard Pinger measurement. The raised sound pressure level at ~63,000 Hz is due to emissions from the Netguard Pingers, with harmonics of the emissions evident at ~130,000 and ~200,000 Hz.

Figures 9 to 12 display some examples of the data recorded at the static receiver. Figure 9 shows a waveform (upper) and spectrogram (lower) for 30 seconds of data around 22:00 (UTC), towards the beginning of the deployment period. From the measurement and modelling study (Warren et al. 2025), it is known that the Netguard Pingers emit sound every 3.975 seconds. Therefore, with this known spacing between emissions from each device, it is possible to ascertain that at least three Pingers could be heard from the static receiver location. Indeed, the collections of three ‘pings’ that are evident in Figure 9 feature greatest pressure associated with the central ‘ping’, and this is assumed to be Pinger 3 situated 33 m from the static receiver. The other two ‘pings’ in each triplet are assumed to be from Pingers 2 and 4, which were 62 and 57 m from the static receiver, respectively. It does not seem that Pinger 1 (which was >100 m from the static receiver) was detectable at the static receiver, but it is possible that lower received level emissions from Pinger 1 could be present in the data, but masked by the other, closer devices. Netguard Pingers activate when they make contact with water, therefore the start time was influenced by the deployment of the length of the set net, and the emission timings were not synchronised.

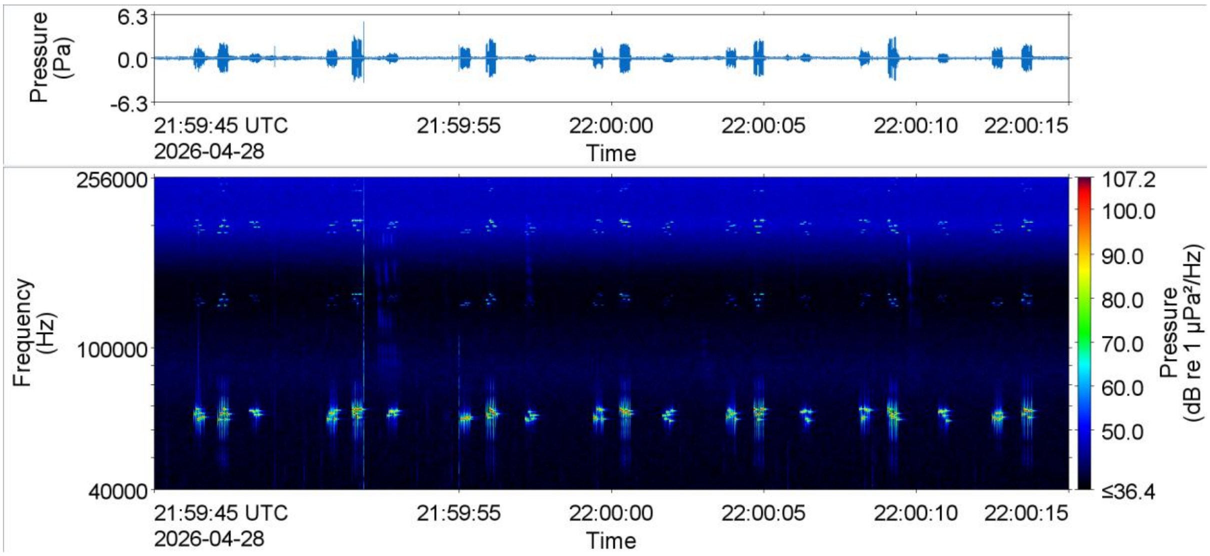


Figure 9. Netguard Pinger, static receiver: 30 second waveform (top) and spectrogram (bottom) showing Netguard Pinger emissions recorded towards the beginning of the deployment (around 22:00, UTC). The emissions from at least 3 Netguard Pingers are evident, with 4 seconds gap between emissions from each device. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

One minute prior to the recording period in Figure 9, the emissions from the Netguard Pingers were received differently, with overlap occurring so emissions from at least one Pinger was masked by another (Figure 10). The received emissions appeared as doublets rather than triplets. Throughout the recording period, the temporal separation of the received device emissions drifted; Figure 11 shows an example of data from towards the end of the deployment period. It is assumed that the drift is a result of propagation effects subtly changing over time, rather than drift within the timing of Pinger emissions, which did not notably vary when measured (Warren et al. 2025).

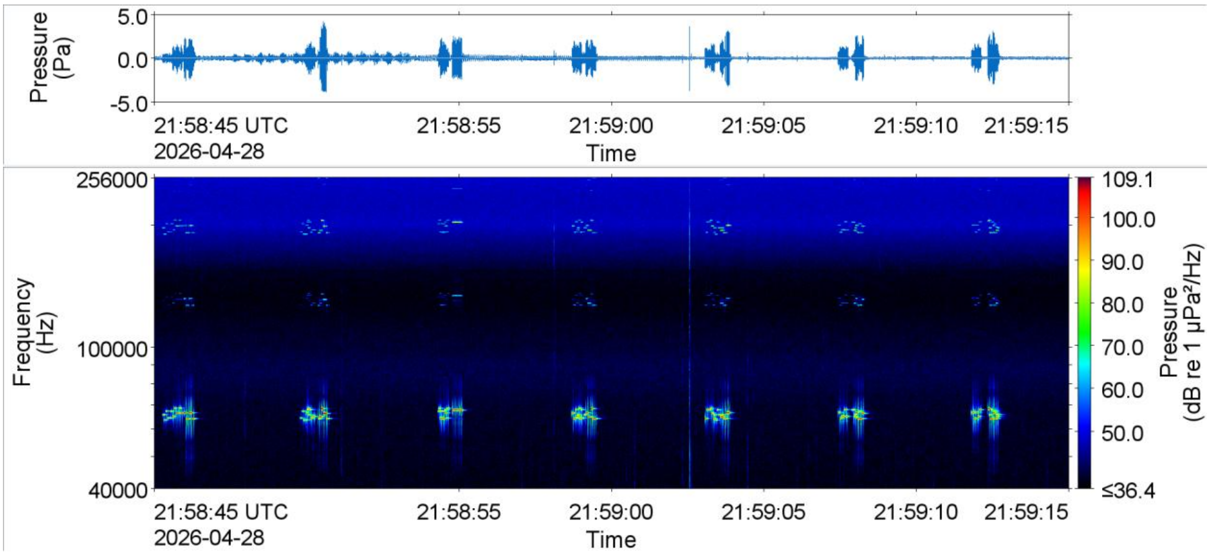


Figure 10. Netguard Pinger, static receiver: 30 second waveform (top) and spectrogram (bottom) showing Netguard Pinger emissions recorded one minute prior to Figure 9. The emissions from at least 2 Netguard Pingers are evident, with 4 seconds gap between emissions from each device. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

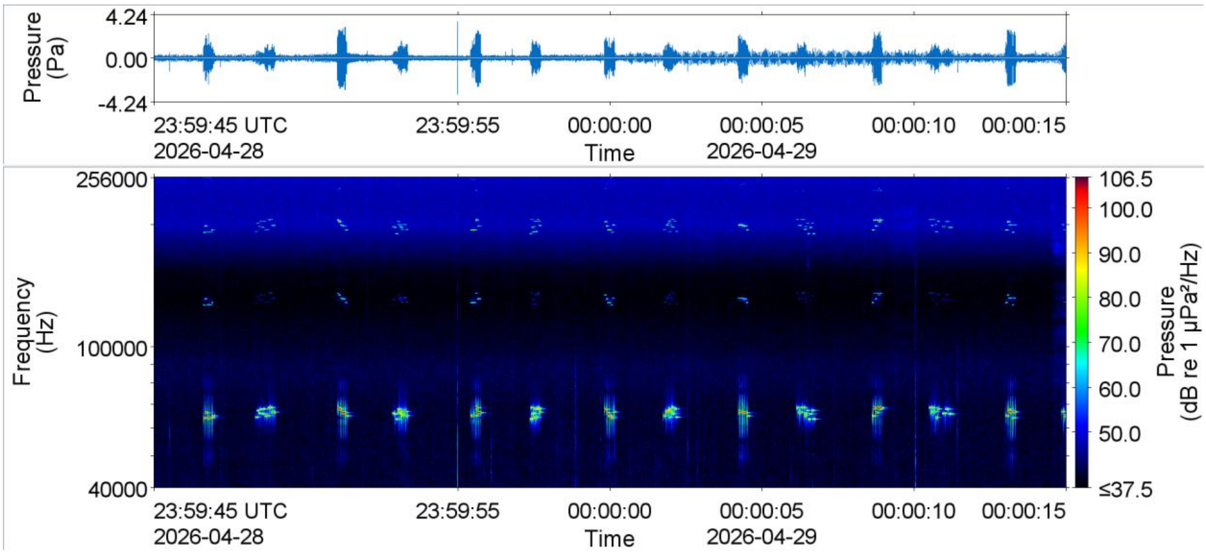


Figure 11. Netguard Pinger, static receiver: 30 second waveform (top) and spectrogram (bottom) showing Netguard Pinger emissions recorded towards the end of the deployment (around 00:00, UTC). The emissions from at least 2 Netguard Pingers are evident, with 4 seconds gap between emissions from each device. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

As seen in Figure 7, five or six 'spikes' in lower frequency energy occurred during the period that the static receiver was deployed, and these were associated with movement of the vessel undertaking mobile measurements. Figure 12 shows an example of such vessel noise, highlighting that the vessel emissions primarily occurred at lower frequencies than the Netguard Pinger emissions.

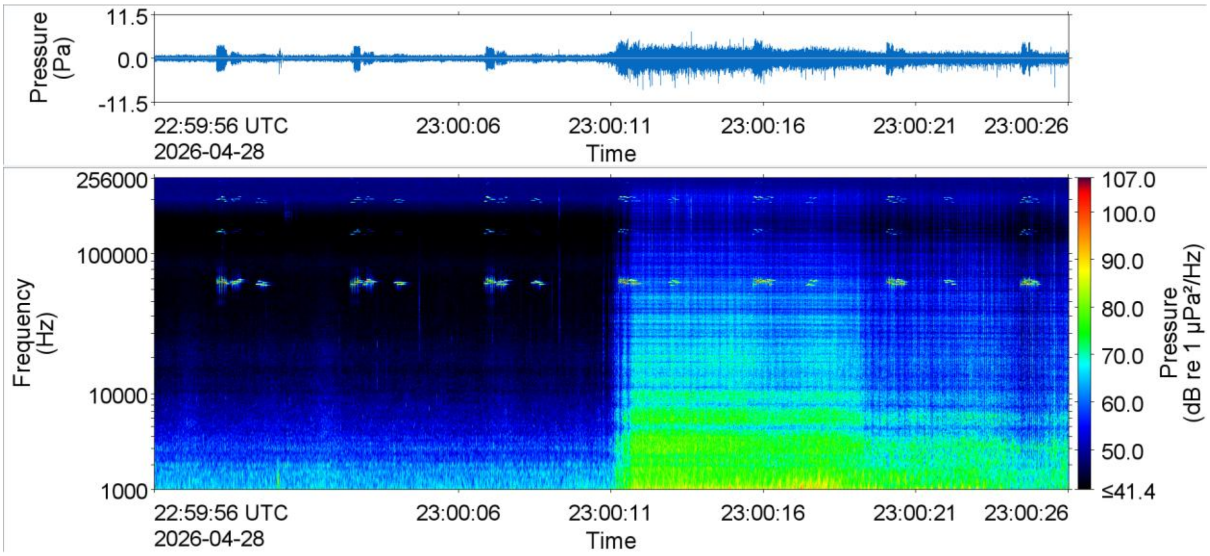


Figure 12. Netguard Pinger, static receiver: 30 second waveform (top) and spectrogram (bottom) showing Netguard Pinger emissions, with vessel noise associated with the mobile measurements evident from 23:00:11. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

Analysis for the Netguard Pinger measurements focused on the 63 kHz-centred decidecade band, as this is the primary frequency of sound emitted by these devices (Warren et al. 2025). Figure 13 shows the band level (SPL, 1 second) for a 30 second subset of the recording period (the same period as shown in Figure 9). The 30 second subset of data shows the peaks associated with Netguard Pinger emissions against the ambient background level troughs (< 80 dB re 1 µPa).

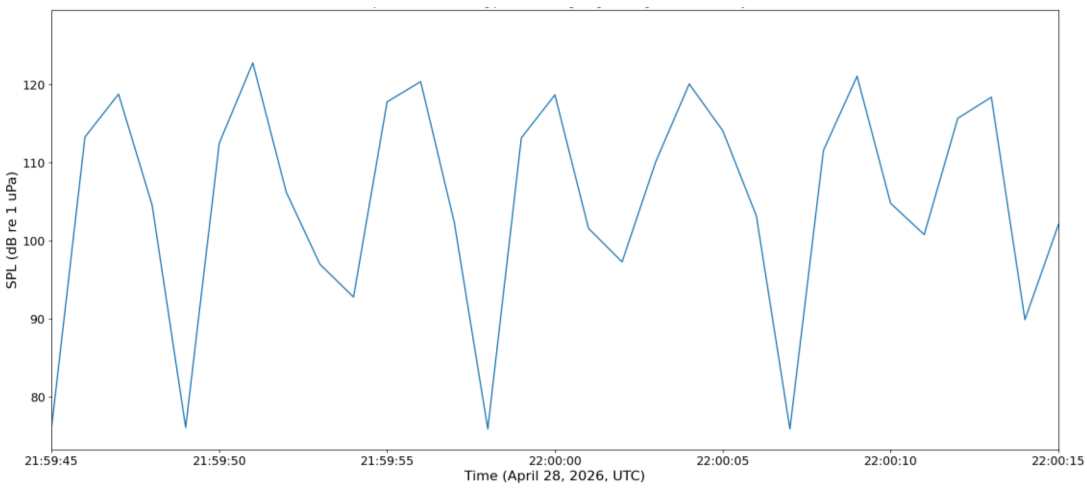


Figure 13. Netguard Pinger, static receiver: Sound pressure level (SPL) in the 63 kHz-centred decidecade band for a 30 second subset of the data (the same period as shown in Figure 9) showing peaks in SPL every ~4 seconds due to Netguard Pinger emissions.

