Annual report – Boundary Pass acoustic monitoring

Year 4 (January to December 2022)

Summary

The Vancouver Fraser Port Authority-led Enhancing Cetacean Habitat and Observation (ECHO) Program manages the analysis of underwater acoustic data acquired by Transport Canada's Boundary Pass Underwater Listening Station (ULS) in southern British Columbia. In Spring 2020, two permanently cabled underwater hydrophone arrays were deployed in place of Autonomous Multichannel Acoustic Recorders (AMARs). This fourth annual report contains a comprehensive analysis of the measurement results for Year 4, from January to December 2022.

What questions was the study trying to answer?

The acoustic analysis seeks to answer the following key questions:

- What are the trends in ambient noise levels at Boundary Pass?
- Which classes and quantities of commercial vessels have been measured in the area, and what is the associated range of noise source levels?
- What marine mammals and other marine biota have been identified in the area?

Who conducted the project?

JASCO Applied Sciences (Canada) Ltd. were retained by Transport Canada to deploy the Boundary Pass ULS, and by the Vancouver Fraser Port Authority to conduct and report on data analysis.

What methods were used?

During the Year 4 reporting period, data was collected at both ULS arrays A and B for each day within the year. The Acoustic Doppler Current Profiler (ADCP) was deemed inoperable following the October 2021 servicing operation and remained offline for the duration of the Year 4 reporting period. A temporary ADCP was deployed separate from the array from May 13, 2022 until November 10, 2022 and was correlated to acoustic readings as part of the annual reporting. Water current data to evaluate speed through water for vessel measurements, and for periods where the ADCP was not deployed in 2022 were derived from the WebTide prediction model.

Each hydrophone of the ULS recorded at 512,000 samples per second (10 Hz to 256 kHz recording bandwidth) with 24-bit resolution. Ambient noise analysis was conducted using JASCO's PAMlab acoustic analysis software suite, which presented spectrograms, decade-band and 1/3-octave band level statistics, power spectral density percentiles, and plots of sound levels as a function of day of the week and hour of the day. Vessel source levels were calculated using ShipSound, a component of JASCO's PortListen online noise measurement system. Automatic Identification System (AIS) messages from vessels and weather data were collected proximate to the ULS.

An automated detector developed by JASCO was used to detect the vocalizations of killer whales, humpback whales, Pacific white-sided dolphins, and fish sounds from acoustic recordings. An experienced analyst manually verified all detections.

What were the key findings?

Ambient Noise

- Fast currents in Boundary Pass can cause elevated sound levels, affecting long-term trends, particularly at lower frequencies and as such ambient noise readings were only compared for levels where the current readings near the hydrophones was less than 0.25m/sec.
- Sound levels trends were generally consistent between years, including 2022, with a decrease in noise between July and October, likely due to lower vessel noise from participation in the ECHO seasonal slowdowns.
- Ambient noise level statistics collected at each ULS frame showed good agreement at mid frequencies. However, some differences were observed at low frequencies (below ~40 Hz) and high frequencies (above ~10 kHz)

Marine Mammal Detections

- Over 12,100 marine fauna detections (fish sounds and cetacean vocalizations) were recorded in the 12-month study period, 89% of these detections were from killer whales (65% Transient/Bigg's and 33% southern resident killer whales (SRKW).
- Killer whale vocalizations were detected on 75 days in 2022 compared to 57 in 2021, in all months except December. SRKW vocalizations were absent June, November and December and peaked in March, while Transient/Bigg's vocalizations were present every month except September and December.
- Humpback whale vocalizations were detected on 18 days over 8 months, with detections peaking in September. No Pacific white-sided dolphins were detected.

Vessel Source Levels

- A total of 12,600 source level measurements of 1,812 unique vessels were collected during the study period. Of these, approximately 78% (9,833 measurements) passed manual quality control checks.
- The maximum accepted radiated noise level (RNL) measurement made in 2022 was 205.6 dB re 1 μPa m for a container ship.
- The minimum accepted radiated noise level measurement made in 2022 was 151.4 dB re 1 μPa m for a recreational vessel transit.
- Bulkers made up approximately 50% of all accepted measurements, while container ships accounted for approximately 21% of the measurements during the study period.
- The mean difference in source level measurements between the two arrays was 1.2 dB (between the two arrays with a standard deviation of 0.3 dB indicating good agreement between frames.

Conclusions and next steps

Acoustic measurements were made using at least one ULS array every day in 2022. The two arrays showed good agreement in source level measurements and ambient noise readings, although some differences were evident at very low and very high frequencies.

In the fourth annual Boundary Pass report, detections and classifications of marine mammal vocalizations were dominated by killer whale vocalizations which occurred in every month except December.

The ULS location is well-positioned to maximize the collection of accurate vessel source levels for vessels transiting the inbound and outbound lanes of Boundary Pass. Bulkers and container ships constitute the most accepted source level measurements at Boundary Pass, and large containerships are the loudest vessel category measured at the station.

The Boundary Pass ULS operates on a continual basis, collecting ambient noise, vessel source levels, and marine mammal detection data. This is the fourth annual report supporting the long-term Boundary Pass ULS monitoring program.

Annual Report of Boundary Pass Acoustic Monitoring

Year 4, January 2022 to December 2022

JASCO Applied Sciences (Canada) Ltd

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Krista Trounce

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Executive Summary

Vancouver Fraser Port Authority (VFPA) has an agreement with Transport Canada to manage the analysis of a large underwater acoustic data set acquired by Transport Canada's Boundary Pass Underwater Listening Station (ULS), in southern British Columbia. VFPA has contracted JASCO Applied Sciences (JASCO) to perform the data analysis and reporting. This report discusses the data collection corresponding to the calendar year 2022 and provides the results of the analysis of the acquired data.

JASCO is also responsible for operating the ULS and acquiring the acoustic data under a separate agreement with Transport Canada. The project's acoustic data acquisition started December 12, 2018 and will continue to at least March 31, 2023. Details of the data collection and analysis from December 12, 2018 to December 31, 2021 are described in three previous annual reports (Warner and Frouin-Mouy 2020, Cusano et al. 2021, Houweling et al. 2022a). This fourth annual report contains analysis of data acquired between January 1, and December 31, 2022. It is a summary of the ambient noise level statistics, marine mammal vocalizations, and vessel source levels, which have been reported to VFPA's Enhancing Cetacean Habitat and Observations (ECHO) Program. This work also investigates the consistency in estimated sound levels from multiple recorders.

The data acquired for the period analyzed in this fourth annual report were collected on the ULS, which consists of shore-cabled compact tetrahedral hydrophone arrays (with four active hydrophone channels) mounted on pyramid shaped steel frames, referred to as Frames A and B.[1] The two frames for this 2022 study have been in continuous operation since October 9, 2021.

To assist interpretation of the acoustic data, additional metadata were collected, including water current speed from an Acoustic Doppler Current Profiler (ADCP), Automatic Identification System (AIS) messages from vessels, and wind speed and direction measurements from nearby public weather stations. In the case of current data, when ADCP data were not available, the WebTide Tidal Prediction Model (v0.7.1) (Foreman et al. 2000, Institute of Ocean Sciences 2015) was used to estimate the current speeds at each frame. Current speed is required in this analysis to estimate vessel speed through water, as well as to identify time periods of high flow noise. These periods were filtered out only for analysis tasks related to performance comparison between Frames A and B.

Part of this investigation involved comparing the sound levels obtained from different recorders (i.e., Frame A versus B) to assess consistency. In most cases there was generally good agreement between data, with small differences observed at specific frequency bands and differences due to the frequency response of the two different hydrophone types. For the comparison between frames, data was filtered to remove instances which were likely to contain high flow noise. This was done to focus the comparison on the actual performance of the hydrophones, rather than on differences driven by local flow-noise conditions. For quiet periods (no vessels present and low currents) measurements from the two frames are in good agreement to each other in the 100-4,000 Hz bands. Below 100 Hz there are small deviations between the two channels, and above 4,000 Hz there is larger disagreement between recorders, particularly above 8,000 Hz. For the loud periods (i.e., low currents, but now including data likely to contain vessel noise), the differences between the two channels are reduced for all frequencies up to 25,000 Hz.

[1] Throughout this report, we refer to the ULS frames as “Frame A” and “Frame B”. The specific hydrophone arrays, two in each frame, are indicated with a number (i.e., Frames A1, A2, B1 and B2). The hydrophone channels, 4 in each array, are indicated with a dot followed by a number (e.g., Frames A1.1, A1.2, A1.3, and A1.4 correspond to channels 1, 2, 3, and 4, respectively, in Frame A1).

On November 24, 2022, visual inspection of some ShipSound spectrograms suggested performance issues on channel A2.1. At the moment it was thought to be a sudden failure of the channel, which prompted switching to channel A2.2 (located at the base of the Frame A tetrahedral, 1.3 m below channel A2.1). From this date, channel A2.2 was used for processing ambient noise, ShipSound, and marine mammal detections results. During the preparation of this report it was found that this channel failure was instead a gradual degradation that started on August 2022 and which only affected low frequency bands. Due to computational time constraints at the time of this report, the ShipSound, marine mammal detection, and ambient noise results reported here use a combination of data from A2.1 and A2.2. The time periods of the channels used for each component are detailed in the introduction.

For the marine mammal analysis component of this effort, 12,111 manually validated marine fauna detections were found in the acoustic data during the 12-month data collection period of this report. Most of these detections (89%) were killer whale vocalizations (56% Southern Resident Killer Whale and 33% Transient/Bigg's) with detections occurring during all months except December. The remaining marine fauna detections were from fish sounds (9%) and humpback whale vocalizations (2%). No Pacific white-sided dolphin vocalizations were detected.

Regarding vessel traffic, over 12,600 vessel source level measurements of 1,812 unique vessels representing 15 vessel categories, as defined by AIS transmission vessel category, were analyzed with JASCO's ShipSound application for this analysis period (2022). Out of all these measurements, 9,833 were accepted (389 unique passes measured at only one ULS frame and 4,722 passes measured at both ULS frames). Most measurements were from the Bulker or Container ship categories. Most vessels transiting through Boundary Pass were measured on both ULS frames, separated by 300 m. These double measurements allowed investigation of consistency of measured RNL between Frames A and B, which yielded a mean difference of −1.18 dB with standard deviation of 1.3 dB.

1. Introduction

Underwater acoustic data have been collected continuously in Boundary Pass since December 2018 as part of a long-term measurement program sponsored by Transport Canada. The measurement program began with deploying JASCO's calibrated Autonomous Multichannel Acoustic Recorders (AMARs G3 and G4) as a temporary method of collecting acoustic data until the cabled real-time Underwater Listening Station (ULS) was deployed in May 2020. The ULS system includes two tetrahedral-shaped aluminum frames (Frames A and B), with each frame supporting multiple hydrophone sensors, cabled to a shore station on Saturna Island.

The last servicing operation to the ULS took place in October 2021. Since then, acoustic data have been collected from Frames A and B. Figure 1 shows a map of the instrument locations. Water current speed profiles, wind speed, and vessel traffic data have been collected as part of this measurement program to assist with acoustic data interpretation.

Vancouver Fraser Port Authority (VFPA) has commissioned JASCO to analyze the underwater sound recordings as part of VFPA's Enhancing Cetacean Habitat and Observation (ECHO) program. The analysis is an ongoing effort that has generated status reports every three months since the ULS was installed. The ongoing analysis includes:

- Ambient noise statistics,
- Automated detection and manual validation of marine fauna vocalizations, and
- Approximate ANSI (12.64-2009 (R2014)) vessel radiated noise levels (RNL), and monopole source levels (SL) using a similar measurement approach but using a full-wave model propagation loss correction.

Acoustic data from December 2018 to December 2022, corresponding to five previous autonomous recorder deployments plus approximately 30 months of continuous ULS recordings, have been analyzed and reported for ambient noise statistics and marine mammal vocalizations in quarterly reports and reported in more detail annually. Vessel source level measurements from the same period have been analyzed and are accessible through ShipSound, a component of JASCO's online PortListen® sound measurement system.

The first annual report (Warner and Frouin-Mouy 2020) presented analysis of measurements from December 2018 to October 2019, the second annual report (Cusano et al. 2021) from October 2019 to December 2020, and the third annual report (Houweling et al. 2022a) from January to December 2021 . This (the fourth annual) report contains a comprehensive analysis of the measurement results for Year 4, from January to December 2022.