Table 4 provides received level information for the 63 kHz-centred decidecade band for the deployment of the static receiver (trimmed to remove deployment and retrieval noise from start and end). Received level is presented as the absolute minimum level, the average level, the absolute maximum level, and the average maximum level (the average height of all peaks).

Table 4. Netguard Pinger, static receiver: received level results

Frequency range (centred of decidecade band)	Minimum Received Level (SPL, dB re 1 µPa)	Average Received Level (SPL, dB re 1 µPa)	Maximum Received Level (SPL, dB re 1 µPa)	Average Maximum Received Level (SPL, dB re 1 µPa)
63 kHz	75.8	114.7	127.0	120.5

3.1.1.2. Mobile Receiver

The OSM2 dipped measurements were made in the presence of strong current, despite otherwise calm conditions. Accordingly, it was not possible to undertake the planned 5-minute dip durations at a static location (given that the vessel engine was switched off to avoid excess noise, and could therefore not hold station). Nonetheless, the mobile measurement dips proceeded, but careful notes and GPS positions were taken with regard to the measurement locations. Dip durations were shortened in the field or split in post-processing across more than one average distance where necessary as a result of significant drift from the intended site.

It should also be noted that the acoustic device locations were marked with surface buoys, which were also affected by drift within the relatively short amount of slack in the line. Measured distances are accurate to the device locations as recorded via GPS points.

Table 5 summarises the 63 kHz-centred decidecade frequency band results from the mobile measurements across the three dip depths (2, 20 and 38 m) and across different distances from the closest Netguard Pinger. The rows associated with each dip depth are ordered by average horizontal distance (closest to furthest) and the associated SPL levels are shaded as coloured bins, with the darkest colours indicative of the highest received levels. In general, the average received levels showed minimal correlation with the horizontal distance to the closest Netguard Pinger, which is expected as the average level also captures ambient noise between Pinger emissions. However, the maximum received level, and to a lesser extent, the average maximum received level, were higher at closer distances to the nearest Netguard Pinger.

Table 5. Netguard Pinger, mobile receiver: OSM2 dip depth, duration, and horizontal and slant distances to closest Netguard Pinger and received level results (SPL) for the 63 kHz centred decidecade frequency band. SPL levels are shaded in four shades of grey based on their value from light to dark (≤115 dB, 115-120 dB, 120-125 dB, ≥125dB), and rows are ordered by horizontal distance to closest Netguard Pinger.

Average horizontal distance to closest Pinger + range (m)	Average slant distance to closest Pinger (m)	Dip duration (mins:secs)	Average Received Level (SPL, dB re 1 µPa)	Maximum Received Level (SPL, dB re 1 µPa)	Average Maximum Received Level (SPL, dB re 1 µPa)
2 m dip depth					
10 (2.4 - 17.7)	37.0	05:00	119.0	125.1	121.3
43.8 (38.8 - 48.9)	56.5	01:55	115.4	121.3	118.4
54 (48.9 - 59)	64.7	01:55	114.1	120.6	117.7
59 (51.1 - 66.9)	69.0	00:19	113.9	119.1	117.1
60.7 (65.9 - 55.6)	70.4	02:23	114.9	119.7	116.7
64.9 (59.8 - 70)	74.0	01:14	112.2	116.8	114.1
71.1 (76.3 - 65.9)	79.5	02:25	115.8	121.5	117.8
104 (98.5 - 109.5)	110.0	05:12	110.4	114.3	112.2
20 m dip depth					
16.6 (22.8 - 10.4)	24.2	04:10	122.4	129.6	126.6
127.2 (122.3 - 132.1)	128.4	05:56	110.4	112.1	111.0
38 m dip depth					
19.8 (11 - 28.5)	19.8	05:00	120.1	126.5	122.4
31.4 (34.7 - 28.1)	31.4	05:00	116.5	123.9	119.8
32.7 (27.1 - 38.3)	32.7	02:41	118.8	126.8	123.2
43.9 (38.3 - 49.5)	43.9	02:40	119.3	128.7	122.6
51.8 (58.5 - 45.1)	51.8	01:39	117.1	123.4	121.0
55.1 (49.5 - 60.7)	55.1	02:41	118.3	126.6	121.5
65.1 (71.8 - 58.5)	65.1	01:40	116.5	123.0	120.1
100.9 (90.2 - 111.6)	100.9	01:46	115.0	122.1	118.5
122.3 (111.6 - 133)	122.3	01:46	113.3	119.1	116.8
122.8 (109.1 - 136.5)	122.8	01:48	117.3	120.4	118.5
151.9 (138 - 165.8)	151.9	04:00	111.5	112.9	111.9
153.1 (148.9 - 157.4)	153.1	00:37	111.7	115.6	113.7

Figures 14 and 15 summarise the maximum and average maximum SPL measurements in the 63 kHz-centred decidecade frequency band for each measurement dip against the respective GPS track points of the measurements. The mobile measurements from all three dip depths (2, 20 and 38 m) are included in the figures together. Both figures confirm that the greatest sound pressures were recorded close to the acoustic devices, with decreasing levels recorded at further distances. This aids in confirming that the intended sound sources (the Netguard Pingers) were driving the value of the 63 kHz-centred decidecade frequency band, and external sound sources did not unduly influence the results.

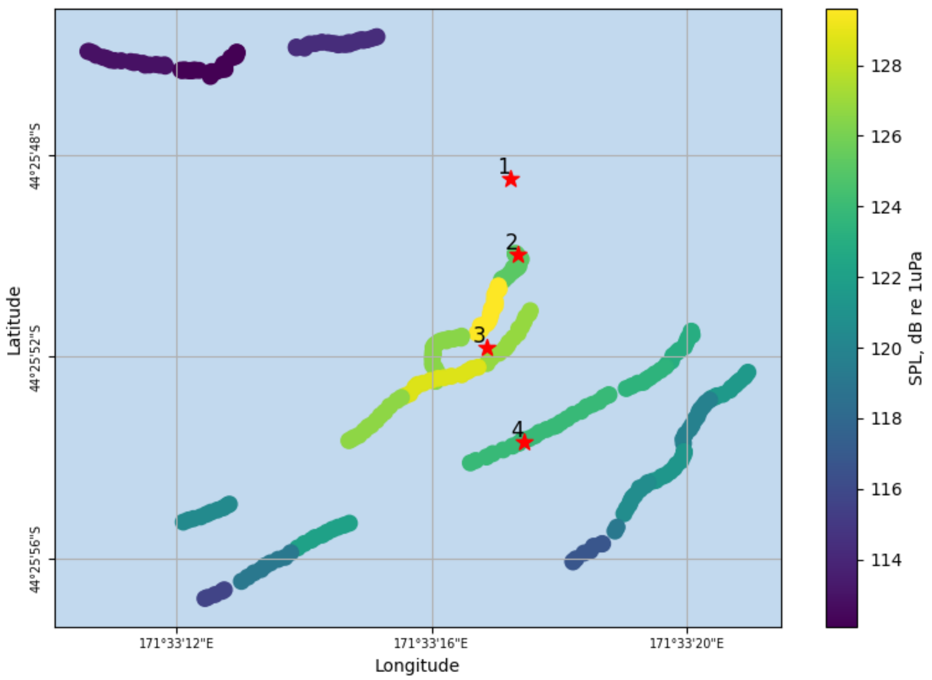


Figure 14. Netguard Pinger, mobile receiver: GPS track points associated with the mobile measurements, coloured by the maximum 1-second sound pressure level (SPL) in the 63 kHz-centred decidecade band for each measurement dip. All dip depths are included.

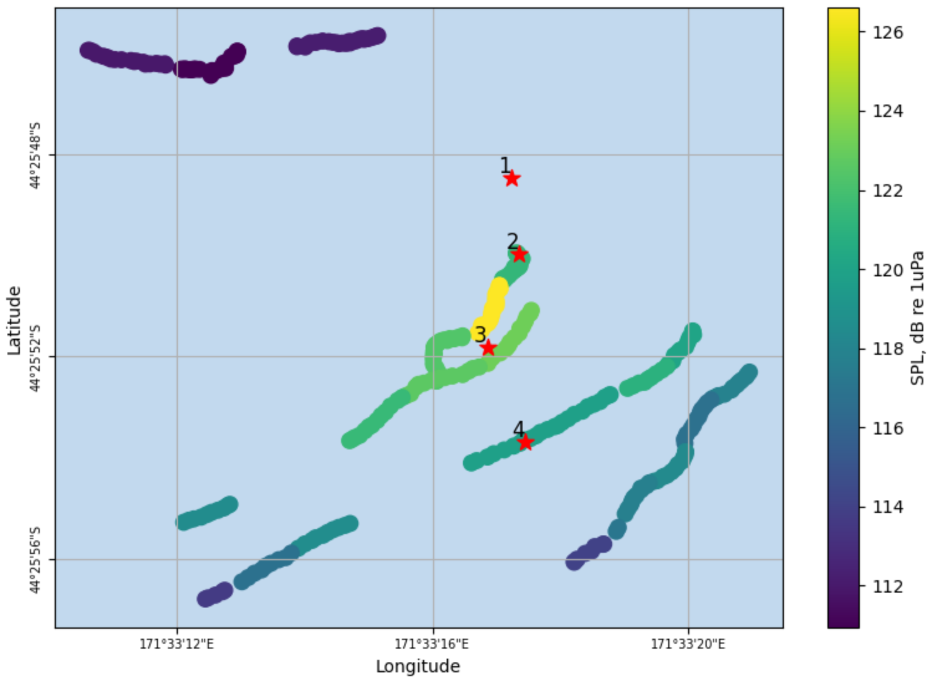


Figure 15. Netguard Pinger, mobile receiver: GPS track points associated with the mobile measurements, coloured by the average maximum 1-second sound pressure level (SPL) in the 63 kHz-centred decidecade band for each measurement dip. All dip depths are included.

3.1.2. Results Summary and Comparison to Modelled Results

Figures 16 and 17 display the at-sea measured levels from the static and mobile receivers (as per Tables 4 and 5) as a function of horizontal distance. Figure 16 presents the maximum received SPL in the 63 kHz-centred decidecade frequency band from each respective recording period, while Figure 17 presents the average maximum SPL in the 63 kHz-centred decidecade frequency band from each recording period.

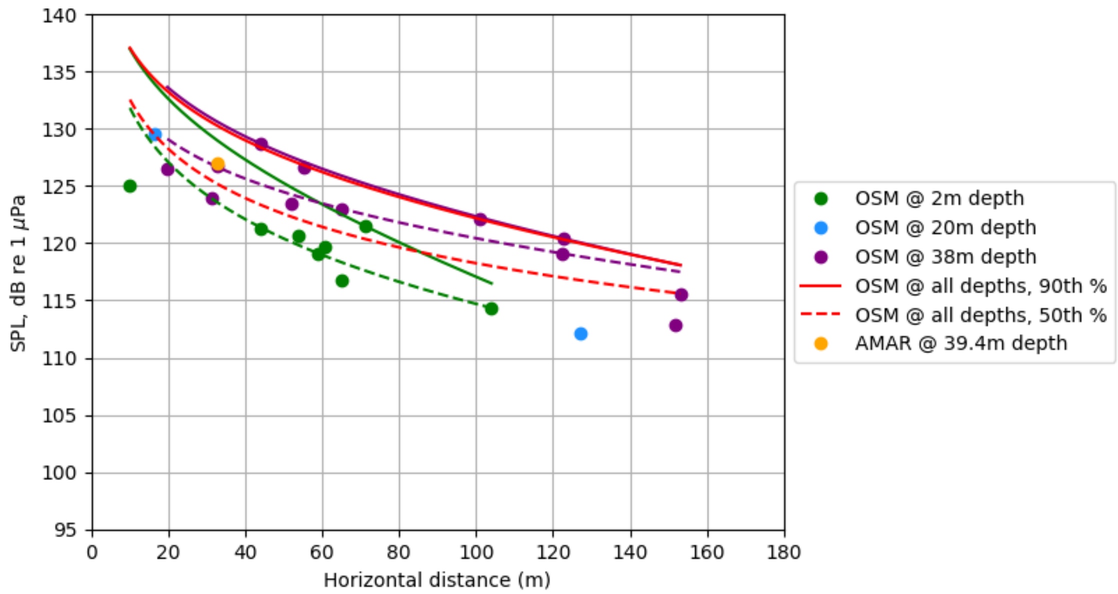


Figure 16. Maximum received SPL levels in the 63 kHz-centred decidecade frequency band for the Netguard Pinger at-sea trials. Lines of best fit show the 90th percentile of data (solid) and the 50th percentile of data (dashed) per dip depth, and across all dip depths. There are no lines of best fit for the OSM dip depth of 20 m due to only two data points.

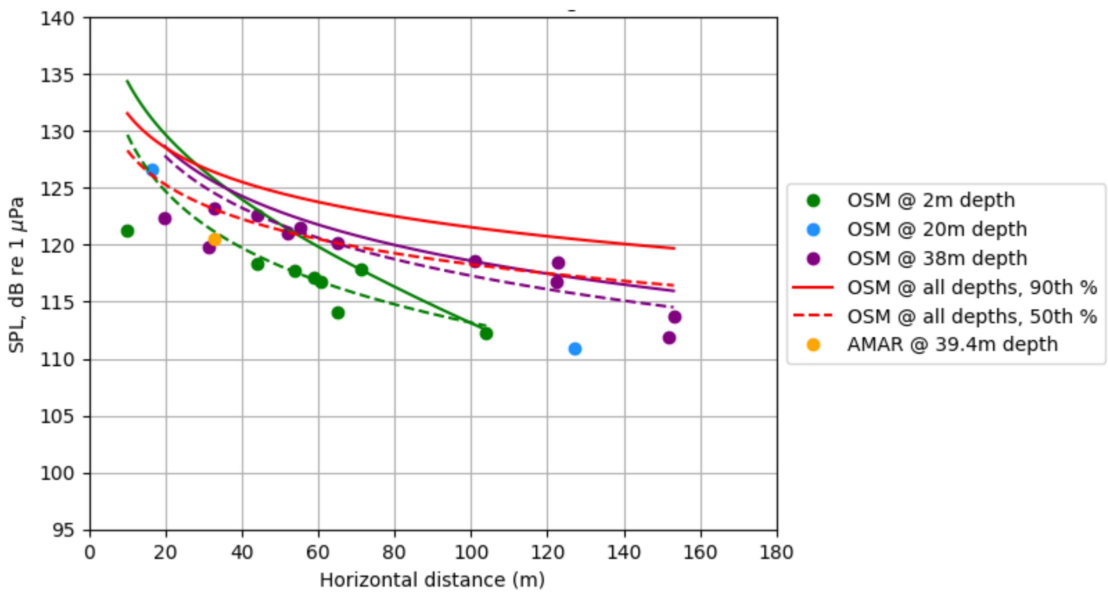


Figure 17. Average maximum received SPL levels in the 63 kHz-centred decidecade frequency band for the Netguard Pinger at-sea trials. Lines of best fit show the 90th percentile of data (solid) and the 50th percentile of data (dashed) per dip depth, and across all dip depths. There are no lines of best fit for the OSM dip depth of 20 m due to only two data points.

Compared to the measurement trials, the most similar single device modelling scenario in the study by Warren et al. (2025) considered 50 m water depth, sand seabed, sea state 0, and with the device mounted near the seafloor (as opposed to near the sea surface). The modelling considered a median source level of 142.1 dB re 1 μPa^{2}m^2 for the Netguard Pingers. The SPL results from the modelled scenario are presented in Table 6. As the modelling environment considered a perfectly flat seabed, the modelled ensonified areas were perfectly symmetrical circles.

Table 6. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to exceedance of the given sound pressure level (SPL) within the single-device modelling for the Netguard Pinger in 50 m water depth.

SPL (L_p; dB re 1 μPa)	Maximum distance to exceedance of SPL value within the single-device modelling, based on median source level
130	–
120[a]	15
110	47
100	163

[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).

Figure 18 shows a plot of the modelled results (Table 6) for comparison against the at-sea measurement results for this study. The at-sea measurement results have been adjusted to represent the median source level of the Netguard Pingers (-5.7 dB from maximum levels, refer to Section 2.3.3).

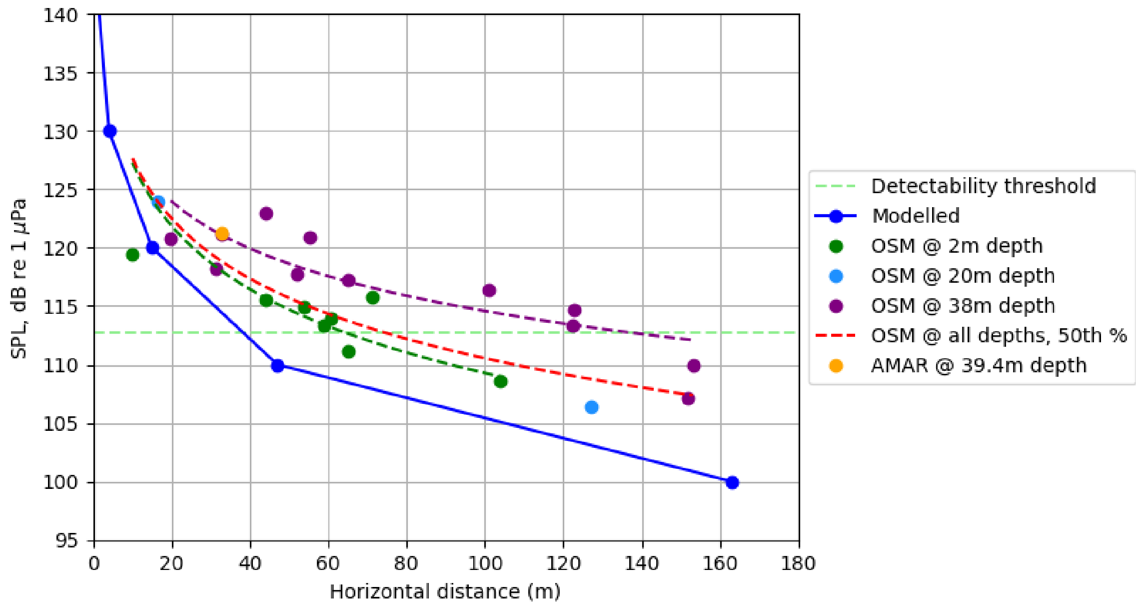


Figure 18. Median-adjusted received SPL levels in the 63 kHz-centred decidecade frequency band for the Netguard Pinger at-sea trials, along with equivalent modelled results for the most similar single-device modelled scenario, in addition to the Hector's and Māui dolphin detectability threshold of 112.8 dB. Lines of best fit show the 50th percentile of data (dashed) per dip depth, and across all dip depths. There are no lines of best fit for the OSM dip depth of 20 m due to only two data points.

The modelled results presented a 'maximum-over-depth' value, which means that within a given radial distance, the relevant received SPL value was exceeded at at least one depth point within the water column. In the real-world measurements, the OSM2 was dipped at varying water depths, and therefore the slant range between the OSM2 and the closest Pinger can be markedly different to the horizontal range (refer to Table 5). Therefore, Figures 16 to 18 must be considered with this in mind. Dips obtained at 38 m depth, and the static receiver at 39.4 m depth, were most similar in depth to the

Pingers, and therefore the horizontal and slant ranges are almost identical; these measurements revealed the highest received levels at any given horizontal distance. Conversely, the dips made at 2 m depth featured the longest slant ranges and therefore revealed lower received levels at any given horizontal distance.

Figure 18 reveals that in during the measurements made during the at-sea trials for the Netguard Pingers, the received sound levels of Pinger emissions were higher than predicted by the modelling at all horizontal distances, except at the closest horizontal distance, which was measured with a 2 m dip depth and was therefore strongly influenced by the slant distance to the closest Pinger (Table 5).

The most similar single device modelling scenario featured water depths 10 m deeper than the measurement trials were conducted in, and in the modelling study deeper waters featured smaller propagation ranges, so it is unsurprising that the measurements obtained in this study have slightly louder received levels at each horizontal distance. Nonetheless, the real-world underwater environment does seem to be more conducive to sound propagation than the environment applied within the modelling, with higher received levels recorded at all horizontal distances than were predicted by the modelling (Figure 18).

The study by Warren et al. (2025) calculated that the median source level of the Netguard Pingers would be audible to Hector's and Māui dolphins at received SPL values of 112.8 dB re 1 µPa and at distances of up to 30 m in the modelled environment with the shortest propagation distance and up to 60 m in the modelled environment with the longest propagation distance. In this measurement study, a received level of 112.8 dB re 1 µPa was exceeded to a horizontal distance of approximately 60 to 120 m based on the 50th percentile curve fits to the measured levels (Figure 18).

Table 7 presents the calculated sound exposure levels (SELs) for three accumulation periods (10 minutes, 1 hour, and 24 hours) based on the methods outlined in Section 2.3.3. Both median and maximum source levels for the Netguard Pingers are considered. The PTS/Auditory Injury criteria for very high-frequency cetaceans (181 dB re 1 µPa^2·s, Accomando et al. (2025)) was not exceeded at any distance or for any of the three accumulation periods. The TTS criteria for very high-frequency cetaceans (161 dB re 1 µPa^2·s, Accomando et al. (2025)) was exceeded at maximum distances of approximately 10 to 40 metres within the 24 hour accumulation period.

Table 7. Netguard Pinger, sound exposure level (SEL): Estimates for sound exposure levels at a range of horizontal distances, based on the median and maximum source levels and the 50th percentile curves of the OSM2 measurements obtained across all depths (Figures 18 and 16, respectively). Grey shaded cells indicate exceedances of the TTS criteria for very high-frequency cetaceans (161 dB re 1 µPa^2·s, Accomando et al. (2025)). The PTS/AUD INJ criteria for very high-frequency cetaceans (181 dB re 1 µPa^2·s, Accomando et al. (2025)) was not exceeded.

Horizontal distance (m)	Assessment based on median source level				Assessment based on maximum source level			
	Received Level (SPL, dB re 1 µPa)	Weighted SEL (dB re 1 µPa^2·s) over 10 minutes	Weighted SEL (dB re 1 µPa^2·s) over 1 hour	Weighted SEL (dB re 1 µPa^2·s) over 24 hours	Received Level (SPL, dB re 1 µPa)	Weighted SEL (dB re 1 µPa^2·s) over 10 minutes	Weighted SEL (dB re 1 µPa^2·s) over 1 hour	Weighted SEL (dB re 1 µPa^2·s) over 24 hours
5	131.1	146.3	154.0	167.9	136.8	152.0	159.7	173.6
10	126.8	142.0	149.7	163.5	132.5	147.7	155.4	169.2
20	122.5	137.7	145.4	159.2	128.2	143.4	151.1	164.9
40	118.2	133.4	141.1	154.9	123.9	139.1	146.8	160.6
60	115.7	130.8	138.6	152.4	121.4	136.5	144.3	158.1
80	113.9	129.1	136.8	150.6	119.6	134.8	142.5	156.3
100	112.5	127.7	135.4	149.2	118.2	133.4	141.1	154.9
150	110.0	125.1	132.9	146.7	115.7	130.8	138.6	152.4
200	108.2	123.4	131.1	144.9	113.9	129.1	136.8	150.6
250	106.9	122.0	129.8	143.6	112.6	127.7	135.5	149.3

As mentioned, the most similar single device modelling scenario in the study by Warren et al. (2025) considered 50 m water depth, sand seabed, sea state 0, and with the device mounted near the seafloor (as opposed to near the sea surface). The model considered only the median source level for the Netguard Pingers. Within the modelled scenario, the very high-frequency cetacean PTS/AUD INJ criteria was not exceeded for any of the three accumulation periods. The very high-frequency cetacean TTS criteria was exceeded within 7 m within the 24-hour accumulation period. The median-adjusted results presented here suggest that the range to the 24-hour accumulation threshold for TTS was slightly longer in the real-world environment (Table 7), but confirmed that TTS would not be expected to occur within the 10 minute or 1 hour accumulation periods, and PTS/AUD INJ would not occur over any of the accumulation periods.

3.2. STM DDD

3.2.1. Measurement Results

3.2.1.1. Static Receiver

The static AMAR recorder was situated closest to DDD 1 (Table 8, Figure 6). The water depth at the study site was 27 m, and the hydrophone was mounted approximately 60 cm above the seabed on a baseplate mooring (Section 2.2.1). The STM DDDs were mounted at 3 m above the seabed, therefore the hydrophone was located approximately 2.4 m lower in the water column than the DDDs.

Table 8. STM DDD, static receiver: AMAR depth and distance to each STM DDD

Water depth (m)	Hydrophone depth (m)	Horizontal distance from DDD 1 (m)	Horizontal distance from DDD 2 (m)
27	26.4	40	85

Figure 19 presents the full data period recorded by the static receiver as a band-level plot (top panel) and a long-term spectral average (LTSA) spectrogram (bottom panel). Both panels provide an overview of the sound variability in time and frequency, as well as the presence and level of contributions from different sources. Short-term events appear as vertical stripes on the spectrogram and spikes on the band level plots. Long-term events appear in the spectrograms as horizontal bands of colour. Raised levels at the start and end of the recording are related to deployment and retrieval activities. A passing vessel is evident at frequencies below 3000 Hz from the beginning of the deployment until approximately 21:40 (UTC) (bottom panel). The ~7 broadband 'spikes' up to 10 kHz during the recording period are related to the study vessel manoeuvring for mobile measurements. Horizontal lines above ~6 kHz (bottom panel) are due to emissions from the STM DDDs. Other than these notable features, the ambient noise environment is generally quiet.

Overall, the ambient noise environment across all frequency bands remained approximately consistent across the measurement period (Figure 19, top panel), besides the features mentioned above. There were no notable trends in level across the recording, such as might be caused by tidal movement or the arrival of another sound source (biological, geological or anthropogenic).

Figure 20 presents the full data period recorded by the static receiver as a percentile figure showing box-and-whisker plots by decidecade frequency band (top panel) and power spectral density (PSD) by percentile (bottom panel) across the whole recording period. In both panels, the raised sound pressure levels above ~6 kHz are due to emissions from the STM DDDs.