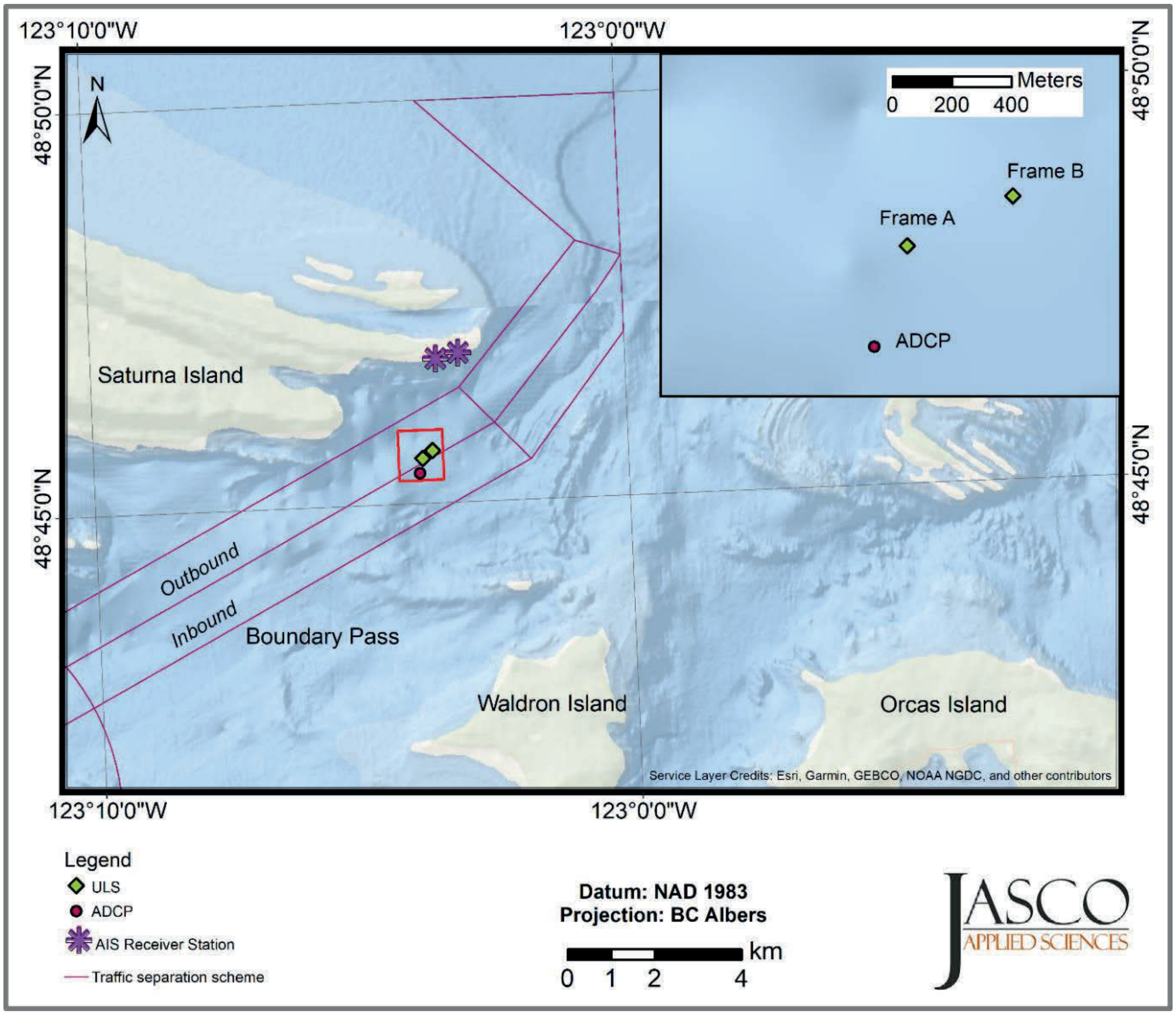

Figure 1. Map showing the locations of the data acquisition equipment in Boundary Pass. The locations of the Underwater Listening Station (ULS) frames during Year 4 are shown on the inset map. The vessel traffic lanes are shown as purple lines.

2. Methods

2.1. Data Acquisition

2.1.1. Acoustic Measurements

The acoustic measurements during the Year 4 reporting period were made at the ULS using two shore-cabled compact tetrahedral hydrophone arrays, which are referred to as Frame A and Frame B. Each frame supports two separate hydrophone arrays (referred to as Frames A1 and A2, and Frames B1 and B2), one activated for recording and one as a backup. Each array has four hydrophones and provides simultaneous four-channel recordings. Frames A1 and B1 have GTI M35-V35-100 hydrophones and Frames A2 and B2 have HTI 99-HF hydrophones. All ULS recorders were deployed on the seabed between the inbound and outbound international shipping lanes in Boundary Pass (see Figure 1). Table 1 lists the deployment locations and recording periods of each recorder.

Since the first ULS deployment in May 2020, a failure in one of the HTI hydrophones led to the selection of the GTI hydrophones in both frames. After the second deployment in October 2021, we expected to continue using the GTI hydrophones, for consistency with the first deployment. However, a new component failure caused all four of the hydrophones on Frame A1 to become unresponsive, prompting JASCO to switch to Frame A2 (HTI 99-HF) while continue to use of GTI hydrophones on Frame B.

On November 24, 2022, visual analysis of spectrograms acquired from hydrophone 1 on Frame A2 (i.e., A2.1) suggested data quality issues with this channel. Initially this was thought to be a sudden failure in the channel, which prompted switching to channel A2.2 to continue all ambient noise, ShipSound, and marine mammal data analysis. During the preparation of this report it was found that this channel failure started back in August 2022 as a slow but steady channel degradation, which only affected low frequency bands. The failure became most evident by November 2022 mostly for frequencies ≤100 Hz. Due to computational time constraints, the ShipSound and marine mammal detection November results in this report include data from A2.1 and A2.2. The November ambient noise results were re-processed to include only channel A2.2.

Table 1. Recorder deployment locations and periods in 2022 (Year 4). The deployment locations are also shown in Figure 1.

<table>
<tr><th>Recorder</th><th>Latitude (N)</th><th>Longitude (W)</th><th>Water depth (m)</th><th>Hydrophone Height off Bottom (m)</th><th>Active hydrophone array</th><th>Hydrophone model</th><th>Component</th><th>Analysis period start</th><th>Analysis period end</th></tr>
<tr><td rowspan="4">Frame A</td><td rowspan="4">48°45.56672'</td><td rowspan="4">123°3.85010'</td><td rowspan="4">193</td><td rowspan="2">2.2</td><td rowspan="2">Frame A2.1</td><td rowspan="2">HTI 99-HF</td><td>Ambient</td><td rowspan="2">Jan 1 00:00</td><td>Oct 31 23:59</td></tr>
<tr><td>ShipSound, marine mamal</td><td>Nov 24 23:59</td></tr>
<tr><td rowspan="2">0.9</td><td rowspan="2">Frame A2.2</td><td rowspan="2">HTI 99-HF</td><td>Ambient</td><td>Nov 1 00:00</td><td rowspan="2">Dec 31 23:59</td></tr>
<tr><td>ShipSound, marine mamal</td><td>Nov 25 00:00</td></tr>
<tr><td>Frame B</td><td>48°45.65731'</td><td>123°3.65912'</td><td>195</td><td>2.2</td><td>Frame B1.1</td><td>GTI M36-V35-100</td><td>Ambient, ShipSound, marine mamal</td><td>Jan 1 00:00</td><td>Dec 31 23:59</td></tr>
</table>

The hydrophone arrays were mounted on the tetrahedral ULS frames, with the top hydrophone (channel 1) 2.2 m above the seafloor and the bottom three hydrophones (channels 2–4) 0.9 m above the seafloor (Figure 2). Each channel of the activated ULS arrays recorded at 512,000 samples per second (10 Hz to 256 kHz recording bandwidth) with 24-bit resolution. As described in Section 2.2, ULS sound levels in this report are from channel 1 of the chosen active hydrophone array, unless otherwise noted (see Table 1).

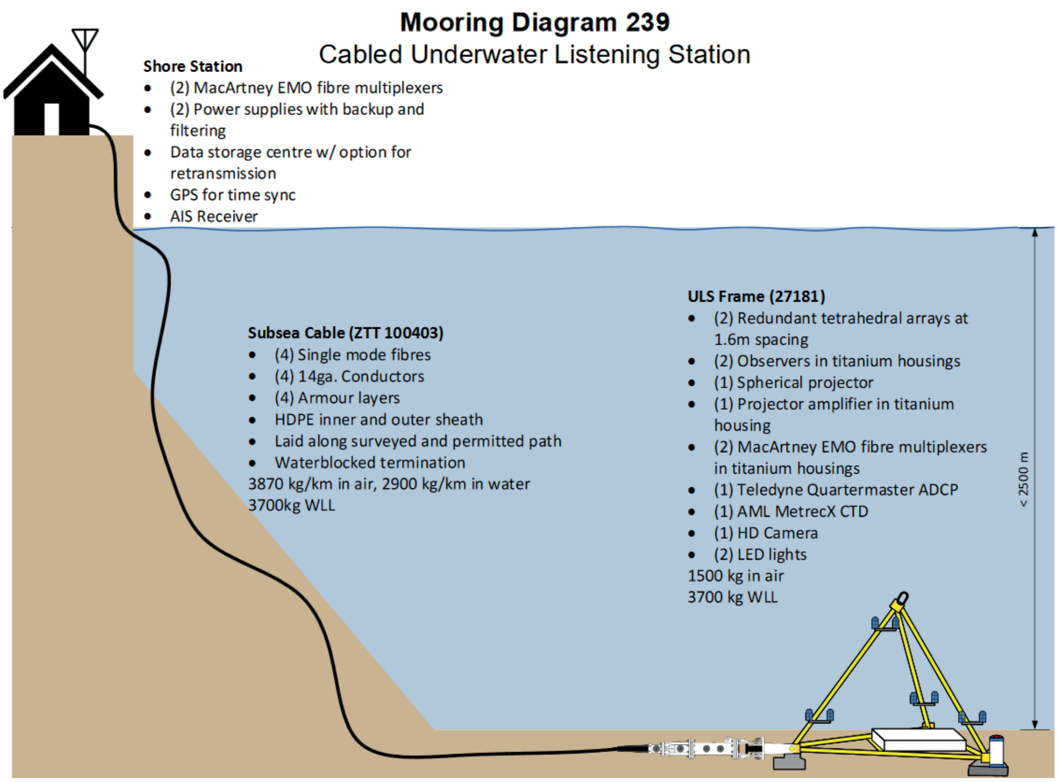

Figure 2. Boundary Pass Underwater Listening Station (ULS) mooring (JASCO mooring design 239).

2.1.2. Water Current Measurements

Water current was measured using a Quartermaster Acoustic Doppler Current Profiler (ADCP; Teledyne) deployed near the ULS stations (see Figure 1). The ADCP was oriented vertically to measure water current profiles. It operated at 150 kHz. The ADCP was deployed approximately 1 m above the seafloor and measured currents from 10 m above the ADCP in 8 m bins over a range of 158 m.

Table 2. Acoustic Doppler Current Profiler (ADCP) recorder location and recording periods during Year 4 (2022).

ADCP serial number	Centre frequency (kHz)	Latitude	Longitude	Water depth (m)	Start (UTC)	End (UTC)
24647	150	48°45.38400' N	123°3.91000' W	205	2022 May 13 19:00	2022 Nov 10 17:51

In addition, the WebTide Tidal Prediction Model (v0.7.1) (Foreman et al. 2000, Institute of Ocean Sciences 2015) was used as source of current data for time periods outside of the operation of the ADCP. The WebTide model predicts current speeds in the north-south and east-west directions as a function of time and location.

Knowledge of the water currents is important for this analysis, since high currents have been associated with high current-induced flow noise at the hydrophones, mostly affecting the 10-100 Hz band. For this reason, the ADCP data was studied to determine the current at which a significant increase in flow noise was observed. Figure 3 shows SPL noise distributions in the 10-100 Hz band, parameterized by the current speed measured by the ADCP. It was found that the noise distribution shifts to higher sound levels for currents greater than 0.25 m/s. At higher speeds, the hydrophone acoustic data is presumed to be significantly affected by current-induced flow noise. This information was used for the frame comparison in Section 3.1.1, to exclude instances of data that is likely affected by high flow noise.

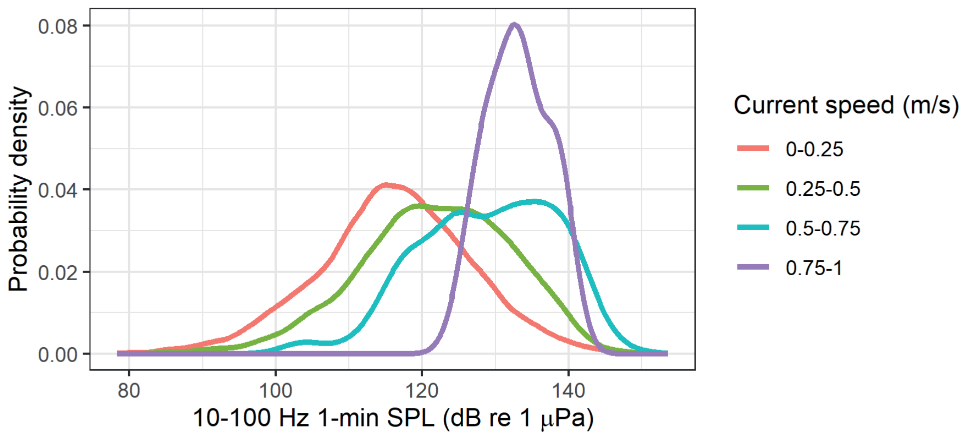

Figure 3. Low-frequency 10–100 Hz sound pressure level (SPL) distributions for different current speed intervals measured by the Acoustic Doppler Current Profiler (ADCP) near the ULS frames. To remove the potential effect of shipping noise, this plot excludes data corresponding to instances when vessels were in the proximity of the ULS.

2.1.3. Vessel Traffic Logging

Automatic Identification System (AIS) data were acquired by onshore recording stations on Saturna Island (see Figure 1). The AIS data are a reliable source of traffic information for large vessels. Small vessels are not required to transmit AIS data, but some choose to do so for traffic safety reasons. AIS vessel traffic data, therefore, represents most large commercial vessel traffic but only a portion of the non-commercial vessel traffic.

2.1.4. Wind Speed Measurements

Hourly wind speed measurements were downloaded from Environment Canada. Wind speed measurements were obtained from the Saturna Island CS weather station, located at East Point on Saturna Island, approximately 3 km from the ULS frame locations. Wind speed measurements from the Kelp Reefs weather station, located in Haro Strait approximately 27 km from the ULS frames, were used for times when the Saturna Island CS weather station data were unavailable.

The effects of wind speed on sound levels were similar to what was found in the previous years for the ULS recordings, where sound levels in the 10–100 Hz, 100–1000 Hz, 1–10 kHz, and 10–100 kHz bands increased when wind speeds exceeded between 2–7 m/s, depending on the band (Cusano et al. 2021). We therefore do not present the repeated analysis results in this report. Wind speeds are also used by ShipSound, since high winds can cause frictional drag on vessels and affect ocean surface conditions, both potentially influencing vessel noise emissions.

2.2. Data Analysis

2.2.1. Ambient Noise Analysis

For most of 2022, the ULS sound levels in this report are from channel 1 (the top hydrophone) of the chosen active hydrophone array. The only exception is for Frame A when we swapped over from channel 1 (A2.1) to channel 2 (A2.2) due to the performance issues with channel 1. Channel 2 (1.43 m deeper than channel 1) has been used from that point forward. Channel 2 on Frame A was selected as the primary channel from November 1 to December 31.