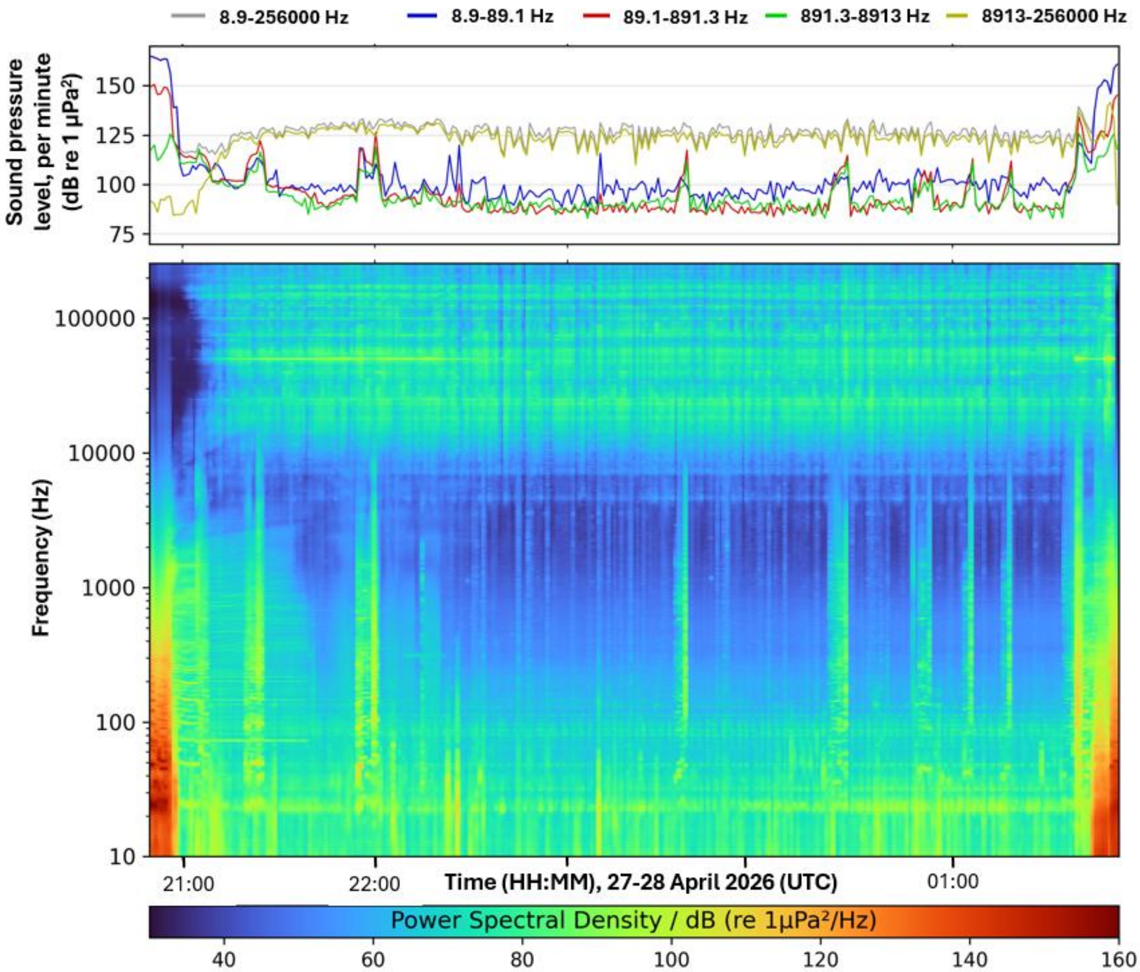


Figure 19. STM DDD, static receiver: In-band sound pressure level (SPL) plot (top panel) and long-term spectral average (LTSA) spectrogram (bottom panel) of data recorded on the static receiver for the STM DDD measurement. High energy at the start and end of the recording are related to deployment and retrieval activities. A passing vessel is evident at frequencies below 3000 Hz from the beginning of the deployment until approximately 21:40 (UTC) (bottom panel). The ~7 broadband 'spikes' up to 10,000 Hz during the recording period are related to the study vessel manoeuvring for mobile measurements. Horizontal lines above ~6,000 Hz (bottom panel) are due to emissions from the STM DDDs.

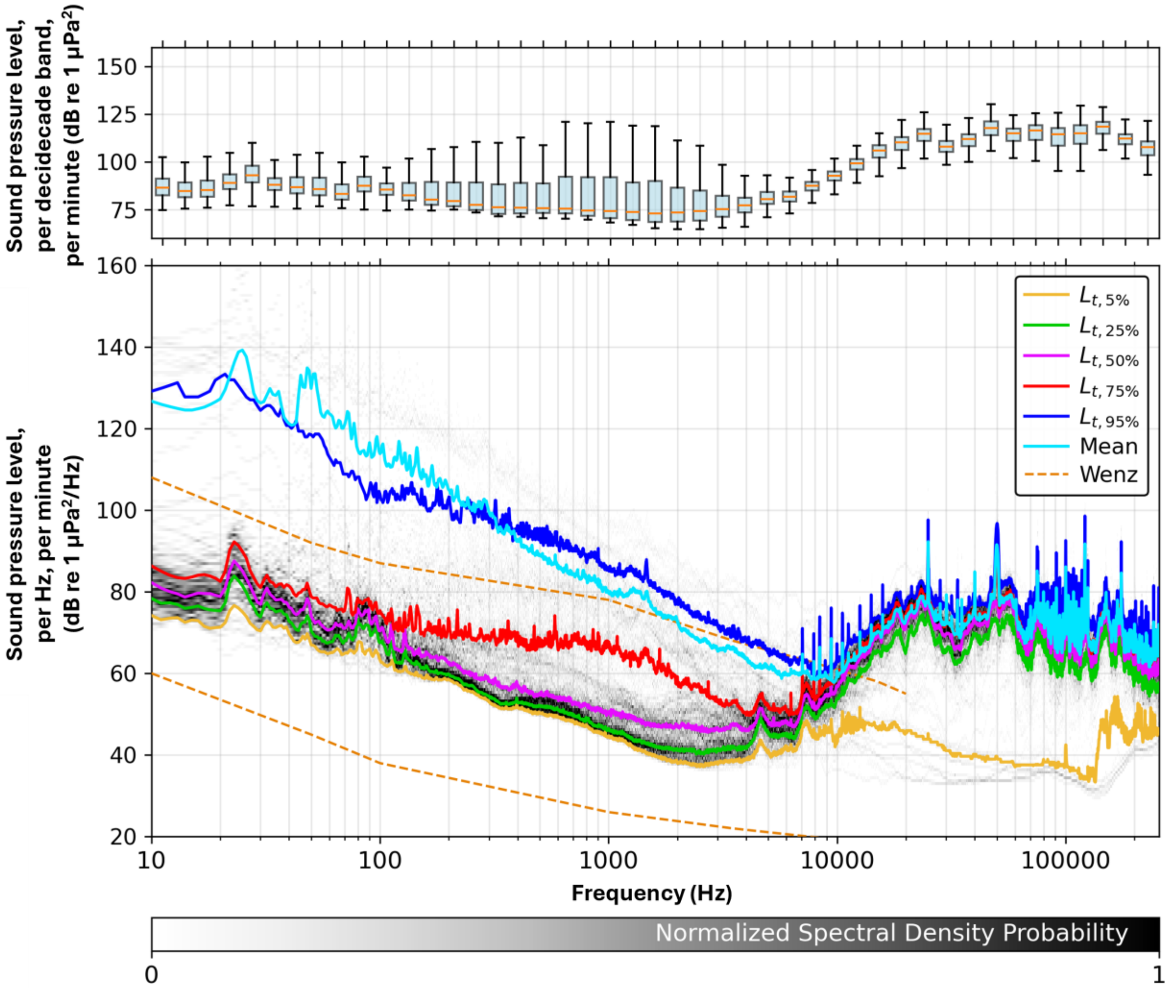


Figure 20. STM DDD, static receiver: Percentiles and mean of decidecade band sound pressure level (SPL) (top panel) and percentiles and probability density (grayscale) of 1 min power spectral density levels (bottom panel) compared to the limits of prevailing noise (Wenz 1962) for data recorded on the static receiver for the STM DDD measurement. Raised sound pressure levels above ~6,000 Hz are due to emissions from the STM DDDs.

The LTSA in Figure 19 reveals increased power spectral density levels around 50 kHz at the start of the recording period between 21:00 and 22:45 (UTC), and also at the end of the recording period from 01:40 (UTC). Figure 21 shows an example of data recording during the first of these two periods, and a broadband sound with greatest energy at 50 kHz is present, producing continuous ‘ticks’. The source of this sound is unknown, but is suspected to have either been produced inadvertently by the mobile vessel (the engine and echosounder of the vessel were switched off during measurements), or a malfunction of one of the STM DDDs. After 22:45 (UTC) the sound was no longer evident.

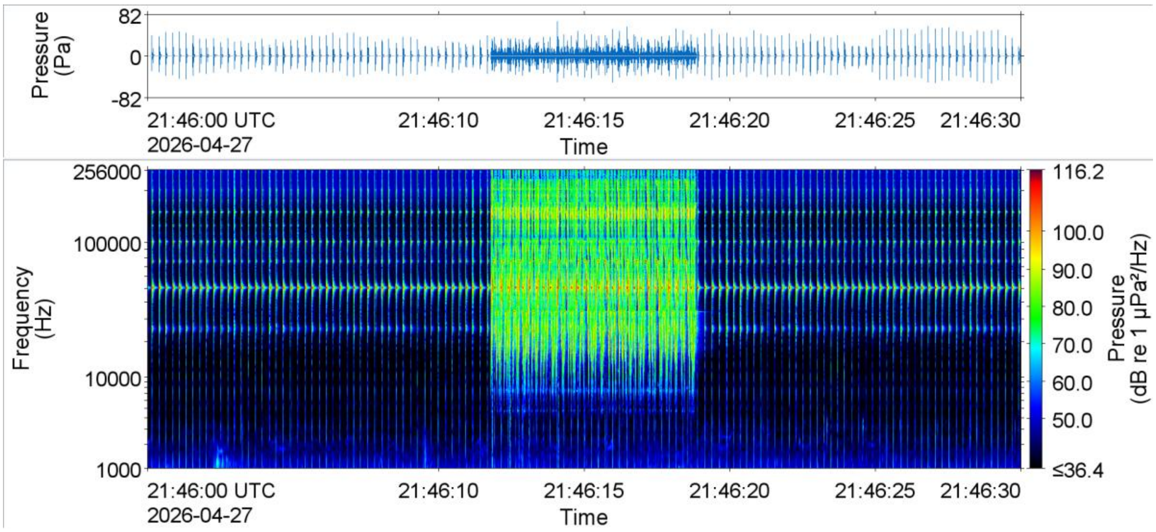


Figure 21. STM DDD, static receiver: 30 second waveform (top) and spectrogram (bottom) showing an STM DDD emission (21:46:12 to 21:46:19, UTC), along with an unidentified continuous 'ticking' sound. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

Figures 22 to 24 display some examples of the data recorded at the static receiver after 22:45 (UTC). All three figures show a waveform (upper) and spectrogram (lower) of recorded STM DDD emissions, with the two devices, located at 40 m and 85 m from the static receiver, producing emissions at random intervals. Due to variability in emission types and level, the device responsible for each emission is not always clear, but can be considered when each emission is viewed in context with others. Emissions from the closer device (40 m) were generally received with higher levels of pressure, and inclusive of energy at lower frequencies (below 10,000 Hz). However, there is frequency variation among emission types and the presence or absence of frequencies below 10,000 Hz may not be a reliable parameter. Temporal spacing of ~40 seconds between emissions from the same device can help to guide interpretation, but emissions are produced at random so this is also not a reliable indicator.

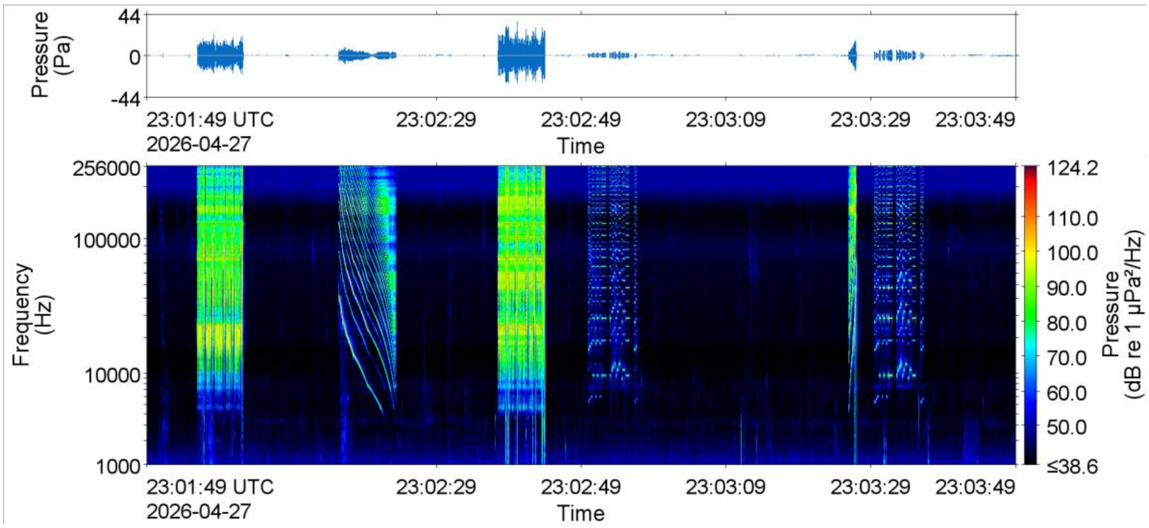


Figure 22. STM DDD, static receiver: 2 minute waveform (top) and spectrogram (bottom) showing six STM DDD emissions. It is assumed that emissions are evident from both STM DDDs (spaced at 40 and 85 m from the receiver) in this example. The 1st, 3rd and 5th emissions are assumed to have been produced by the closer device as they contain energy below 10,000 Hz, however it is not clear which device(s) emitted the 2nd, 4th and 6th emissions. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

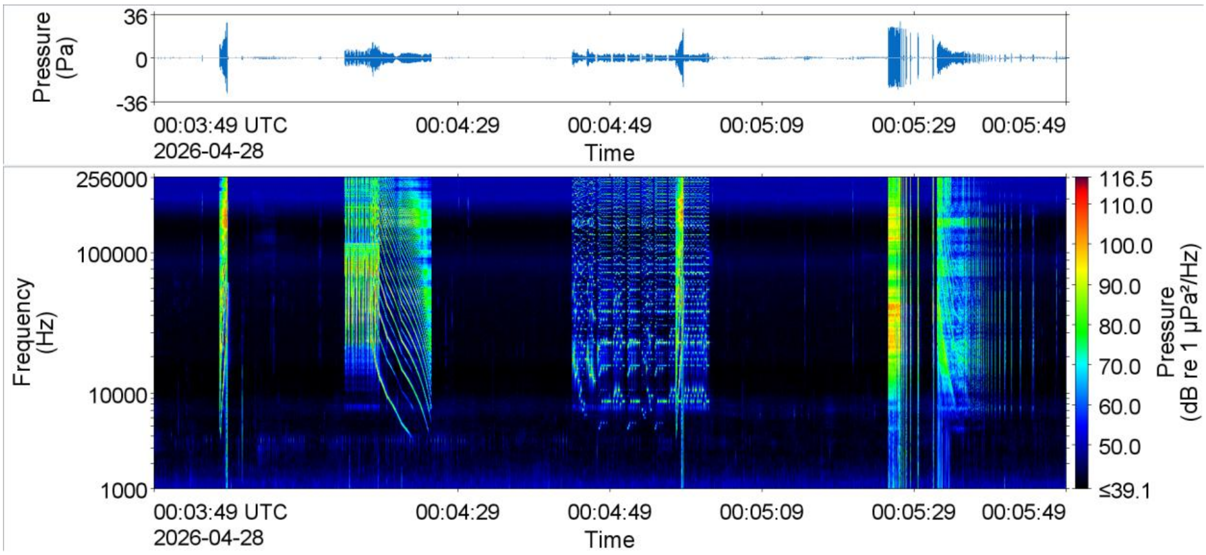


Figure 23. STM DDD, static receiver: 2 minute waveform (top) and spectrogram (bottom) showing seven overlapping STM DDD emissions. The first emission is assumed to have been produced by the closer DDD (40 m), while the second emission is likely from the further DDD (85 m) which overlaps in time with the next emission (down-sweeping) from the closer device. Similarly the fourth emission, presumed to be from the further DDD, is overlapped with a louder received level, presumed to be from the closer device. Emissions produced after 00:05:26 (UTC) are less clear, but are likely to be from the closer DDD followed by the further DDD. Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

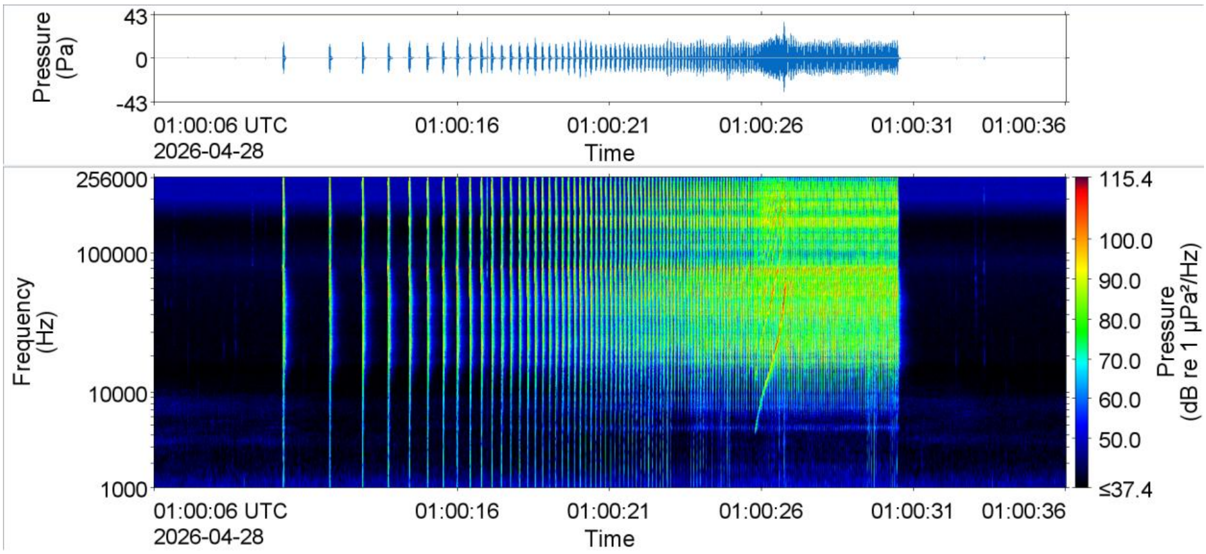


Figure 24. STM DDD, static receiver: 30 second waveform (top) and spectrogram (bottom) showing two overlapping STM DDD emissions (overlap is most apparent at 01:00:26). It is not clear which of the emissions was produced by the closer DDD (40 m) and which was produced by the further DDD (85 m). Spectrogram settings: 64 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hann window.

Analysis for the STM DDD measurements focused on the 25 kHz-centred decidecade band (Warren et al. 2025). Figure 25 shows the band level (SPL, 1 second) for a 2 minute subset of the recording period (the same period as shown in Figure 22). Figure 25 shows the peaks associated with emissions from both STM DDDs against the ambient background level troughs (< 80 dB re 1 μPa).

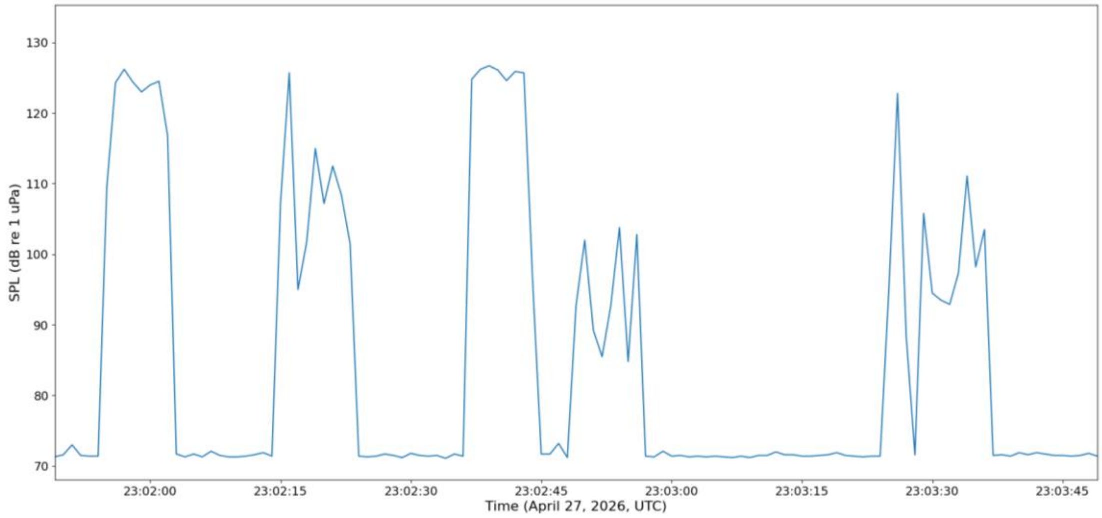


Figure 25. STM DDD, static receiver: Sound pressure level (SPL) in the 25 kHz-centred decidecade band for a 2 minute sub-set of the data (the same period as shown in Figure 22) showing peaks in SPL due to STM DDD emissions.

Table 9 provides received level information for the 25 kHz-centered decidecade band for the deployment period of the static receiver (trimmed to remove deployment and retrieval noise from start and end, as well as unidentified broadband noise until 22:45). Received level is presented as the absolute minimum level, the average level, the absolute maximum level, and the average maximum level (the average height of all peaks). The average maximum level is influenced by the height of peaks associated with different emission types and level differences related to the closer STM DDD (40 m distance) and the further STM DDD (85 m distance), and is therefore markedly lower than the absolute maximum received level.

Table 9. STM DDD, static receiver: received level results

Frequency range (centred of decidecade band)	Minimum Received Level (SPL, dB re 1 µPa)	Average Received Level (SPL, dB re 1 µPa)	Maximum Received Level (SPL, dB re 1 µPa)	Average Maximum Received Level (SPL, dB re 1 µPa)
25 kHz	71.1	116.6	132.3	123.2

3.2.1.2. Mobile Receiver

The OSM2 dipped measurements were made in the presence of strong current, despite otherwise calm conditions. Accordingly, it was not possible to undertake the planned 10-minute dip durations at a static location (given that the vessel engine was switched off to avoid excess noise, and could therefore not hold station). Nonetheless, the mobile measurement dips proceeded, but careful notes and GPS positions were taken with regard to the location of the beginning and end of each measurement. Dip durations were shortened or split across more than one average distance where necessary as a result of significant drift from the intended site.

It should also be noted that the acoustic device locations were marked with surface buoys, which were also affected by drift within the relatively short amount of slack in the line. Measured distances are accurate to the device locations as recorded via GPS points.

Table 10 summarises the 25 kHz-centred decidecade frequency band results from the mobile measurements across the three dip depths (2, 12.5 and 23 m) and across different distances from the closest STM DDD. The rows associated with each dip depth are ordered by average horizontal distance (closest to furthest) and the associated SPL levels are shaded as coloured bins, with the darkest colours indicative of the highest received levels. In general, the average received levels showed minimal correlation with the horizontal distance to the closest STM DDD, which is expected as the average level also captures ambient noise between DDD emissions. However, the maximum received level, and to a lesser extent, the average maximum received level, were higher at closer distances to the nearest STM DDD.

Table 10. STM DDD, mobile receiver: OSM2 dip depth, duration, and horizontal and slant distances to closest STM DDD and received level results (SPL) for the 25 kHz centred decidecade frequency band. SPL levels are shaded in four shades of grey based on their value from light to dark (≤110 dB, 110-120 dB, 120-130 dB, ≥130dB), and rows are ordered by horizontal distance to closest STM DDD.

Average horizontal distance to closest DDD + range (m)	Average slant distance to closest DDD (m)	Dip duration (mins:secs)	Average Received Level (SPL, dB re 1 µPa)	Maximum Received Level (SPL, dB re 1 µPa)	Average Maximum Received Level (SPL, dB re 1 µPa)
2 m dip depth					
21.1 (23.5 - 18.6)	30.4	03:25	123.1	130.4	124.8
26.0 (28.5 - 23.5)	34.0	03:26	122.3	130.7	123.9
28.4 (27.1 - 29.7)	35.9	10:47	116.8	133.1	119.1
55.6 (49.2 - 61.9)	59.8	03:24	103.9	118.0	112.0
68.2 (61.9 - 74.6)	71.7	03:22	101.9	112.0	107.0
158.3 (151.1 - 165.4)	159.8	05:50	107.3	121.1	116.3
179.3 (172.2 - 186.5)	180.7	08:44	107.3	121.0	114.3
204.0 (200 - 208.1)	205.2	03:53	102.3	115.6	109.5
341.9 (318.8 - 365)	342.6	09:10	100.3	113.8	107.4
431.2 (429 - 433.4)	431.7	04:02	96.6	111.5	106.5
450.8 (444.6 - 457.1)	451.4	05:31	97.6	110.6	106.6
12.5 m dip depth					
9.1 (12.4 - 5.8)	14.7	03:01	123.9	138.0	126.2
14.3 (9.7 - 19)	18.4	03:04	126.4	135.8	128.0
15.7 (19 - 12.4)	19.5	03:02	122.3	131.7	124.2
18.3 (21.1 - 15.4)	21.6	10:30	122.7	131.7	124.3
23.7 (19 - 28.3)	26.3	03:03	124.4	134.6	126.1
32.9 (28.3 - 37.5)	34.9	03:02	124.4	133.5	126.2
42.2 (37.5 - 46.8)	43.7	03:03	122.7	130.6	124.2
82.5 (75.7 - 89.3)	83.3	06:23	102.8	115.2	109.9
149.0 (146.2 - 151.8)	149.4	07:42	108.9	120.9	115.3
198.4 (191.5 - 205.3)	198.7	05:25	103.8	116.7	109.9
309.4 (310.9 - 307.9)	309.6	04:00	98.8	110.8	105.2
380.3 (369 - 391.5)	380.5	05:21	100.9	113.2	109.2
431.8 (424.9 - 438.8)	432.0	05:31	96.0	104.8	102.2
23 m dip depth					
18.0 (16.1 - 20)	18.1	10:58	124.6	137.0	126.6
59.9 (52.5 - 67.3)	59.9	02:35	124.4	127.0	127.0
93.1 (91.5 - 94.8)	93.1	05:37	104.8	117.3	112.0
132.2 (122.5 - 141.8)	132.2	05:54	108.6	120.1	114.1
211.7 (208.2 - 215.1)	211.7	03:16	100.2	110.4	105.3
217.7 (207.1 - 228.2)	217.7	06:54	105.9	120.8	111.8
307.9 (307.3 - 308.6)	307.9	03:09	97.7	108.6	104.2
399.2 (394.5 - 403.9)	399.2	05:19	99.6	115.2	108.1
412.8 (405.2 - 420.3)	412.8	05:31	97.6	107.2	104.1
428.9 (431.9 - 425.9)	428.9	03:24	94.8	102.2	101.7

Figures 26 and 27 summarise the maximum and average maximum SPL measurements in the 25 kHz-centred decidecade frequency band for each measurement dip against the respective GPS track points of the measurements. The mobile measurements from all three dip depths (2, 12.5 and 23 m) are included in the figures together. Both figures confirm that the greatest sound pressures were recorded close to the acoustic devices, with decreasing levels recorded at further distances. This aids in confirming that the intended sound sources (the STM DDDs) were driving the value of the 25 kHz-centred decidecade frequency band, and external sound sources did not unduly influence the results.

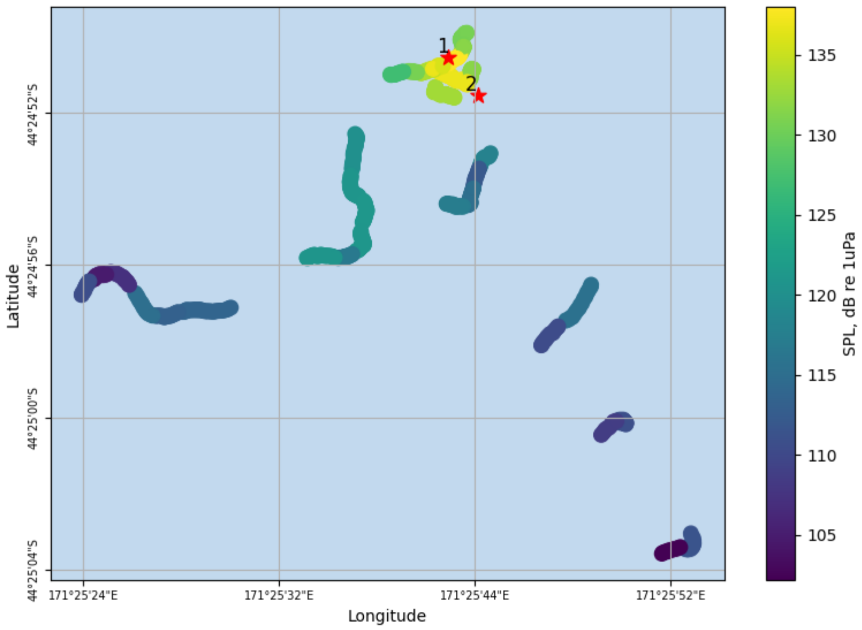


Figure 26. STM DDD, mobile receiver: GPS track points associated with the mobile measurements, coloured by the maximum 1-second sound pressure level (SPL) in the 25 kHz-centred decidecade band for each measurement dip. All dip depths are included.