Analysis of ambient noise was conducted using JASCO's PAMlab acoustic analysis software suite. The quarterly ambient noise reports submitted to VFPA throughout the year presented spectrograms, decade-band and decidecade-band (approximately equivalent to 1/3-octave-band) level statistics, power spectral density percentiles, and plots of sound levels as a function of day of the week and hour of the day (Grooms and Warner 2021, Zammit and Warner 2021b, 2021a, Grooms and Warner 2022). Those initial analyses were conducted on acoustic data spanning the entire reporting period. Appendix A shows an example ambient noise analysis report for one month, which includes the data analysis methods. The ambient noise analysis in the present report investigates differences between sound levels measured on different hydrophone channels for 2022, and also summarizes ambient noise statistics for the entire 2019-2022 period. These quarterly reports are generated using data collected from Frame B1.1 and are therefore unaffected by any changes in hydrophone or performance issues noted of Frame A.

2.2.2. Marine Fauna Detections

Automated detectors for killer whale, humpback whale, Pacific white-sided dolphin, and fish sounds were applied to channel 1 data from each ULS frame. The detectors, which are customized for each species and call type, are part of JASCO's PAMlab software suite. The killer whale detector does not differentiate between ecotype populations of killer whales, so ecotype classification was manually performed by an experienced analyst (A. Houweling) by listening to and viewing spectrograms of the automatically detected killer whale calls and reclassifying them to ecotype level. This report includes a division of the killer whale detections into two ecotype classifications:

- Southern Resident killer whale (SRKW), and
- Transient/Bigg's killer whale.

It is important to note that the comparative number of detections between SRKW and Transient/Bigg's can be misleading in terms of presence because SRKW are much more vocal.

All detections were manually verified by experienced analysts, and false detections were identified and reclassified. The verified detection results were presented in reports by calendar month (Houweling and Belanger 2022, Houweling et al. 2022a, Houweling et al. 2022b, Belanger and Maxner 2023). Appendix B shows an example marine mammal detection report, which describes the detection algorithms. The present report summarizes the verified marine fauna detection results for Year 4 (2022).

The two ULS frames (A and B) were used to collect acoustic data in Boundary Pass during Year 4. Most calls were detected on both frames as the frames were relatively close to each other (~300 m apart). To prevent double counting detections, both frames' acoustic data were analyzed and only the highest detection count per encounter was reported. This allows only one recorder's analyzed data to be used at a time. Thus, acoustic data presented in this report were from channel 1 of Frame B and channels 1 and 2 for Frame A (see periods in Table 1).

We are satisfied with the killer whale detector, even though there was a fairly high false positive rate (45%) in the presence of certain types of vessel noise, such as when an engine/propeller speed changed rapidly. The detector performed accurately in most instances of visual killer whale detections made from Saturna Island as well as citizen science sightings reported from vessels. In addition, acoustic detections were present when no visual identifications were made. The few instances of false positives, not related to vessel noise, were triggered by humpback whale songs that occur at high frequencies, usually in late fall. These vocalizations can be identified manually and reclassified by viewing spectrograms while simultaneously listening to the humpback calls. This does not support retraining the killer whale detectors, as we must account for variability in overlap between marine mammal vocalizations. Due to the diverse repertoire of humpback whales and overlapping frequencies of humpback whale songs and killer whale whistles, it is unlikely to have no killer whale false positives. When using detectors for research purposes, false positives are favored to minimize the probability of missing any calls (false negatives) and can be corrected following manual verification of the detected calls. In alternative applications where automatic detections are not verified manually to remove false positives, additional consideration must be given to favour less sensitive detectors in order to balance the percentage of false positives that are acceptable to the percentage of false negatives. Continuing to operate the original detectors provides and maintains consistency in the results of this multi-year project.

A new reclassification feature added to PAMview in 2022 allows experienced analysts to manually reclassify species that were misclassified by the detector. Another feature added allows for manual ecotype analysis of killer whale detections to be recorded in PAMview. This feature has proven to be beneficial in exploring diurnal trends specific to killer whale ecotype through presence/absence plots (see Section 3.2).

2.2.3. Vessel Source Levels

Vessel source levels were calculated using ShipSound, a component of JASCO's PortListen® online noise measurement system. The methods are fully described in Appendix C. Acoustic data from channel B1.1 and channels A2.1 and A2.2 were utilized for this purpose. The analysis for this report consists of a summary of the number of measurements that passed the quality control checks described in Appendix C. The quality control acceptance criteria include the signal-to-noise-ratio thresholds of ANSI S12.64 but not the distance-from-station or propagation angle criteria.

3. Results

3.1. Ambient Noise Results

Monthly ambient noise results have been provided in quarterly reports submitted to VFPA throughout the year 2022. In this section we present results to quantify the consistency between sound levels measured simultaneously on the two frames, and the variability in ambient noise levels over time.

3.1.1. Comparison of Sound Levels Between Frames and Channels

Frames A and B were operating within approximately 300 m of each other, and the relatively minor environmental differences between deployment locations are not expected to significantly influence sound levels. To verify the agreement between recorder channels, we considered data from the following periods and compared the cumulative distribution functions (CDFs) of the measured SPL:

1. January 1 to October 31, 2022: Frame A2 channel 1 and Frame B1 channel 1
2. November 1 to December 31, 2022: Frame A2 channel 2 and Frame B1 channel 1

For consistency with previous annual reports this section compares channel performances based on the CDF of the measured SPL. For completeness, Appendix E provides similar plots corresponding to the probability density functions (PDFs).

Figures 4 and 5 show the decidecade band level CDFs from the first overlap period of January 1, to October 31, 2022, for quiet and loud periods, respectively. Frame B1 was operating with GTI (GeoSpectrum Technologies Inc.) hydrophones and Frame A2 was using HTI (High Tech Inc.). The data for these CDFs were pre-filtered to exclude periods that are likely to be affected by high flow noise associated with current speeds greater than 0.25 m/s (as explained in Section 2.1.2). For quiet periods, data collected while AIS vessels were within 6 km of the hydrophones were excluded. For loud periods, no filter was applied for the presence of vessels. For the quiet periods (Figure 4), the CDFs from the two frames are in good agreement to each other in the 100-4,000 Hz bands. Below 100 Hz there are small deviations between the two channels which is attributed to data between August and October affected by the performance issues with A2.1 (Section 2.1.1). Above 4,000 Hz there is larger disagreement between recorders, particularly above 8,000 Hz due to the difference in hydrophone models. For the loud periods (Figure 5), the differences between CDFs from the two channels are significantly reduced for all frequencies up to 25,000 Hz. The agreement between channels is excellent between 50-8,000 Hz, and there are only minor differences at frequencies lower than 50 Hz. The CDF differences between 31,500-250,000 Hz were approximately the same as for periods without AIS-broadcasting vessels. The good agreement between channels at low frequencies when vessels were present suggests that the differences during quiet times are likely driven by local noise conditions at each frame, as well as the performance issues with channel A2.1 between August and October.

The progression of the performance issues on channel A2.1 is evident when comparing the time series SPL between the two frames(Figure 6): for most of the period there is good agreement between the two frames, but in mid August 2022, the performance of channel A2.1 seems to steadily degrade for frequencies ≤250 Hz. This degradation of channel A2.1 is more evident in quiet scenarios, as evidenced by the CDF comparisons in Figure 4 (quiet) versus Figure 5 (loud).

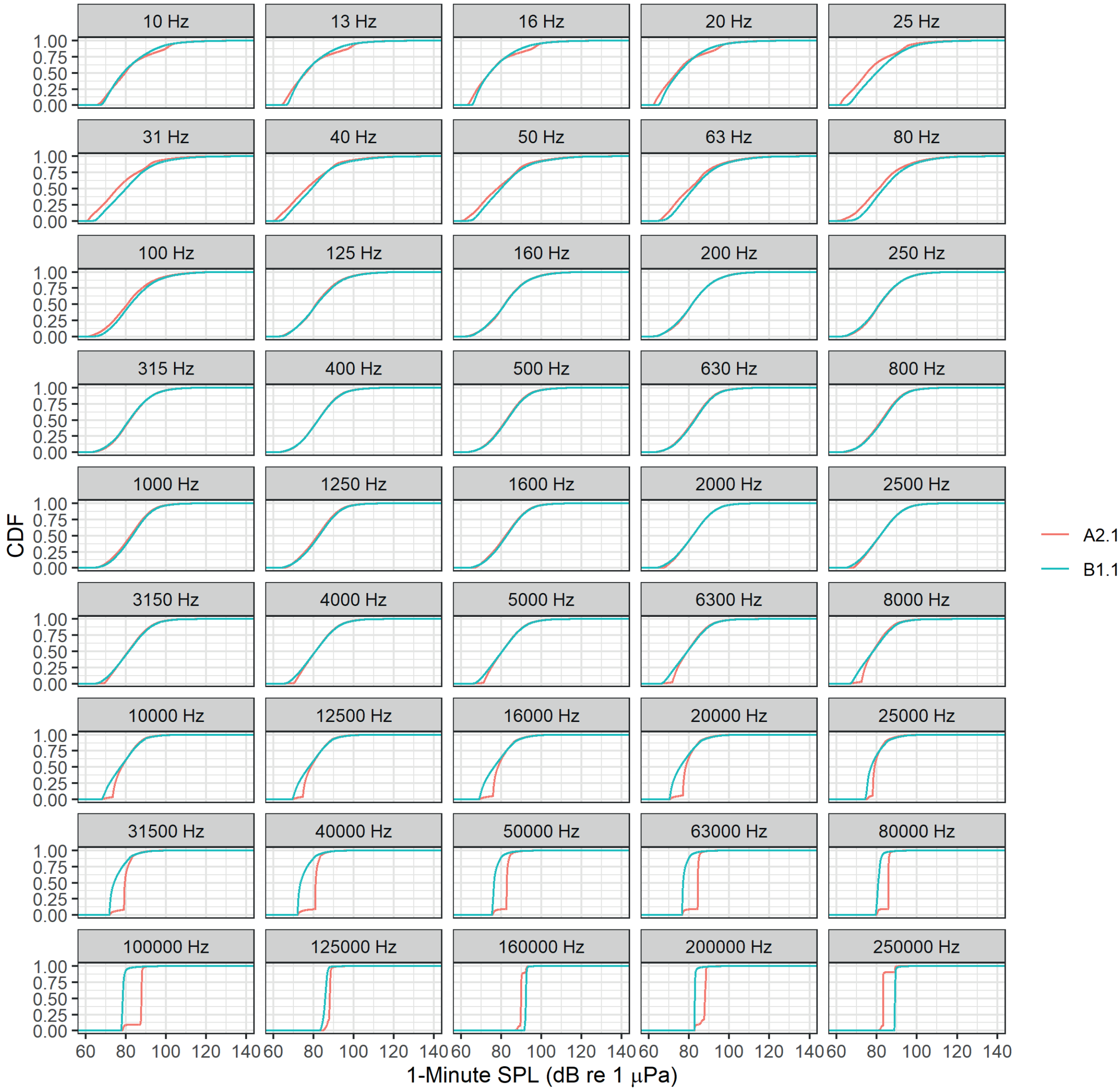

Figure 4. 1 Jan to 31 Oct 2022, during quiet periods: Cumulative distribution functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.1 and B1.1). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.25 m/s. Panel headings indicate the centre frequency of the decidecade band.

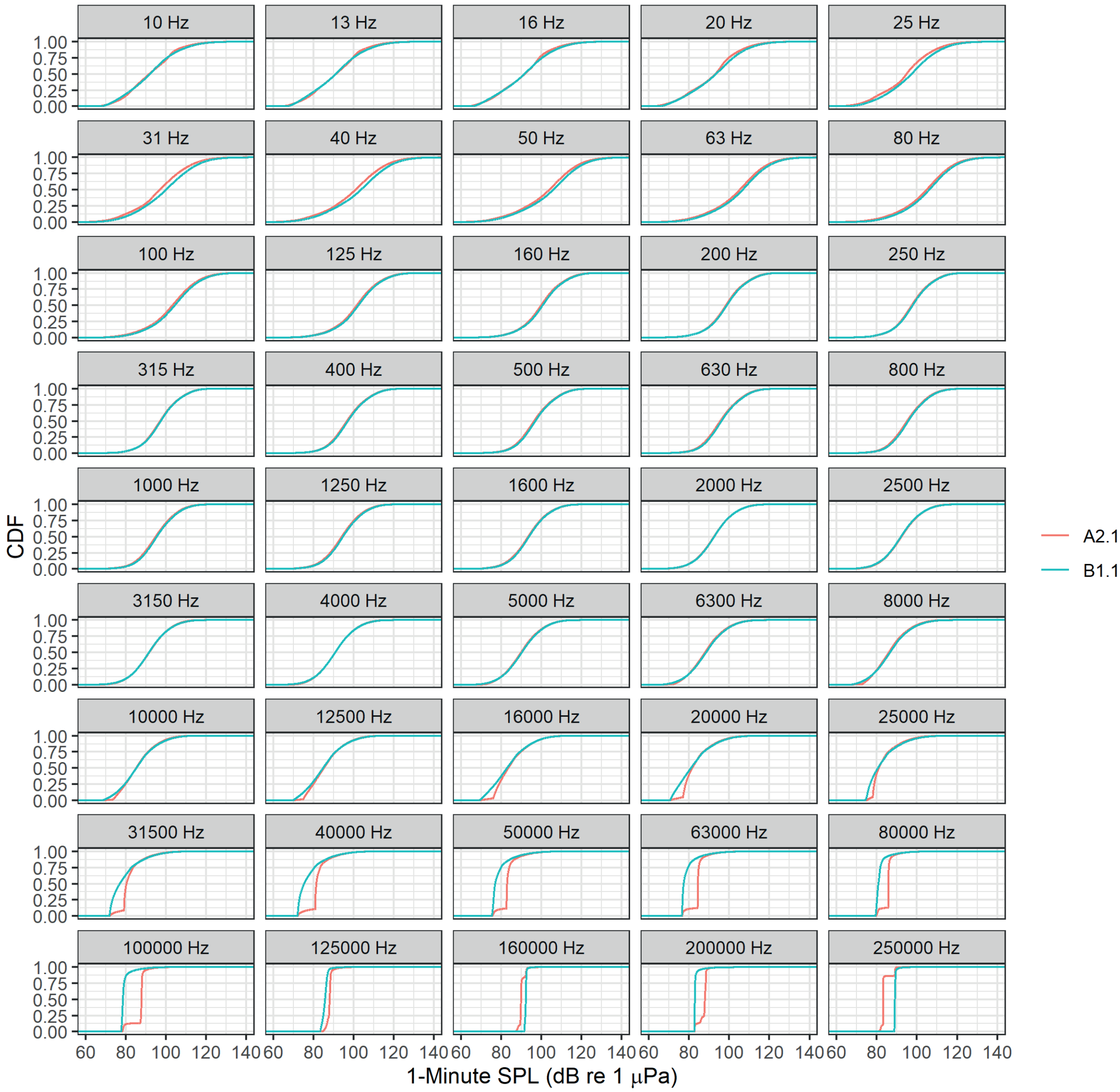

Figure 5. 1 Jan to 31 Oct 2022, during loud periods: Cumulative distribution functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.1 and B1.1). Data were pre-filtered to exclude minutes when current speeds were greater than 0.25 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.

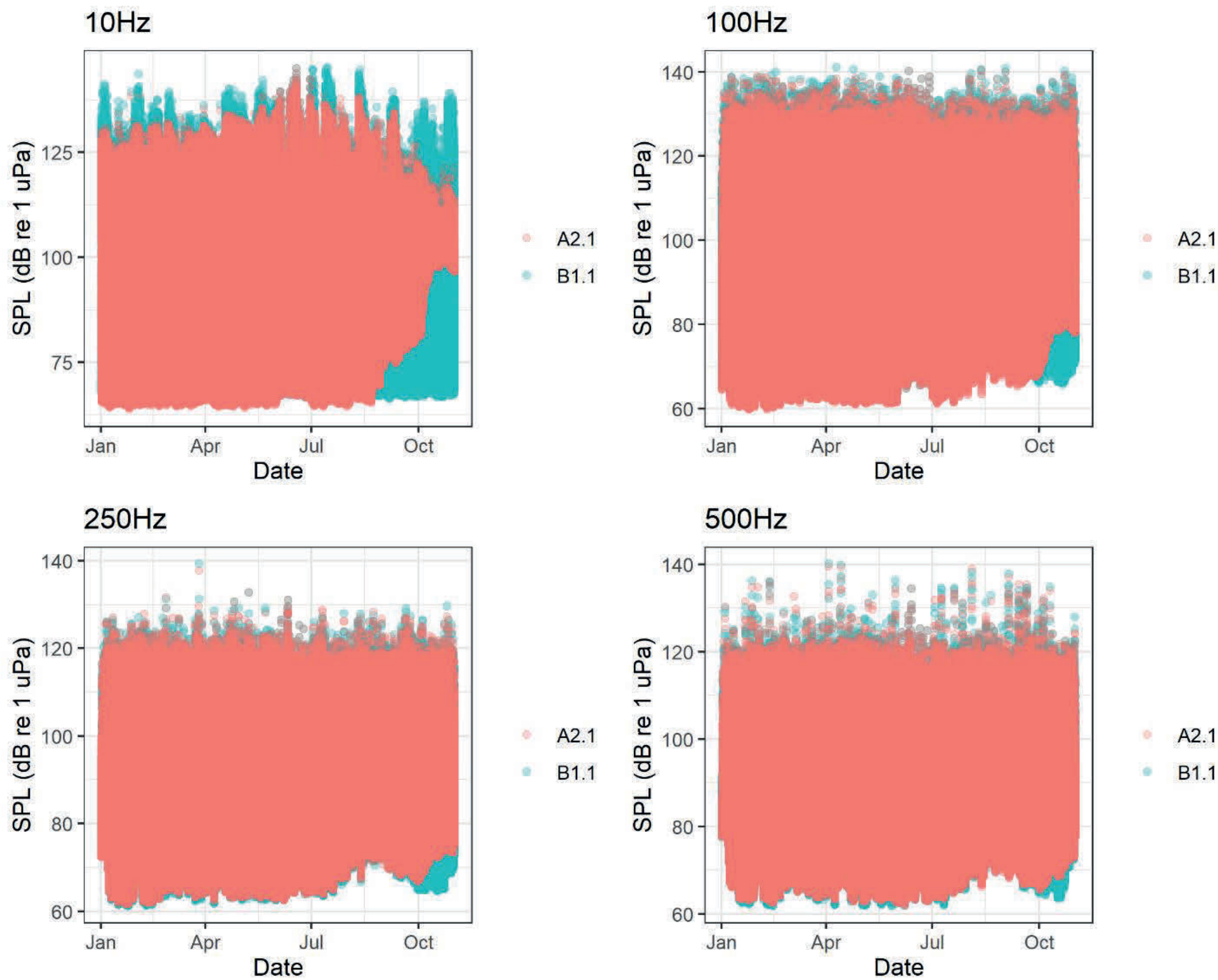

Figure 6. 1 Jan to 31 Oct 2022: SPL in the 10, 100, 250, and 500 Hz bands measured by channels A2.1 and B1.1, showing steadily increasing performance degradation for channel A2.1 from Aug 2022. Frequencies above 500 Hz (not shown here) were not affected by this issue.

Figures 7 and 8 show a similar comparison of CDFs for quiet and loud periods, respectively, but this time on Channels B1.1 and A2.2 for November 1 to December 31, 2022. For the quiet period (Figure 7), measurements from both channels are in excellent agreement for frequencies 160-5,000 Hz. Below 160 Hz small differences between channels can be observed, with A2.2 yielding slightly lower SPL compared to B1.1. As in Figure 4, the main differences between channels occur at frequencies greater than 8,000 Hz. During the loud period (Figure 8), there is excellent agreement between channels at all frequencies <12,500 Hz. At higher frequencies, the comparison between the CDFs is similar to the quiet period.

The agreement between the channels for Dec 2022 is also shown as a the time series comparison of the SPL (Figure 9).

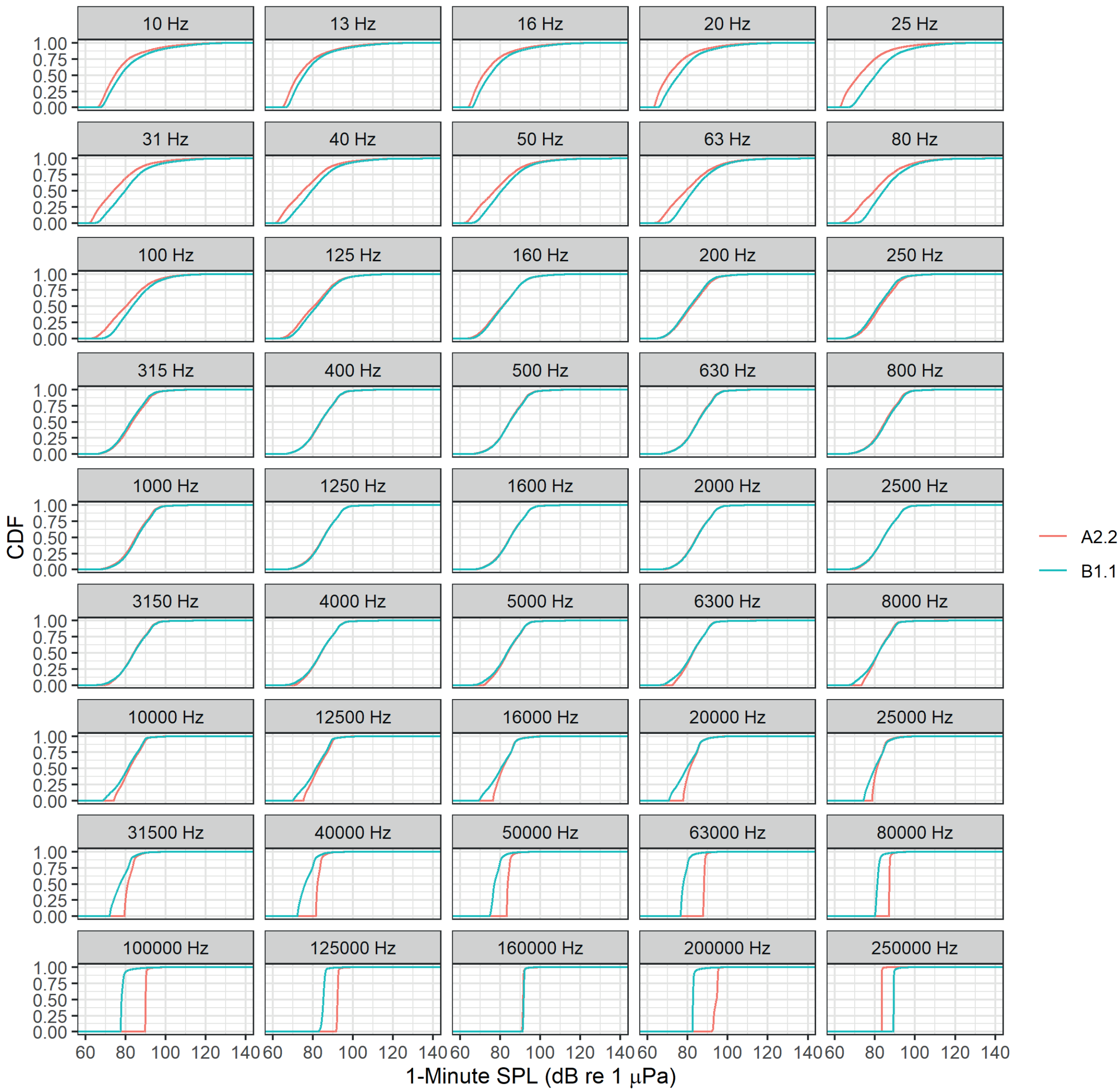

Figure 7. 1 Nov to 31 Dec 2022, during quiet periods: Cumulative distribution functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.2 and B1.1). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.25 m/s. Panel headings indicate the centre frequency of the decidecade band.

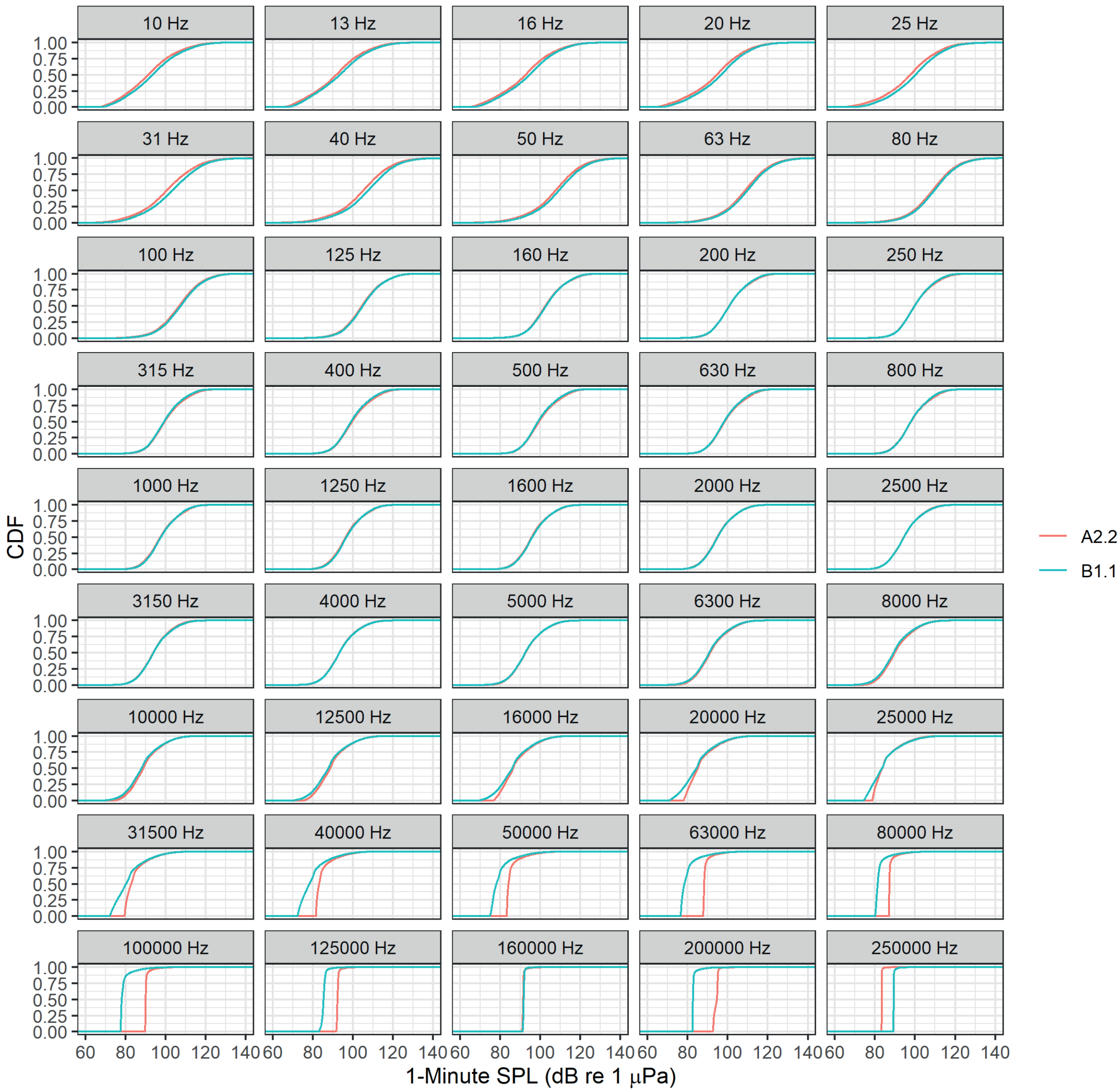

Figure 8. 1 Nov to 31 Dec 2022, during loud periods: Cumulative distribution functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.2 and B1.1). Data were pre-filtered to exclude minutes when current speeds were greater than 0.25 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.