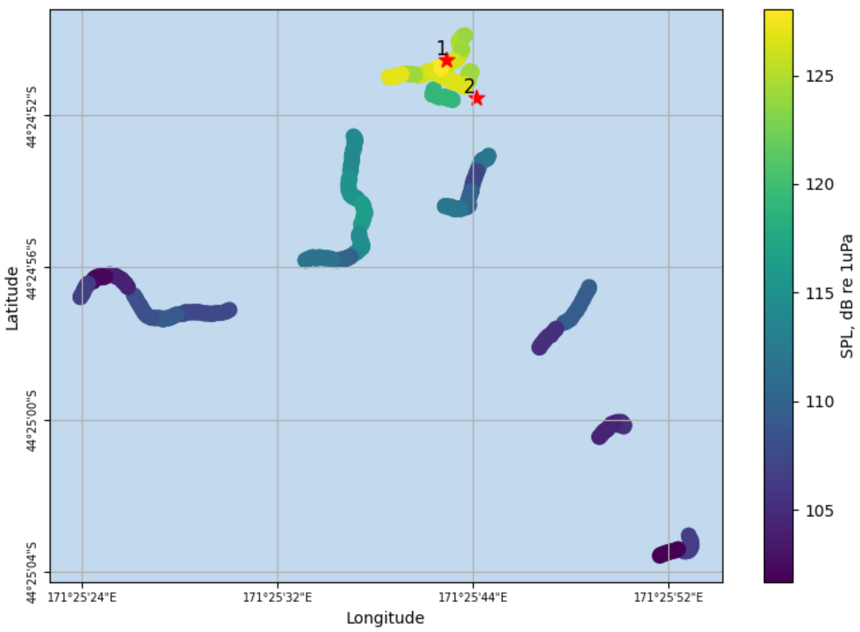


Figure 27. STM DDD, mobile receiver: GPS track points associated with the mobile measurements, coloured by the average maximum 1-second sound pressure level (SPL) in the 25 kHz-centred decidecade band for each measurement dip. All dip depths are included.

3.2.2. Results Summary and Comparison to Modelled Results

As discussed in Section 2.3.3, at-sea measured levels for the STM DDDs are relevant to the 25 kHz-centred decidecade frequency band. To convert to an overall broadband level from the devices an additional 18.7 dB was added to the measured 25 kHz-centred levels, based on the source characterisation results obtained by Warren et al. (2025). Accordingly, Figures 28 and 29 present the broadband received SPL values from the static and mobile receivers (as per Tables 9 and 10) measured levels plus an additional 18.7 dB). Figure 28 presents the maximum received broadband SPL from each recording period, while Figure 29 presents the average maximum broadband SPL from each recording period.

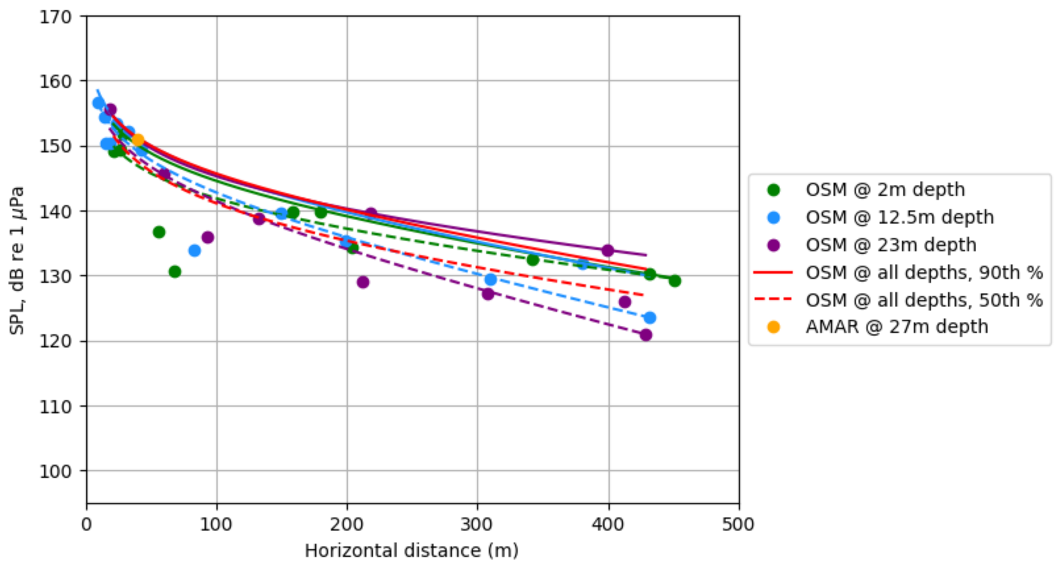


Figure 28. Maximum received SPL levels, approximated to broadband levels (25 kHz band level +18.7 dB), for the STM DDD at-sea trials. Lines of best fit show the 90th percentile of data (solid) and the 50th percentile of data (dashed) per dip depth, and across all dip depths.

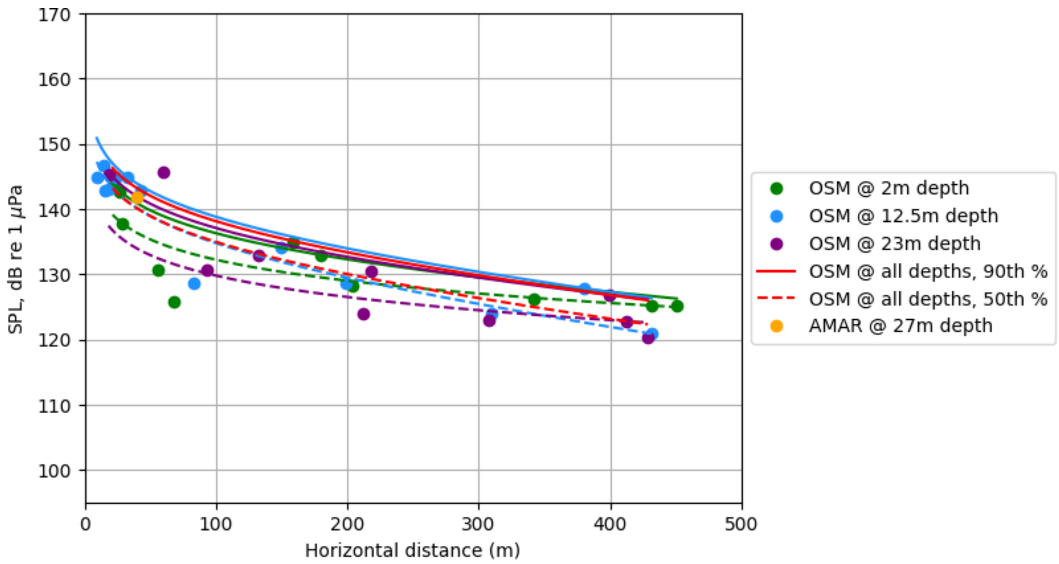


Figure 29. Average maximum received SPL levels, approximated to broadband levels (25 kHz band level +18.7 dB), for the STM DDD at-sea trials. Lines of best fit show the 90th percentile of data (solid) and the 50th percentile of data (dashed) per dip depth, and across all dip depths.

Compared to the measurement trials, the most similar single device modelling scenario in the study by Warren et al. (2025) considered 25 m water depth, sand seabed, sea state 0, and with the device mounted near the seafloor (as opposed to near the sea surface). The modelling considered a median source level of 161.2 dB re 1 μPa^{2}m^2 for the STM DDDs. The SPL results from the modelled scenario are presented in Table 11. As the modelling environment considered a perfectly flat seabed, the modelled ensonified areas were perfectly symmetrical circles.

Table 11. *SPL*: Maximum (R_{max}) horizontal distances (in metres) to exceedance of the given sound pressure level (SPL) within the single-device modelling for the STM DDD in 25 m water depth.

SPL (L_p; dB re 1 μPa)	Maximum distance to exceedance of SPL value within the single-device modelling, based on median source level
150	–
140	14
130	45
120[a]	151
110	367
100	779

[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).

Figure 30 shows a plot of the modelled results (Table 11) for comparison against the at-sea measurement results for this study. The at-sea measurement results have been adjusted to represent the median source level of the STM DDDs (-12.4 dB from maximum levels, refer to Section 2.3.3).

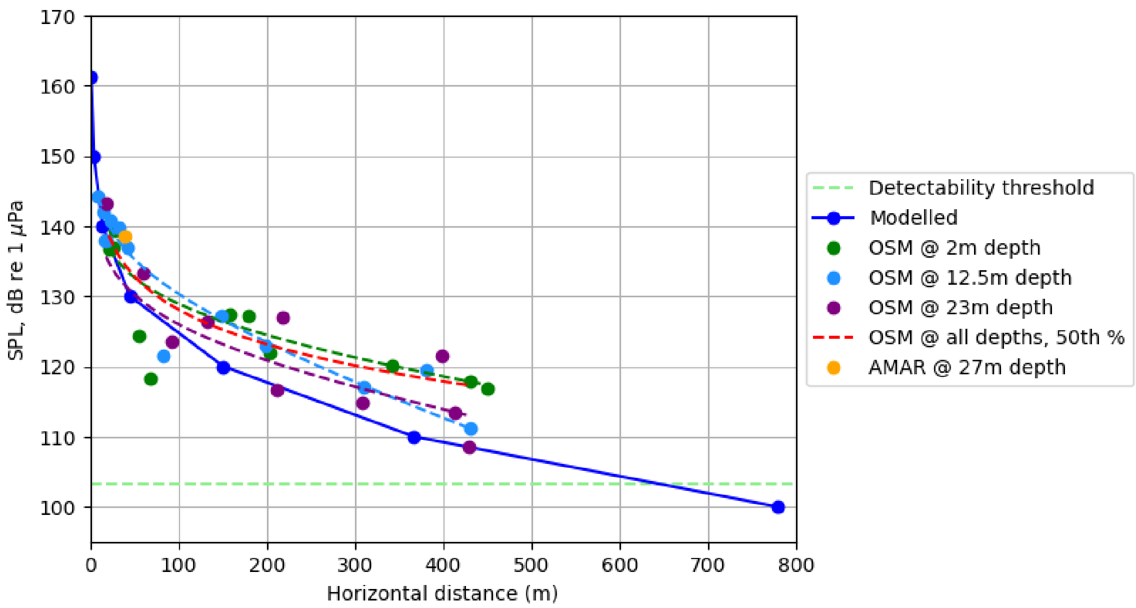


Figure 30. Median-adjusted received broadband SPL levels for the STM DDD at-sea trials, along with broadband modelled results for the most similar single-device modelled scenario, in addition to the Hector's and Māui dolphin detectability threshold of 103.2 dB. Lines of best fit show the 50th percentile of measured data (dashed) per dip depth, and across all dip depths.

As discussed in Section 3.1.2, the modelled results presented a 'maximum-over-depth' value, and therefore the horizontal range and slant range (with regard to OSM2 dip depth) must both be considered for context. For the STM DDD, neither the maximum nor average maximum received SPL comparisons showed the highest received levels at one specific dip depth (Figures 28 and 29) and there is variability in received level among measurement depths and distances.

Measurement values reported here were approximated to broadband levels based on a correction factor, while the modelling undertaken by Warren et al. (2025) modelled all frequency bands. As such, the modelled results incorporate frequency-specific sound propagation, which would not be fully captured by the measurement correction factor, therefore the Figure 30 provides an approximate comparison rather than an exact comparison.

In general, the real-world underwater environment was more conducive to sound propagation than was predicted by the model, with higher received levels recorded at each given distance than were predicted by the modelling (Figure 30).

The study by Warren et al. (2025) calculated that STM DDDs would be audible to Hector's and Māui dolphins at received SPL values of 103.2 dB re 1 µPa. In this measurement study, a received level of 103.2 dB re 1 µPa was exceeded to a horizontal distance of approximately 1000 m based on the 50th percentile curve fits to the measured levels (Figure 30).

Table 12 presents the calculated sound exposure levels (SELs) for three accumulation periods (10 minutes, 1 hour, and 24 hours) based on the methods outlined in Section 2.3.3. Both median and maximum source levels for the STM DDDs are considered. When maximum source levels were considered, the PTS/Auditory Injury criteria for very high-frequency cetaceans (181 dB re 1 µPa^2·s, Accomando et al. (2025)) was exceeded at distances less than 10 m for the 1 hour accumulation period, and at distances up to ~80 m in the 24 hour accumulation period. When median source levels were considered, the PTS/AUD INJ criteria was exceeded up to a maximum of 10 m for the 24 hour accumulation period only. The TTS criteria for very high-frequency cetaceans (161 dB re 1 µPa^2·s, Accomando et al. (2025)) was exceeded within all three considered accumulation periods, for both median and maximum source levels, up to a distance of 550-600 m over the 24 hour accumulation period (when maximum source level is considered).

As mentioned, the most similar single device modelling scenario in the study by Warren et al. (2025) considered 25 m water depth, sand seabed, sea state 0, and with the device mounted near the seafloor (as opposed to near the sea surface). The model considered only the median source level for the STM DDDs. Within the modelled scenario, the very high-frequency cetacean PTS/AUD INJ criteria was only exceeded within the 24 hour accumulation period, at a distance of 10 m. The very high-frequency cetacean TTS criteria was exceeded within the 10 minute, 1 hour and 24 hour accumulation periods, at distances of 7 m, 21 m and 127 m, respectively. The results presented here considering a median source level provide very similar results to the modelled scenario, albeit with a slightly longer distance to the TTS threshold in the 24 hour accumulation period (~200 m) (Table 12).