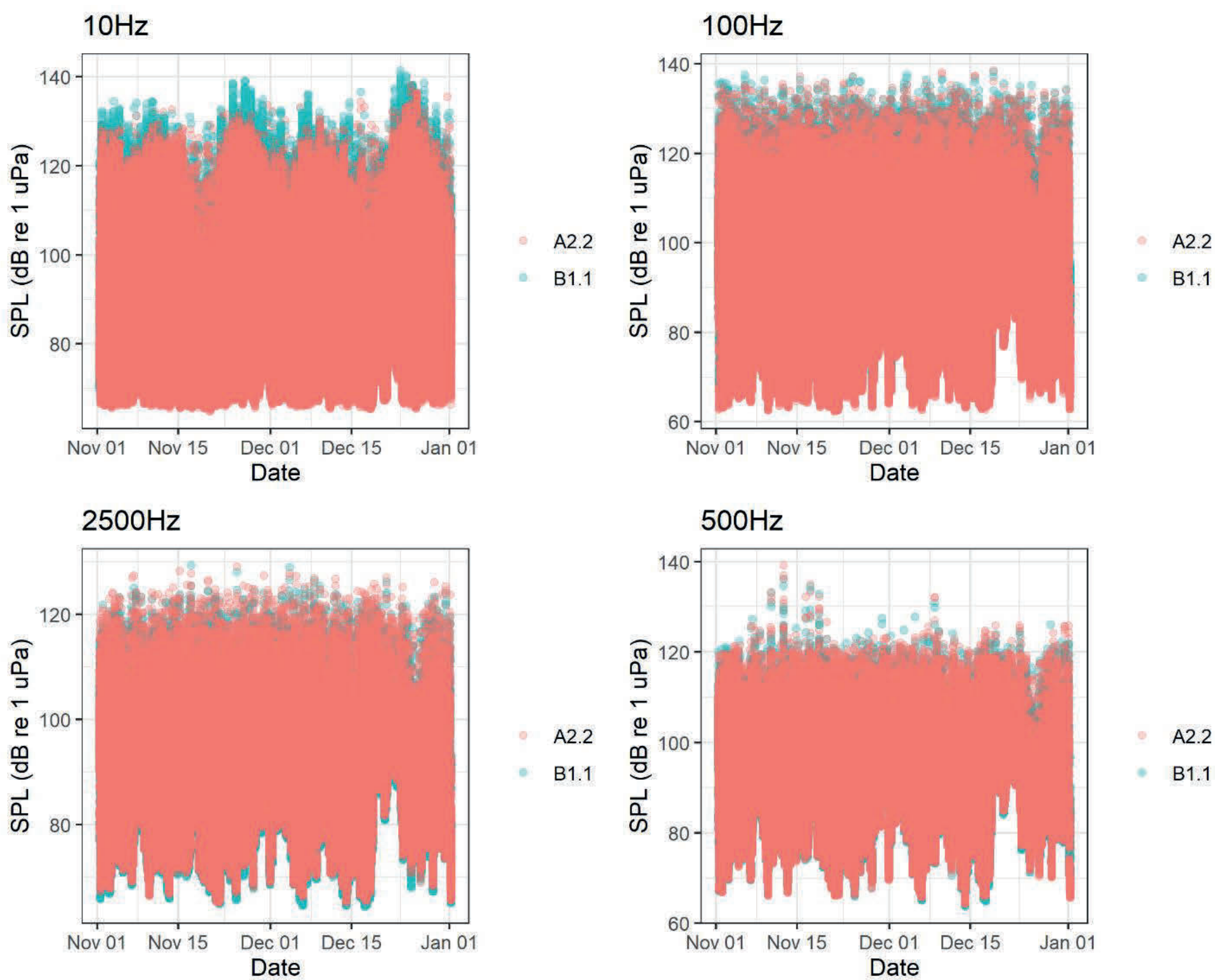

Figure 9. 1 Nov to 31 Dec 2022: SPL in the 10, 100, 250, and 500 Hz bands measured by channels A2.2 and B1.1, showing good agreement to each other.

3.1.2. Noise statistics for 2019-2022

Figure 10 shows box-and-whisker monthly statistics of ambient noise (maximum, minimum, and 75th, 50th, and 25th percentiles) over the period 2019-2022. The following general features can be observed:

- Prior to June 2020 data were collected using Autonomous Multichannel Acoustic Recorder (AMAR) G3 and G4 units, which were found to be affected by low frequency flow noise. This was likely due to their mooring deployment configuration. The mooring in the G4 units (February 2020 - June 2020) were more affected by this type of noise, thereby yielding the highest broadband noise levels.
- There is a noticeable drop in broadband SPL after June 2020, once data collection switched to the cabled ULS. The rigid frame of these units generated less noise than the AMAR moorings (which included noisier flotation and mechanical joints between components).
- There is a small increase in the measured ambient noise right after servicing the ULS in October 2021, likely due to the characteristics of the second deployment.

- In all years there is a decrease in noise around July through October, likely due to lower vessel noise from slower commercial vessels participating in the ECHO Program Haro Strait and Boundary Pass voluntary vessel slowdown. This decrease can also be observed in Figure 11 for 10-100 Hz, which is a band known to be heavily influenced by vessel noise.

Figures 11 and 12 show similar noise trends for bands 10-100 Hz and 100-1,000 Hz, respectively, although the impact of the voluntary slowdown is not as evident in the 100-1,000 Hz band. For the 1,000-10,000 Hz band (Figure 13), the difference in measured noise between AMARs (G3 and G4) and the ULS deployments tend to disappear.

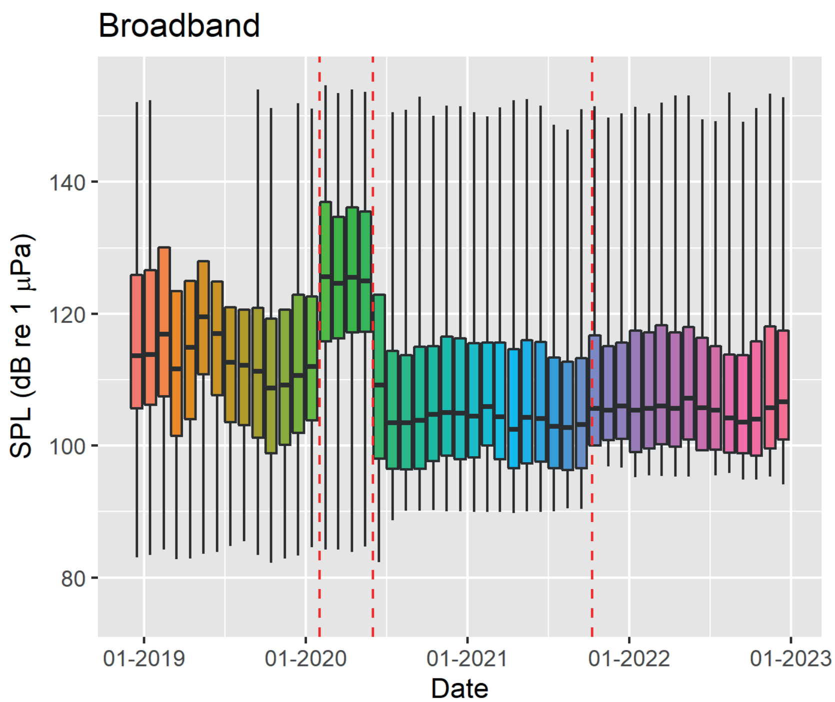

Figure 10. Broadband sound pressure level (SPL; 1 minute) monthly statistics over for 2019-2022. The vertical lines indicate changes in the equipment used for data collection: Autonomous Multichannel Acoustic Recorder (AMAR) G3 were used for data collection prior to Feb 2020, and switched to AMAR G4 from Feb 2020 to mid Jun 2020. From Jun 2020 to Oct 2021 the data were collected on ULS Frames corresponding to the first deployment, and from Oct 2021 to the present, data has been collected on ULS Frames corresponding to the second deployment. Broadband levels include frequencies up to 64 kHz for AMAR units, and up to 256 kHz for ULS units.

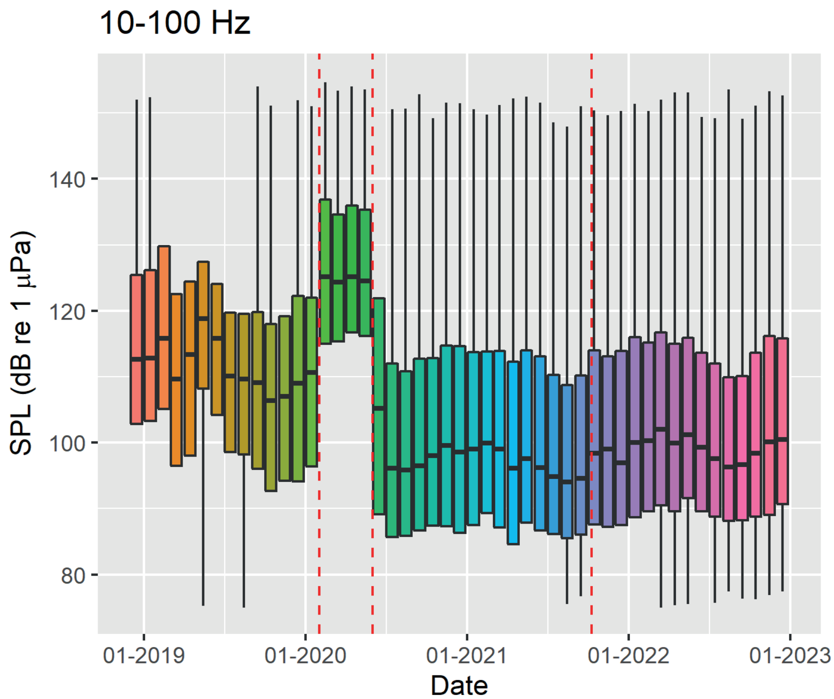

Figure 11. Sound pressure level (SPL; 1 minute) monthly statistics in the 10-100 Hz band for 2019-2022. The vertical lines mark the changes in data collection equipment described in Figure 10.

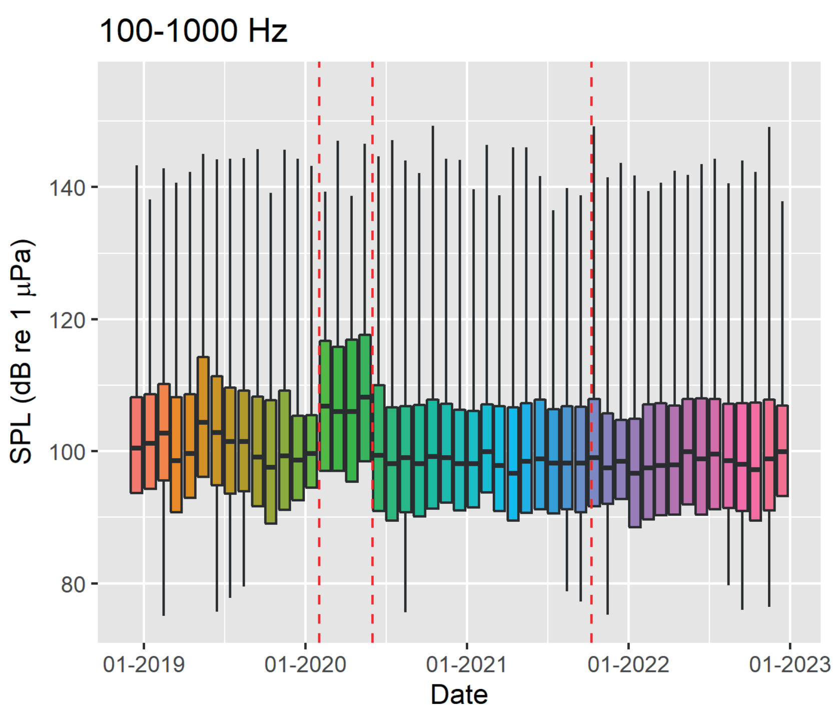

Figure 12. Sound pressure level (SPL; 1 minute) monthly statistics in the 100-1000 Hz band for 2021-2022. The vertical lines mark the changes in data collection equipment described in Figure 10.

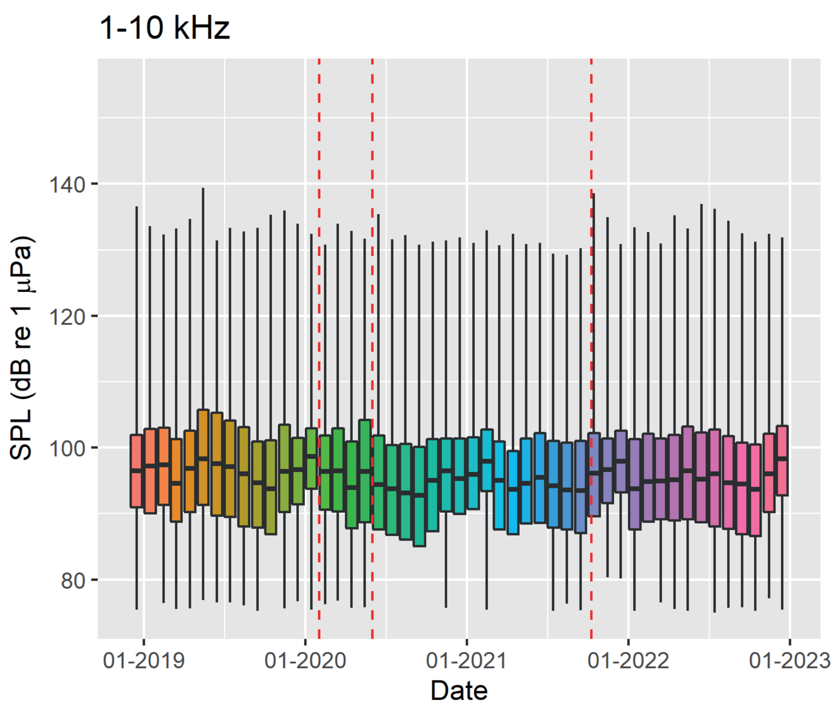

Figure 13. Sound pressure level (SPL; 1 minute) monthly statistics in the 1000-10000 Hz band for 2021-2022. The vertical lines mark the changes in data collection equipment described in Figure 10.

3.2. Marine Fauna Detection Results

During Year 4 (1 Jan to 31 Dec 2022), the manually confirmed detections from the automated detectors reported 10,807 killer whale vocalizations (3978 SRKW and 6829 Transient/Bigg's), 191 humpback whale vocalizations, and 1113 fish sounds (groans, croaks, and knocking) in Boundary Pass. No Pacific white-sided dolphins were detected during this year. Figure 14 shows the proportion of detections by species/group for 2022, with killer whale vocalizations displayed at the ecotype level.

The hourly and monthly detection counts of killer whale vocalizations, humpback whale vocalizations, and fish sounds are detailed in Sections 3.2.1, 3.2.2, and 3.2.3, respectively. All graphs are in astronomical noon time for longitude, where noon on the plot is set based on the time at which the sun is directly overhead, unless otherwise indicated.