Table 12. STM DDD, sound exposure level (SEL) : Estimates for the sound exposure level of the measured devices at a range of horizontal distances, based on the median and maximum source levels and the 50th percentile curves of the OSM2 measurements obtained across all depths (Figures 30 and 28, respectively). Dark grey shaded cells indicate exceedances of the PTS/AUD INJ criteria for very high-frequency cetaceans (181 dB re 1 μPa²·s), per Accomando et al. (2025). Grey shaded cells indicate exceedances of the TTS criteria for very high-frequency cetaceans (161 dB re 1 μPa²·s), per Accomando et al. (2025).

Horizontal distance (m)	Assessment based on median source level				Assessment based on maximum source level			
	Received Level (SPL, dB re 1 μPa)	Weighted SEL (dB re 1 μPa²·s) over 10 minutes	Weighted SEL (dB re 1 μPa²·s) over 1 hour	Weighted SEL (dB re 1 μPa²·s) over 24 hours	Received Level (SPL, dB re 1 μPa)	Weighted SEL (dB re 1 μPa²·s) over 10 minutes	Weighted SEL (dB re 1 μPa²·s) over 1 hour	Weighted SEL (dB re 1 μPa²·s) over 24 hours
5	147.7	164.6	172.3	186.1	160.1	177.0	184.7	198.5
10	143.6	160.5	168.2	182.0	156.0	172.9	180.6	194.4
20	139.4	156.3	164.0	177.8	151.8	168.7	176.4	190.2
40	135.1	151.9	159.7	173.5	147.5	164.3	172.1	185.9
60	132.4	149.2	157.0	170.8	144.8	161.6	169.4	183.2
80	130.4	147.2	155.0	168.8	142.8	159.6	167.4	181.2
100	128.7	145.6	153.4	167.2	141.1	158.0	165.8	179.6
150	125.5	142.4	150.2	164.0	137.9	154.8	162.6	176.4
200	123.0	139.9	147.6	161.4	135.4	152.3	160.0	173.8
250	120.9	137.7	145.5	159.3	133.3	150.1	157.9	171.7
300	119.0	135.8	143.6	157.4	131.4	148.2	156.0	169.8
350	117.2	134.1	141.8	155.6	129.6	146.5	154.2	168.0
400	115.6	132.4	140.2	154.0	128.0	144.8	152.6	166.4
450	114.1	130.9	138.7	152.5	126.5	143.3	151.1	164.9
500	112.6	129.4	137.2	151.0	125.0	141.8	149.6	163.4
550	111.2	128.0	135.8	149.6	123.6	140.4	148.2	162.0
600	109.8	126.7	134.5	148.3	122.2	139.1	146.9	160.7
650	108.5	125.4	133.2	147.0	120.9	137.8	145.6	159.4
700	107.3	124.1	131.9	145.7	119.7	136.5	144.3	158.1
750	106.0	122.8	130.6	144.4	118.4	135.2	143.0	156.8
800	104.8	121.6	129.4	143.2	117.2	134.0	141.8	155.6
850	103.6	120.4	128.2	142.0	116.0	132.8	140.6	154.4
900	102.4	119.2	127.0	140.8	114.8	131.6	139.4	153.2
950	101.2	118.1	125.9	139.7	113.6	130.5	138.3	152.1
1000	100.1	116.9	124.7	138.5	112.5	129.3	137.1	150.9
1100	97.8	114.7	122.5	136.3	110.2	127.1	134.9	148.7
1200	95.6	112.5	120.2	134.1	108.0	124.9	132.6	146.5
1300	93.5	110.3	118.1	131.9	105.9	122.7	130.5	144.3
1400	91.3	108.2	116.0	129.8	103.7	120.6	128.4	142.2
1500	89.2	106.1	113.9	127.7	101.6	118.5	126.3	140.1

4. Discussion

This measurement study assessed the real-world underwater propagation of sound from acoustic devices used in New Zealand waters to alert marine mammals to the presence of fishing gear, and/or to deter them from areas of risk or potential feeding opportunities. The two devices were the Netguard Dolphin Pinger (60 – 120 kHz model); and the STM Dolphin Deterrent Device (DDD) (DDD03H model). The purpose of the measurement study was to assess the effectiveness of these devices in the marine environment around an active fishing operation, and to compare against calculated sound propagation as obtained in the modelling study undertaken by Warren et al. (2025).

At-sea measurements were undertaken using both static and mobile receivers to consider whether the propagation environment varied over time (temporal variability) and to examine how sound propagated over distance and depth (spatial variability). Measurements were undertaken during calm weather, with wind speeds below 10 knots and wave heights of less than 0.1 m (Sea State 1). Nonetheless, significant drift in vessel location occurred during the mobile measurements. Careful notes and GPS positions were taken during mobile measurements.

The measurements obtained by the static recorders revealed that there was no notable temporal variation in ambient noise conditions during the two measurement trials, and as such it remained acceptable to compare results among mobile measurements undertaken across the recording duration. Spatial variation in sound propagation is discussed in the device specific sections below, along with comparisons to the modelled propagation of the devices calculated in the study by Warren et al. (2025). The following sections also identify any additional factors to consider for effective use of these devices in operational settings, as well as recommendations for future research.

4.1. Netguard Pingers

The Netguard Pinger analysis focused on the 63 kHz-centred decidecade frequency band and the maximum and average maximum received sound pressure levels (SPLs) within this band. The 63 kHz-centred decidecade frequency band is the primary frequency range of Pinger emissions (Figure 5) although it should be noted that in this at-sea measurement region, lower level harmonics at ~130 and ~200 kHz were also received.

The analysis considered 1-second resolution SPL. Each Netguard Pinger produced one 0.3 s ‘ping’ every 4 seconds. When a ‘ping’ occurred within a 1-second window, the SPL value for that 1-second window was higher than adjacent windows that occurred between ‘pings’. The highest ‘peaks’ in SPL for the 63 kHz-centred decidecade frequency band therefore occurred every 4 seconds, but because additional, more distant pingers, were detectable within the recordings, lower level ‘peaks’ also occurred in the gaps between emissions from the closest Pinger. This was illustrated in Figures 9 and 13, where secondary high SPL levels occurred within each peak at a slightly lower level than the absolute maximum peak every 4 seconds. Throughout the recording period, the temporal separation of the received device emissions drifted, which was assumed to be a result of propagation effects subtly changing over time, rather than notable drift within timing of Pinger emissions, which did not notably vary when measured (Warren et al. 2025). Lower level ‘pings’ received from Pingers located at further distances on the set net were the driver behind the average maximum SPL levels being notably lower than the absolute maximum levels in both the static and mobile measurements.

Spatial variation in propagation was evident within the mobile measurement results reported in Table 5. The results associated with the 151.9 m horizontal measurement (38 m dip depth) and the 153.1 m horizontal measurement (38 m dip depth) show that measurements made at similar distances (~1 m difference in average measurement distance), resulted in 2.7 dB difference in maximum received level from the Pingers. This comparison provides an insight into spatial variability in sound propagation because the measurement made at 151.9 m was taken during OSM2 Dip #2 (beyond the end of the net, in parallel, Section 2.1.1), whereas the measurement made at 153.1 m was taken from the opposite direction during OSM2 Dip #6, perpendicular to the net, Section 2.1.1).

Overall, the Netguard Pingers functioned as intended, and the entire net region was ensonified by the ‘pings’ emitted by the four devices. This achieves the primary aim of attaching Pingers to set nets, which is to provide an alert system to marine mammals to raise awareness of an object of potential risk. The Pinger spacing applied (60 m) was more than adequate in this environment to avoid ‘gaps’ in the sound field along the length of the net.

In the study by Warren et al. (2025), the environment with the longest propagation had a range to detectability of a Netguard Pinger of 60 m for Hector’s and Māui dolphins. Within this measurement study, the real-world underwater environment was more conducive to sound propagation than the environment applied within the modelling and the detectability threshold relevant to Netguard Pinger emissions was found to be exceeded to approximately 60 to 120 m (refer to Section 3.1.2). The reason for the more supportive propagation environment was not investigated, however is likely due to a combination of the calm conditions, localised sediment and bathymetry features. Whilst this was the case for this specific location, the same propagation environment is unlikely to occur at all locations in the New Zealand marine environment. Therefore, it is not recommended that the results from this trial should be extrapolated to other locations around New Zealand, or considered to be the norm for this location given the calm sea conditions. Nonetheless, the results from this measurement trial and the original modelling study could be considered in combination to produce future recommendations for spacing of Netguard Pingers on set nets.

While underwater noise measurements and modelling can speak to the temporal and spatial propagation of the sound fields emitted by the acoustic devices, in order to be confident that the devices function as effective bycatch mitigation tools, the responses of marine mammals to the emitted sounds must be confirmed. This is identified as an area in need of future research as there is limited understanding of the behaviour of free-ranging marine mammals in New Zealand, let alone in relation to active fisheries operations. Animal-mounted telemetry tags that record fine-scale movement (e.g. Foskolos et al. 2025), in combination with passive acoustic monitoring equipment at fishery sites (e.g. Warren et al. 2023), could form a basis for initial investigations on the performance of Pingers as a bycatch mitigation tool.

4.2. STM DDDs

The STM DDD analysis focused on the 25 kHz-centred decidecade frequency band and the maximum and average maximum received sound pressure levels (SPLs) within this band. Within the modelling study, the 25 kHz-centred decidecade frequency band was found to be the furthest propagating band of those considered, and this measurement study focused on a consistent, comparable measure that would be less affected by external sound sources within the environment than a full broadband assessment. For the purposes of comparing the measured levels against the modelled results obtained by Warren et al. (2025), the 25 kHz-centred decidecade frequency band levels were converted to broadband levels with a +18.7 dB correction factor (based on the source spectra (Figure 5), and were also considered for a median source level (-12.4 dB from maximum levels, refer to Section 2.3.3).

Similar to the Netguard Pingers, the average maximum levels in the 25 kHz-centred decidecade frequency band were notably lower than equivalent absolute maximum levels. The difference was largely driven by the two STM DDDs being received after propagating across two different distances, but even at close measurement distances it proved difficult to distinguish between the emissions from the two devices. Temporally overlapping signals were sometimes both received at similar levels, and since the devices emitted signals at random intervals and with differing source levels and frequencies, the outputs of the two devices were not consistent (refer to spectrograms in Section 3.2.1.1 for examples).

As noted within the Netguard Pinger analysis, spatial variation in propagation was evident within the mobile measurement results. Table 10 includes results associated with a measurement made at 211.7 m horizontal distance (23 m dip depth) and a measurement made at 217.7 m horizontal distance (also at 23 m dip depth), revealing that measurements made at relatively similar distances (~6 m, or ~3%, difference in average measurement distance), resulted in 10.4 dB difference in maximum received level. The measurement made at the further distance (217.7 m) was louder, whereas propagation loss would typically lead to quieter levels at further distances from the source. This comparison provides an insight into localised spatial variability in sound propagation because the measurement made at 211.7 m was taken during OSM2 Dip #4 (parallel from the DDD line, Section 2.1.2), whereas the measurement made at 217.7 m was taken from the opposite direction during OSM2 Dip #3 (perpendicular from the centre of the two DDDs, Section 2.1.2).

Within this measurement study, the real-world underwater environment was somewhat more supportive of sound propagation than the environment applied within the modelling (Figure 30). Nonetheless, the overall characterisation of sound propagation from the STM DDDs remained as expected, and the relationship between received level and horizontal distance followed the same trend as per the modelled scenario (Figure 30). The original work conducted by (Warren et al. 2025) verified the sound source characteristics of the STM DDDs, and this measurement study has validated the overall outputs of the modelling study in terms of the propagation of sound, albeit with less transmission loss affecting propagation than was expected from the modelled scenarios. The sound source characteristics and verified modelling approach could now be used in future modelling work to consider the ensonified areas arising from multiple DDD sources, such as might occur across a fleet of fishing vessels operating in a specific area. Such modelling could contribute to management-level decision-making by quantifying acute and cumulative noise exposure that would be experienced by local marine mammal species, potentially allowing for a balance to be struck between adequate deterrence from risk areas and excessive noise pollution within the habitat.

DDDs are utilised in New Zealand fisheries operations to discourage dolphins away from areas of high risk (e.g. trawl net mouths). As recommended for the Netguard Pingers, further research to understand how free-ranging marine mammals respond to the DDD sound source would be valuable to ensure the devices function as effective bycatch mitigation tools. Such insights could also help establish whether the DDDs could be used more conservatively, for example only during net hauling, rather than throughout an entire trawl period. Potential habituation of marine mammals to these sound sources should also be considered, although it is acknowledged that the emission design of the DDDs is intended to mitigate habituation.

Acknowledgements

JASCO would like to acknowledge JASCO field technician Jessica Cafagna and equipment technician Zak Wessels for their work in preparing the acoustic equipment and obtaining these measurements. Furthermore, we are extremely grateful to Nathan Hines, JASCO's Fisheries Consultant, for his experience and insights that helped bring this project together and enabled the field campaign to be a success.

Thanks to Chris Parish with the *FV Apollo* and the vessel master of the *FV Compass Rose* for their involvement in preparing for and undertaking these measurements. Their enthusiasm to improve our understanding of these acoustic devices was thoroughly appreciated and reciprocated, and we were grateful to have received their time and experience.

Glossary of Acoustics Terms

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.

acoustic noise

Sound that interferes with an acoustic process.

acoustic self-noise

Sound at a receiver caused by the deployment, operation, or recovery of a specified receiver and its associated platform (ISO 18405:2017).

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.

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.

background noise

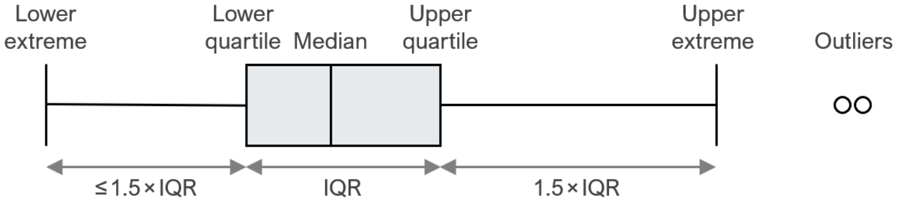
Combination of ambient sound, acoustic self-noise, and, where applicable, sonar reverberation (ISO 18405:2017) that is detected, measured, or recorded with a signal.

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.



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.

cetacean

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

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.

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: (m/s)^2 s/Hz
- If x = sound particle acceleration: (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 μPa^2 m^2 s/Hz.

ensonified

Exposed to sound.

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).

hydrophone

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

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 μPa² can be written in the form *x* dB re 1 μPa².

masking

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

median

The 50th percentile of a statistical distribution.

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.

otariid

Member of the family Otariidae, one of the three groupings of pinnipeds (along with phocids and walrus). These eared seals, commonly called fur seals and sea lions, are adapted to semi-aquatic life; they use their large fore flippers for propulsion underwater and can walk on all four limbs on land.

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^2_{pk}) in a stated frequency band and time window. Defined as $L_{pk} = 10\log_{10}(p^2_{pk}/p^2_0) = 20\log_{10}(p_{pk}/p_0)$. Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 μPa².

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 μPa^2 m^2/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.

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

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 = $10\log_{10}(E/E_0)$ (ISO 18405:2017). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa² 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 (Pa² 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/m²). Symbol: I.

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_{rms}^2) in a stated frequency band and time window: L_p = $10\log_{10}(p_{\mathrm{rms}}^2/p_0^2)$ = $20\log_{10}(p_{\mathrm{rms}}/p_0)$, where rms is the abbreviation for root-mean-square. Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa². 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.

temporary threshold shift (TTS)

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

transmission loss (TL)

The difference between a specified level at one location and that at a different location: 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.

wavelength

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

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Appendix A. Recorder Calibration

The static and mobile recorders were calibrated before deployment and upon retrieval with a pistonphone type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S; Figure A-1). The pistonphone calibrator produced a constant tone at 250 Hz at a fixed distance from the hydrophone sensor in an airtight space of known volume. The recorded level of the reference tone on the AMAR/OSM2 yielded the system gain for the AMAR/OSM2 and hydrophone. To determine absolute sound pressure levels, this gain was applied during data analysis. Typical calibration variance using this method is less than 0.7 dB absolute pressure.

Figure A-1. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M36 hydrophone.

Appendix B. Acoustic Data Analysis

B.1. Ambient Ocean Soundscape

The soundscape of a location is the characterisation of its ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field (ISO 18405:2017). Ambient sound 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. The Wenz (1962) curves (Figure B-1) show the typical frequencies and spectral levels of contributions from distant sources associated with these activities.

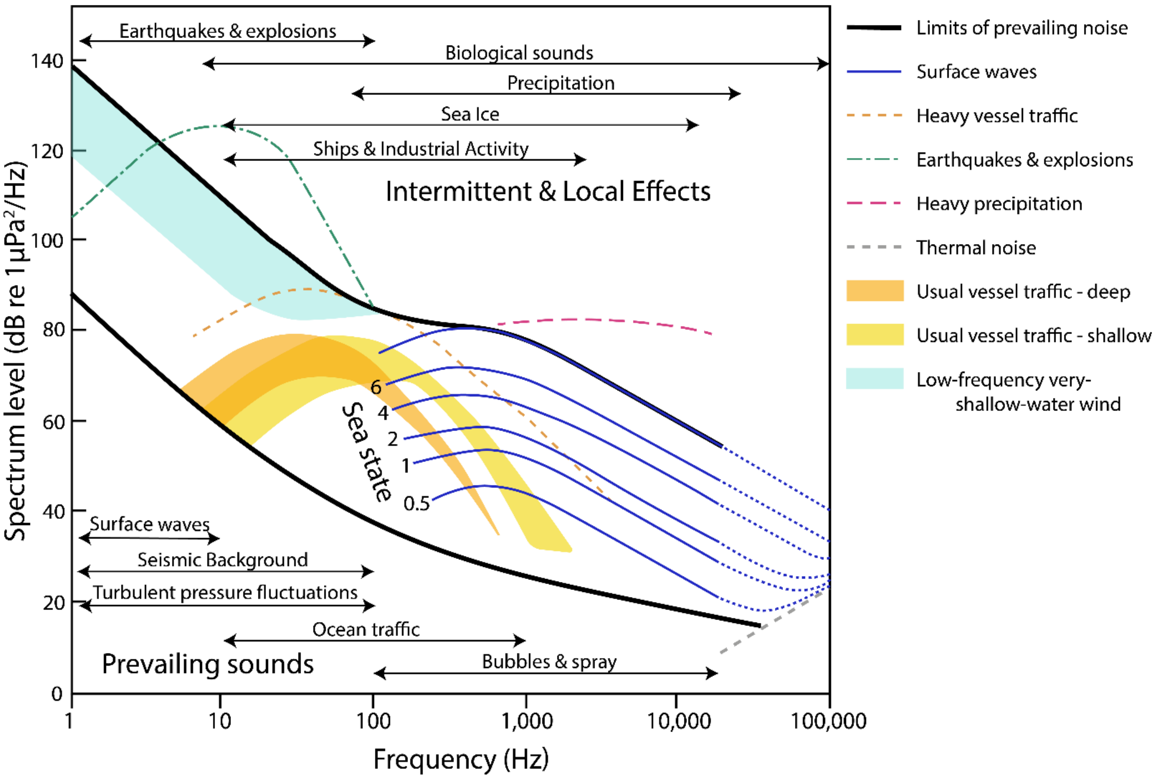

Figure B-1. Wenz curves describing pressure spectral density levels of marine ambient sound from weather, wind, geologic activity, and commercial shipping (adapted from NRC 2003, based on Wenz 1962). The thick lines are the limits of prevailing ambient sound, which are included in some of the results plots to provide context.

In marine environments, the geophonic elements of a soundscape can act as proxies for oceanographic conditions. Knudsen et al. (1948) and Wenz (1962) demonstrated that increased sea state and wind speed commonly correlate with higher sound intensities across frequencies from 500 Hz to 30 kHz due to breaking whitecaps, surface flow noise, wave generation, cavitation, and pressure change (Urick 1983). Rainfall can elevate sound levels in the 1–15 kHz frequency range via sound from surface impacts and bubble entrainment (Heindsmann et al. 1955, Bom 1969, Scrimger et al. 1987). Waves, currents, and seismic activity (such as earth movement and subsea landslides) can also be loud, though short-duration, geophonic contributors. Biophonic contributors include acoustic signals from soniferous (sound-producing) animals such as marine mammals. While geophonic and biophonic contributors comprise the natural soundscape, the total soundscape also includes anthrophonic (related to human activity) sounds.

B.2. Total Ambient Sound Levels

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 impulsive noise 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 noise and its effects on marine life. We provide specific definitions of relevant metrics used in this report. Where possible, we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

The zero-to-peak pressure level, or peak sound pressure level (PK or $L_{p,pk}$; dB re 1 μPa), is the decibel level of the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $\mathrm{p}(\mathrm{t})$:

$$\text{PK} = L_{p,\text{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} \tag{B-1}$$

PK is often included as criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure level (PK-PK or $L_{\text{pk-pk}}$; dB re 1 μPa) is the level of the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $p(t)$:

$$L_{\text{pk-pk}} = 10\log_{10}\frac{(p_{\max} - p_{\min})^2}{p_0^2} = 10\log_{10}\frac{\{\max[p(t)] - \min[p(t)]\}^2}{p_0^2}\ . \tag{B-1}$$

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

$$\text{SPL} = L_p = 10\log_{10}\left[\frac{1}{T}\int_T p^2(t)\,dt \Big/ p_0^2\right] \tag{B-2}$$

The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalisation, the passage of a vessel, or over a fixed duration. Because the window length, T, is the divisor, events with similar sound exposure level (SEL), but more spread out in time have a lower SPL.

The sound exposure level (SEL or L_E, dB re 1 μPa^2 s) is a measure related to the acoustic energy contained in one or more acoustic events (N). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T):

$$\text{SEL} = L_E = 10\log_{10}\left[\int_T p^2(t)\,dt \Big/ T_0 p_0^2\right] \tag{B-3}$$

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

Because the SPL and SEL are both computed from the integral of square pressure, these metrics are related numerically by the following expression, which depends only on the duration of the time window T:

$$L_p = L_E - 10\log_{10}(T)\,. \tag{B-2}$$

B.3. 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. These values directly compare to the Wenz curves, which represent typical deep ocean sound levels (Figure B-1) (Wenz 1962). This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Animals perceive exponential increases in frequency rather than linear increases, so 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:

$$f_c(i) = 10^{\frac{i}{10}}\,\text{kHz} \tag{B-3}$$

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

$$f_{lo,i} = 10^{\frac{-1}{20}} f_c(i) \text{ and } f_{hi,i} = 10^{\frac{1}{20}} f_c(i) \tag{B-4}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure B-2).

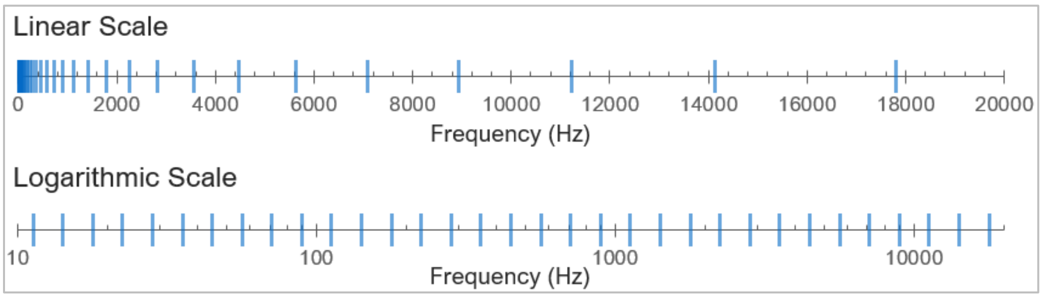

Figure B-2. Decidecade frequency bands (vertical lines) shown on (top) a linear frequency scale and (bottom) a logarithmic scale. On the logarithmic scale, the bands are equally spaced.

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

$$L_{p,i} = 10\log_{10}\int_{f_{lo,i}}^{f_{hi,i}} S(f)\,df\ \text{dB} \tag{B-5}$$

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

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{\frac{L_{p,i}}{10}}\ \text{dB} \quad \text{(B-6)}$$

Figure B-3 shows an example of how the decidecade band SPLs 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. Decidecade band analysis is applied to continuous and impulsive noise sources. For impulsive sources, the decidecade band SEL is typically reported.

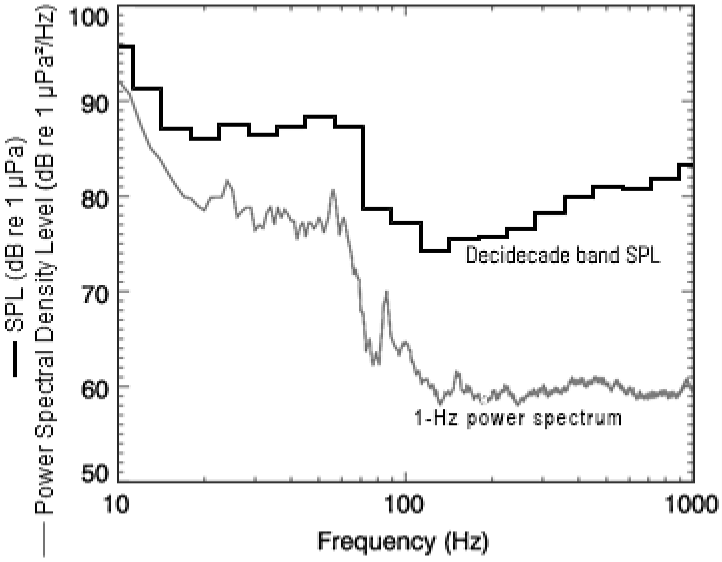

Figure B-3. Power spectral density levels and the corresponding decidecade-band sound pressure levels (SPLs) of example ambient noise shown on a logarithmic frequency scale. Because the decidecade bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum.

Table B-1. Decidecade-band frequencies (Hz).

Band	Lower frequency	Nominal centre frequency	Upper frequency	Band	Lower frequency	Nominal centre frequency	Upper frequency
10	8.9	10.0	11.2	33	1778	1995	2239
11	11.2	12.6	14.1	34	2239	2512	2818
12	14.1	15.8	17.8	35	2818	3162	3548
13	17.8	20.0	22.4	36	3548	3981	4467
14	22.4	25.1	28.2	37	4467	5012	5623
15	28.2	31.6	35.5	38	5623	6310	7079
16	35.5	39.8	44.7	39	7079	7943	8913
17	44.7	50.1	56.2	40	8913	10000	11220
18	56.2	63.1	70.8	41	11220	12589	14125
19	70.8	79.4	89.1	42	14260	16000	17952
20	89.1	100.0	112.2	43	17825	20000	22440
21	112	126	141	44	22281	25000	28050
22	141	158	178	45	28074	31500	35344
23	178	200	224	46	35650	40000	44881
24	224	251	282	47	44563	50000	56101
25	282	316	355	48	56149	63000	70687
26	355	398	447	49	71300	80000	89761
27	447	501	562	50	89125	100000	112202
28	562	631	708	51	111406	125000	140252
29	708	794	891	52	142600	160000	179523
30	891	1000	1122	53	178250	200000	224404
31	1122	1259	1413	54	222813	250000	Out of recording scope
32	1413	1585	1778				

Table B-2. Decade-band frequencies (Hz).

Lower frequency	Nominal centre frequency	Upper frequency
8.9	50	89.1
89.1	500	891
891	5,000	8,913
8,913	50,000	89,125
89,125	500,000	Out of recording scope