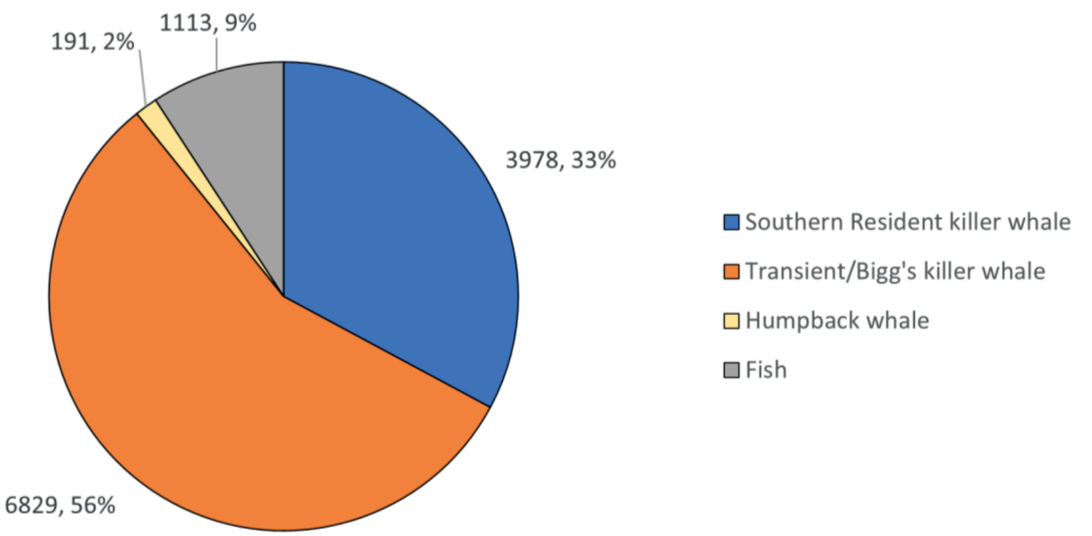

Figure 14. Proportion of detections by marine species/group for Year 4 (1 Jan to 31 Dec 2022).

3.2.1. Killer Whales

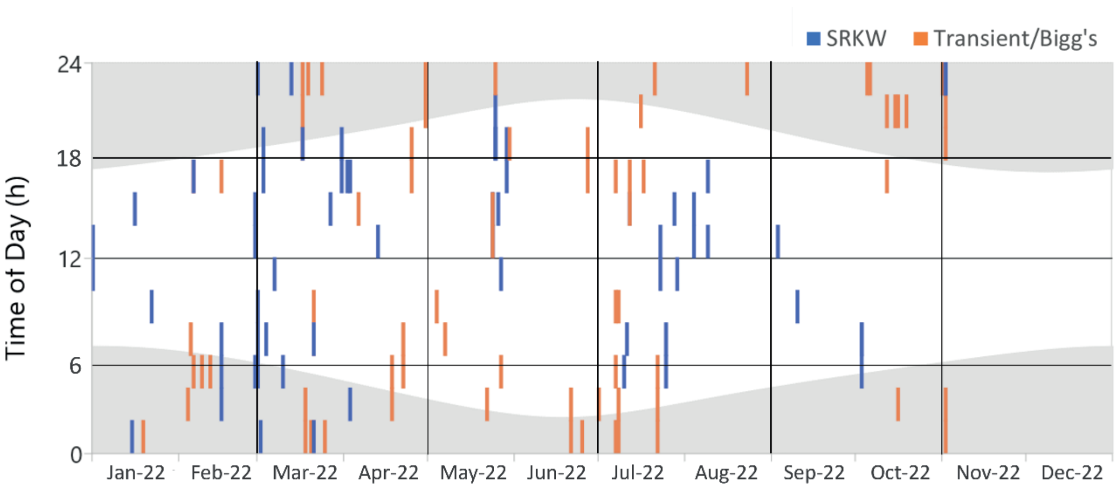

Figure 15. Year 4 (1 Jan to 31 Dec 2022): Daily and hourly occurrence of validated killer whale vocalizations by ecotype—Southern Resident killer whale (SRKW) and Transient/Bigg's—at Frame A or B. Blue blocks indicate validated SRKW detections, orange blocks indicate Transient/Bigg's detections, and grey areas indicate darkness periods. Each block represents an event of 30 minutes of vocal activity or more based on length.

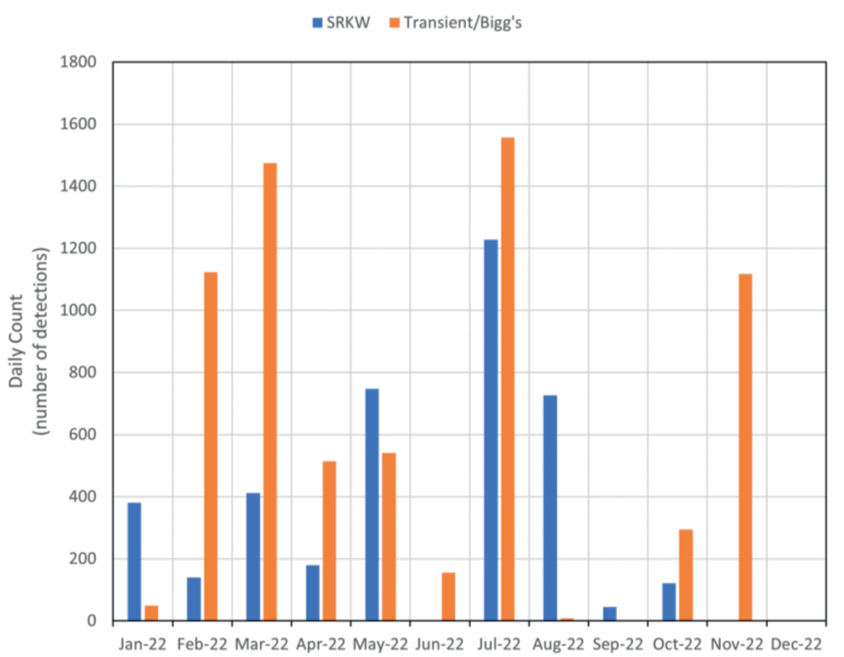

Figure 16. Year 4 (1 Jan to 31 Dec 2022): Monthly validated detection counts of killer whale vocalizations by ecotype—Southern Resident killer whale (SRKW) and Transient/Bigg's—at Frame A or B. The histogram demonstrates killer whale vocal activity across months in 2022, while Figure 15 displays the encounter length per month. When comparing Figure 15 and Figure 16, vocalization density can be inferred. Figure 15 demonstrates the most SRKW events occurred in March and July, while Figure 16 displays vocalizations in March occurred less frequently during each encounter than vocalizations in July, in which a high vocalization density is seen.

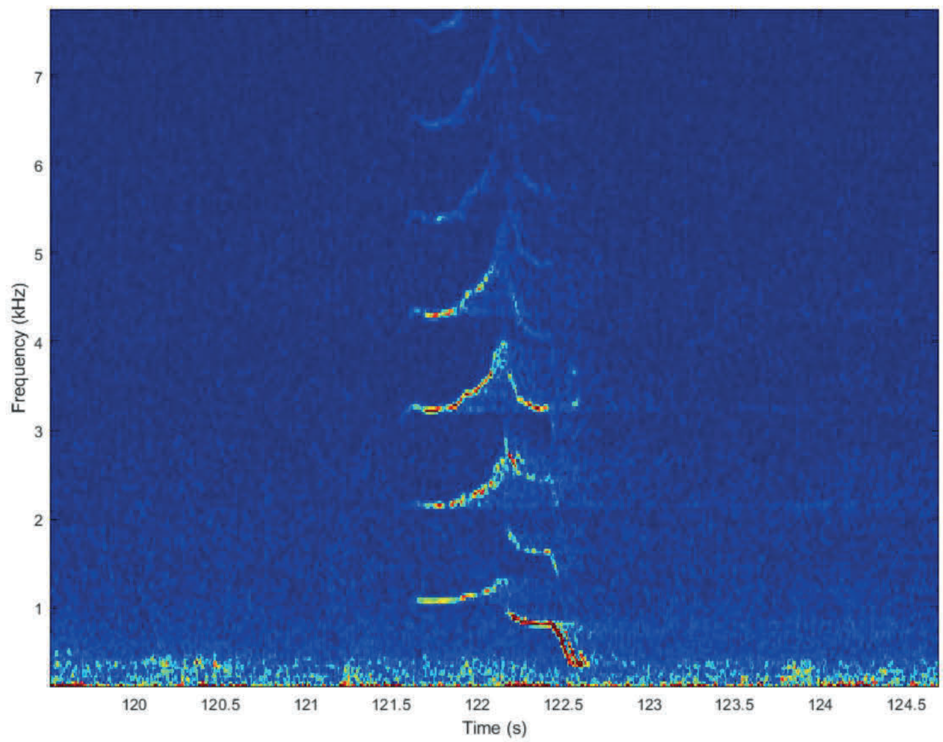

Figure 17. 4 Apr 2022 (01:52): Spectrogram of Southern resident killer whale (SRKW) S01 vocalization at Frame A2.

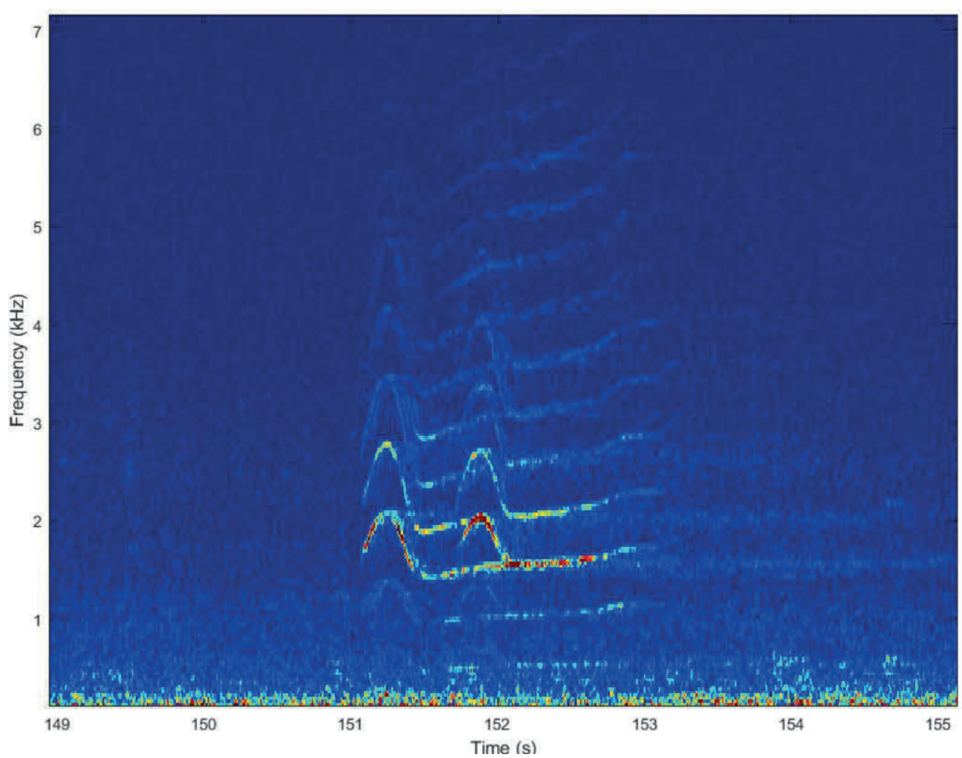

Figure 18. 1 May 2022 (05:03): Spectrogram of Transient/Bigg's killer whale vocalization at Frame A2.

3.2.2. Humpback Whales

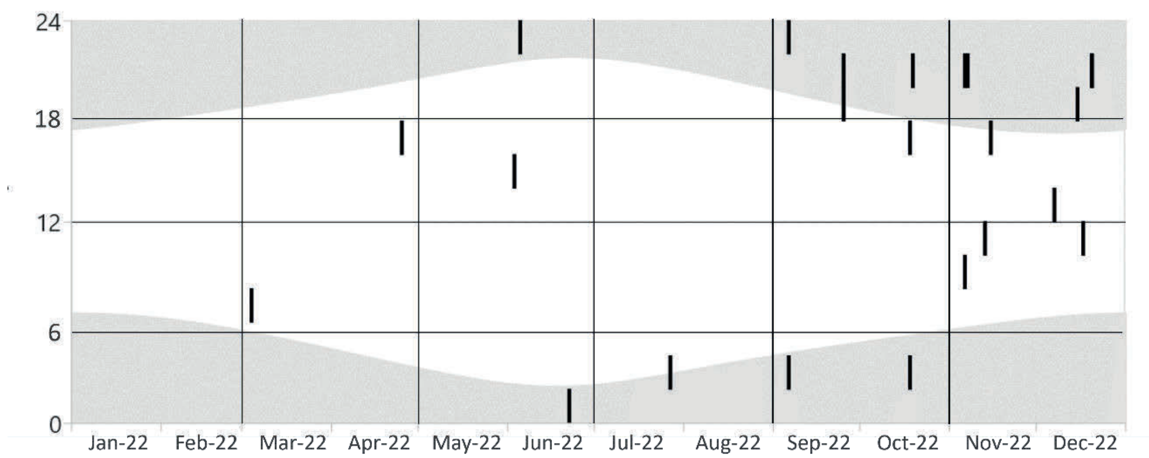

Figure 19. Year 4 (1 Jan to 31 Dec 2022): Daily and hourly occurrence of humpback whale vocalizations at Frame A or B. Black blocks indicate validated detections, and grey areas indicate darkness periods. Each block represents an event of 30 minutes of vocal activity or more based on length.

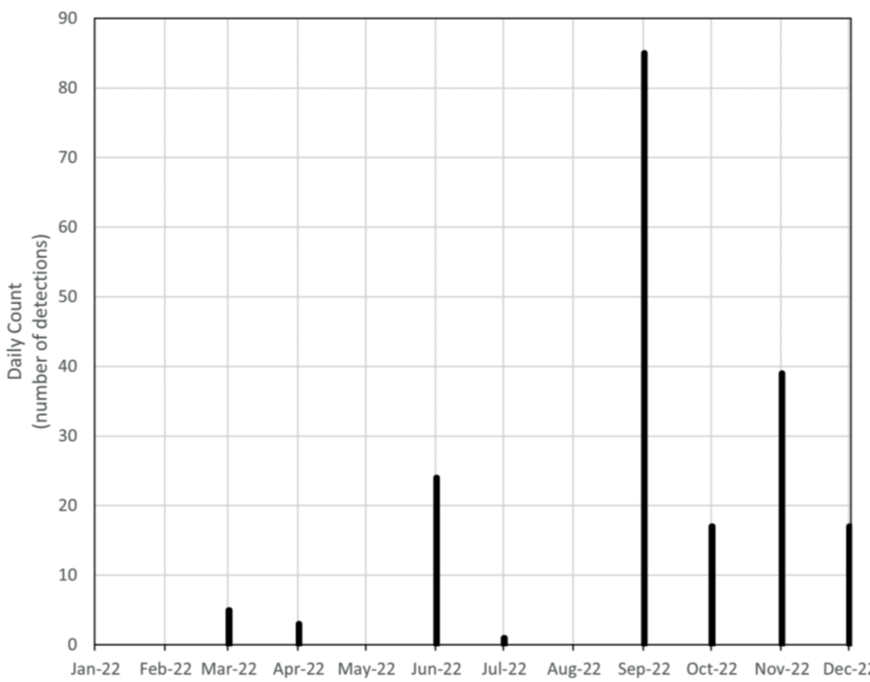

Figure 20. Year 4 (1 Jan to 31 Dec 2022): Monthly validated detection counts of humpback whale vocalizations at Frame A or B. The histogram demonstrates Humpback whale vocal activity across months in 2022, while Figure 19 displays the encounter length per month. When comparing Figure 19 and Figure 20, vocalization density can be inferred. Figure 19 demonstrates the most Humpback whale events occurred in November and December, while Figure 16Figure 20 displays vocalizations in these months occurred less frequently than vocalizations in September, in which a high vocalization density is seen.

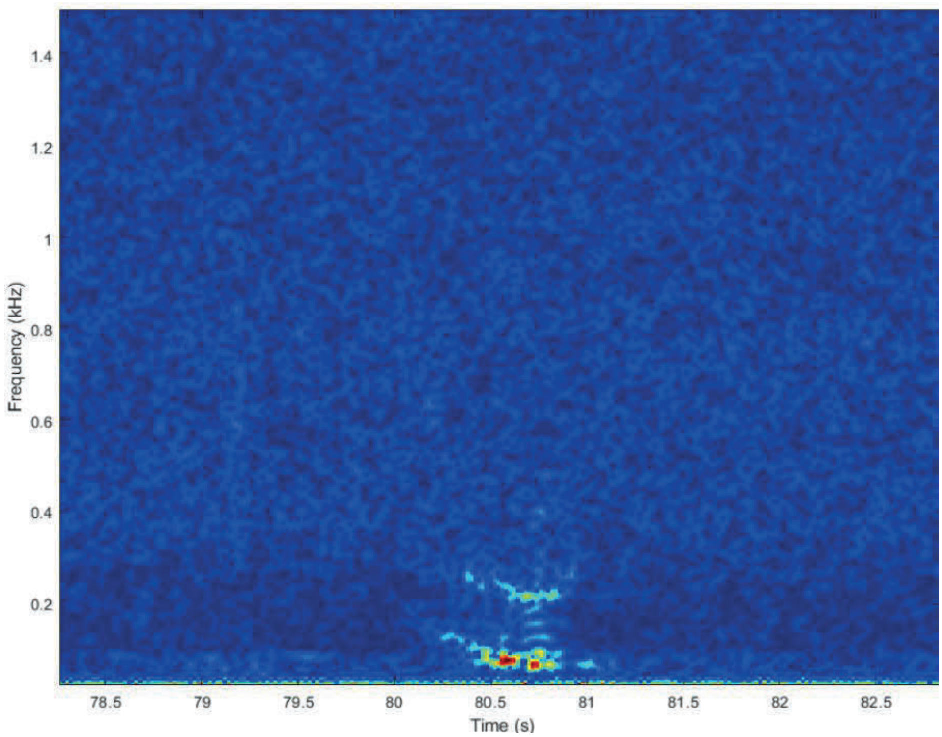

Figure 21. 22 Jun 2022 (09:28): Spectrogram of humpback whale growl at Frame A2.

3.2.3. Fish

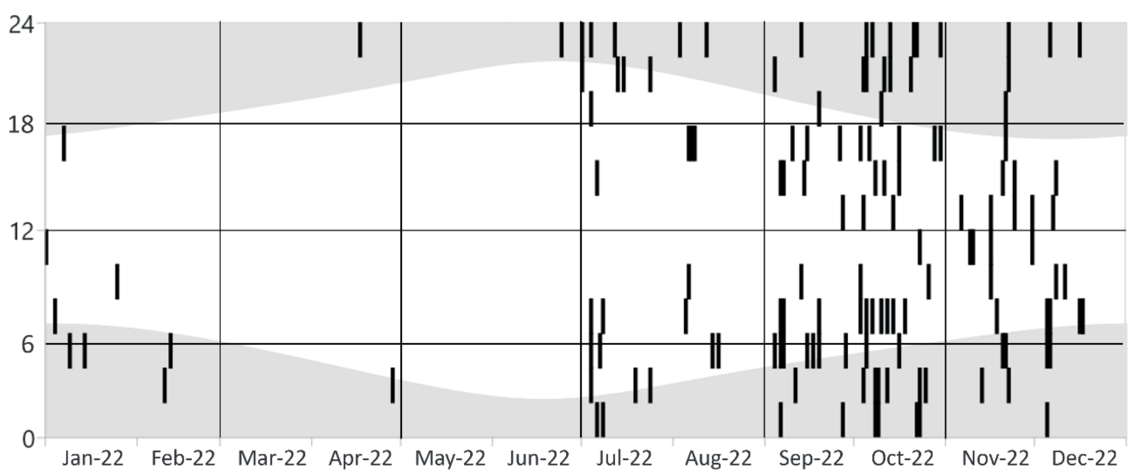

Figure 22. Year 4 (1 Jan to 31 Dec 2022): Daily and hourly occurrence of fish sounds at Frame A or B. Black blocks indicate validated detections, and grey areas indicate darkness periods. Each block represents an event of 30 minutes of vocal activity or more based on length.

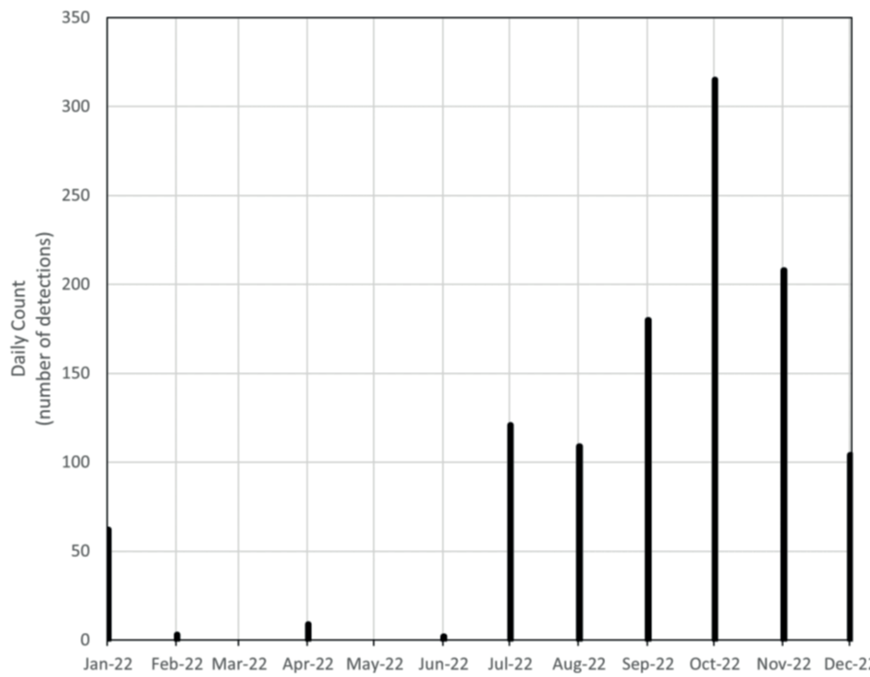

Figure 23. Year 4 (1 Jan to 31 Dec 2022): Monthly validated detection counts of fish sounds at Frame A or B. The histogram demonstrates fish vocal activity across months in 2022, while Figure 22 displays the encounter length per month. When comparing Figure 22 and Figure 23, vocalization density can be inferred. Figure 22 demonstrates the most fish call events occurred in September and October, while Figure 16Figure 23 displays vocalizations in September and November occurred less frequently than vocalizations in October, in which a high vocalization density is seen.

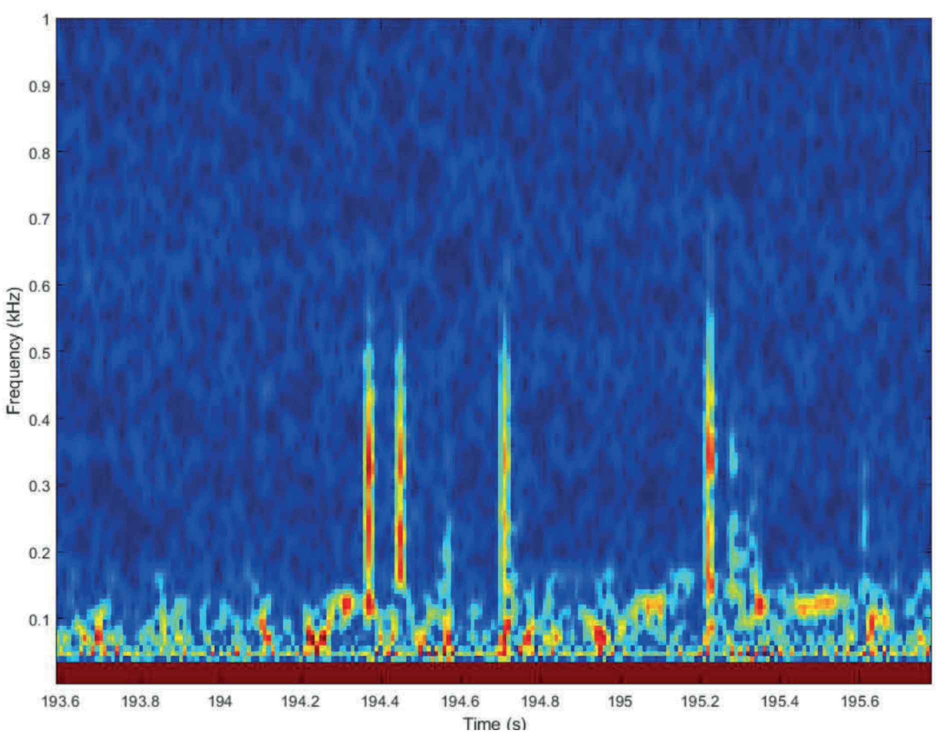

Figure 24. 18 Apr 2022 (06:47): Spectrogram of fish knocks at Frame B1.

3.2.4. Summary

Overall, killer whale vocalizations were detected on 75 days (20.5 % of recording days, see Table 3). The month with the most detection days was July (14 days). Humpback whale vocalizations were detected on 18 days (5 % of recording days, see Table 3) with November having the most detection days (5 days). No Pacific white-sided dolphins were detected on the Boundary Pass recorders during the reporting period. Fish sounds were detected on 84 days (23 % of days analyzed for fish sounds, see Table 3). September had the most days with fish sound detections (14 days).

Table 3. Number of marine mammal detections and days with detections by calendar month for each species/group for Year 4 (1 Jan to 31 Dec 2022).

Month	Humpback whale		Killer whale				Fish	
	Detections	Days with detections	SRKW detections	Bigg's detections	SRKW days with detections	Bigg's days with detections	Detections	Days with detections
Jan	0	0 / 31	381	49	4 / 31	1 / 31	62	5 / 31
Feb	0	0 / 28	140	1123	2 / 28	6 / 28	3	2 / 28
Mar	5	1 / 31	412	1474	7 / 31	4 / 31	0	0 / 31
Apr	3	1 / 30	179	513	4 / 30	4 / 30	9	1 / 30
May	0	0 / 31	747	540	4 / 31	7 / 31	0	0 / 31
Jun	24	3 / 30	0	155	0 / 30	3 / 30	2	1 / 30
Jul	1	1 / 31	1228	1556	6 / 31	8 / 31	121	12 / 31
Aug	0	0 / 31	726	8	3 / 31	1 / 31	109	9 / 31
Sep	85	3 / 30	44	0	2 / 30	0 / 30	180	14 / 30
Oct	17	1 / 31	121	294	1 / 31	6 / 31	315	12 / 31
Nov	39	5 / 30	0	1117	0 / 30	2 / 30	208	12 / 30
Dec	17	3 / 31	0	0	0 / 31	0 / 31	104	7 / 31
Total	**191**	**18 / 365**	**3978**	**6829**	**33 / 365**	**42 / 365**	**1113**	**84 / 365**

3.3. Vessel Source Level Measurement Summary

3.3.1. Measurement Acceptance

Source levels for vessels travelling through Boundary Pass are processed automatically by JASCO's ShipSound application from recordings from both ULS frames. Since the two ULS frames were ~300 m apart and oriented along the shipping lanes, the time window that was processed around the closest point of approach (CPA) to each frame was a bit different, leading to two sets of source levels for most vessel transits through Boundary Pass.

A total of 12,627 vessel source level measurements were made in 2022 and of these, 9,833 (77.9 %) passed the manual quality control checks (see Appendix C for additional details). Since two ULS frames were always operational, it was much more common for both measurements to be accepted than for just one measurement to be accepted. Figure 25 shows the number of vessel transits that yielded zero, one, or two accepted measurements during each month. The graph is dominated by duplicate accepted passes (4,722), followed by zero accepted passes (2,794 cases). The reason for this is that the most common reason for rejection (i.e., the presence of nearby vessels) typically impacts either both or none of the frames.

The 389 cases with a single accepted measurement are rare and could be due to multiple reasons, such as acoustic contamination of the spectrum in one frame but not the other, or cases of a nearby vessel too close to only one of the frames.

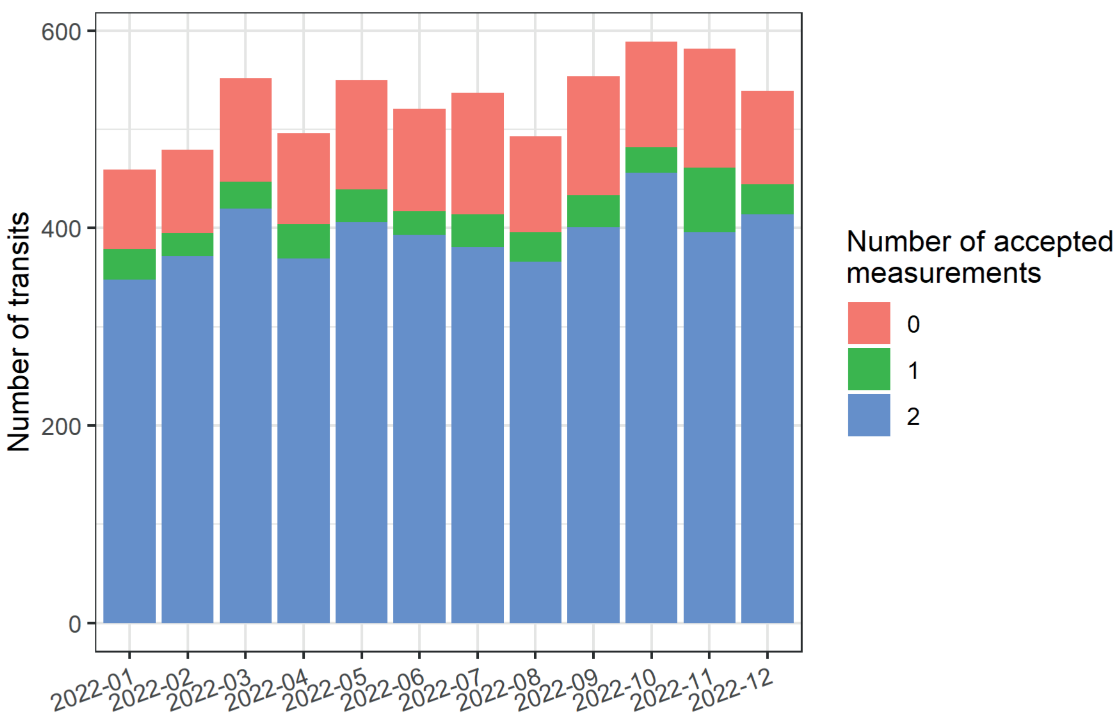

Figure 25. Monthly number of vessel transits through Boundary Pass with zero, one, or two accepted ShipSound measurements in 2022.

The acceptance rates for Frames A and B were 77.0% and 78.8%, respectively. A measurement can be rejected for one or more reasons. Table 4 lists the frequency with which each rejection reason was identified for all measurements, separated by ULS frame. “Other vessels nearby” was the most frequent reason for a measurement rejection. The second-most frequent reason for rejection was that too many frequency bands, especially in the 50–1,000 Hz range, were contaminated by background noise. Ship source levels are typically high in this frequency band, so omitting levels in these frequencies would bias the broadband source levels low.

Some of the louder vessels, or vessels that transited within 100 m of directly over the hydrophone caused some recording system saturation, mainly due to cavitation “pops”. Saturation can introduce artefacts into the measured spectrum that are difficult to remove. Within a measurement window, seconds of data where saturation occurs are removed to avoid these spectral artefacts in the calculated source levels; however, if more than 5 seconds of a measurement were saturated, then the measurement was rejected.

Table 4. Reasons for rejection of source level measurements and the frequency with which they occurred for 2022. Note that rejection reasons are not mutually exclusive.

Rejection reason	Occurrence (%)	
	Frame A	Frame B
Acoustic CPA	0.02	0.00
Vessel sound levels saturated the recording system	2.04	1.12
Many frequency bands contaminated by background noise	5.84	6.03
Other	0.88	0.32
Other vessels nearby	15.66	15.53
Speed range	0.06	0.08

Measurements with larger CPA distances were also found to be less likely to pass the manual quality control checks. Figure 26 shows the cumulative distribution functions for accepted and rejected measurements as a function of CPA distance. Figure 27 shows the acceptance and rejection rates as a function of CPA distance. These findings are similar to those found in the previous annual reports for Years 2 and 3 (Cusano et al. 2021, Houweling et al. 2022a).

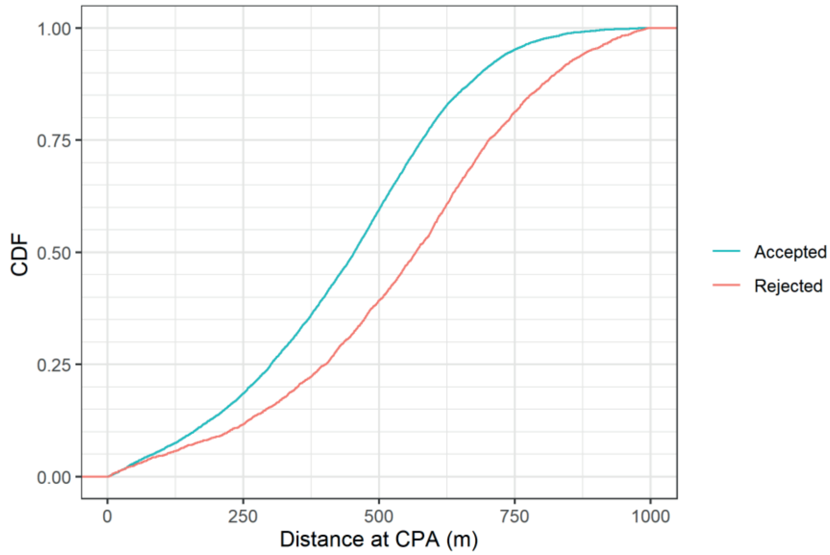

Figure 26. Cumulative distribution functions (CDF) for distance at the closest point of approach (CPA) for vessel measurements that were accepted (passed manual quality control) and rejected (did not pass quality control checks).

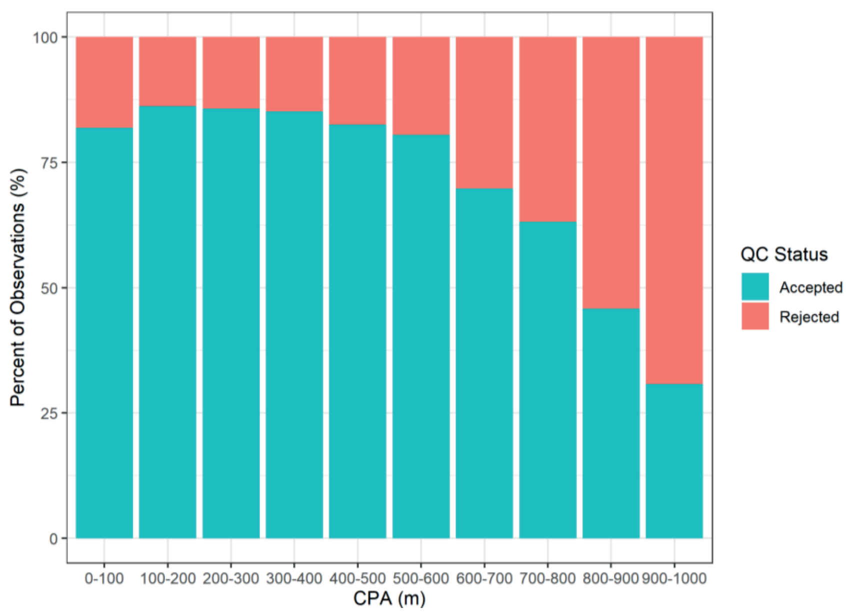

Figure 27. Acceptance and rejection rates of vessels by (horizontal) closest point of approach (CPA) distance.

The hydrophone location was originally chosen to minimize the average horizontal distance of vessel tracks from the ULS based on the historic distributions of inbound and outbound traffic. Figure 28 shows histograms of the CPA distances for accepted and rejected measurements along a line in the cross-track direction. A total of 6,429 outbound measurements (5,044 accepted) and 6,198 inbound measurements (4,789 accepted) are included. Figure 28 is limited to CPA distances of 1 km because that is the maximum measurement distance criterion used in ShipSound. Beyond this distance the rate of rejected measurement is considered too high for repeated measurements as is shown in Figure 27. The histograms in Figure 28 show that the vessels had a more constrained outbound route than when they were inbound (i.e., the outbound histogram was more peaked and narrow around -500 m CPA than the inbound histogram).

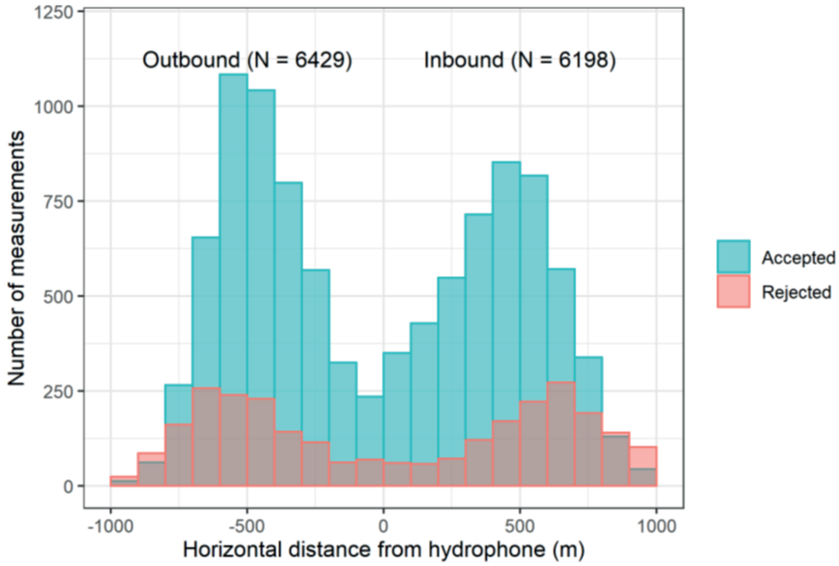

Figure 28. Histogram of closest point of approach (CPA) distances in the cross-track direction. A total of 6,429 outbound measurements (5,044 accepted) and 6,198 inbound measurements (4,789 accepted) are included in the histogram.

3.3.2. Source Level Differences Between Frames

Most vessel transits through Boundary Pass had two accepted measurements during periods when both ULS frames were operating. Some source level differences were expected because each measurement was calculated from a slightly different period centred around the frame-specific CPA time (these differed by up to ~1.5 min depending on the vessel speed). While the time difference is minimal it is possible that vessels may have changed operational parameters during this period and background noise levels may have varied.

Figure 29 shows the CDF for the differences between broadband radiated noise level (RNL) when both frame locations received accepted measurements for the same vessel transit (Frame A RNL minus Frame B RNL). The mean was −1.18 dB with a standard deviation of 1.3 dB (4,722 measurements). These values remain similar to those in October-December 2021, for which the mean was -1.0 dB and the standard deviation was 1.1 dB (Houweling et al. 2022a). The negative difference in means nearly equal to the standard deviation indicates that Frame B source levels were on average slightly higher than Frame A source levels. Regarding the difference in the mean RNL for the two systems we note the following:

- Despite the systemic bias between the two frames, in field measurements, a difference of 1 dB between two systems is generally considered as showing good consistency.
- There is no ANSI or ISO standard compliance guideline for the largest allowable dB difference between two systems.
- The calibration procedure for the ULS allows a ±0.75 dB maximum variation from the shop calibration at 250 Hz prior to deploying (i.e., a measurement differing by as much as ±0.75 dB is still considered as meeting JASCO’s calibration standard).

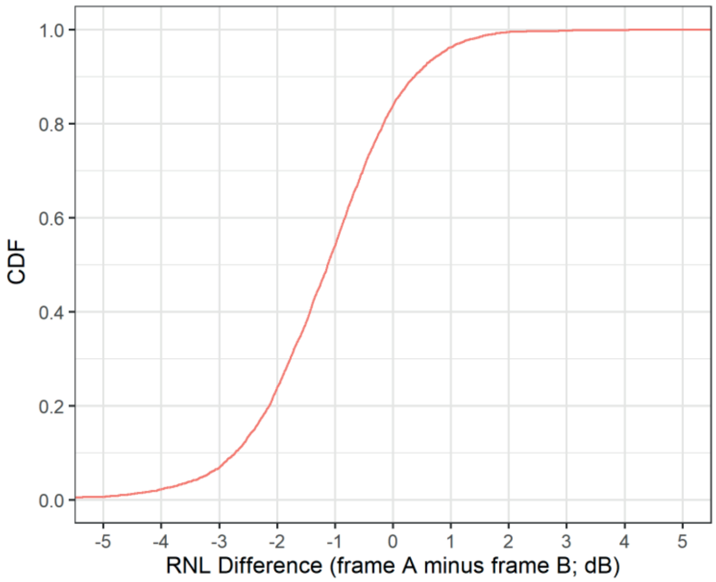

Figure 29. Differences between broadband radiated noise levels (RNL) for the same vessel transit through Boundary Pass as measured by Frames A and B in 2022. A positive difference means source levels were higher on Frame A; a negative difference means source levels were higher on Frame B.

Figure 30 shows boxplots for the differences in decidecade RNL between ULS frames. The distribution and range of these differences at most frequency bands (63-160,000 Hz) is within ±10 dB. A similar graph from the 2021 annual report (Houweling et al. 2022a) shows smaller differences between frames (within ±7 dB for 63-160,000 Hz and ±10 dB for most data below 63 Hz). This change in statistics is likely due to the limited period of analysis in the 2021 report, which was limited to October-December 2021 for to the second ULS deployment.

At frequencies <40 Hz, Figure 30 shows significant outliers reaching differences of +35 dB and -50 dB, which require further analysis. The time series of the differences (Figure 31) shows that these large outliers were not localized in time, but rather occurred throughout the year. Using this graph we isolated some of the most significant outliers and analyzed the corresponding spectrograms from Frames A and B. The subset of events analyzed showed two reasons for large differences: random impulsive events, and flow noise.

For example, the -49 dB outlier in the 10 Hz band that occurred on January 27 2022 was caused by a broadband impulsive noise event, which mostly affected the lower frequency bands (Figure 32). A similar type of impulsive event caused the -44 dB outlier in the 10 Hz band on May 10 2022 (Figure 33). It is unclear whether the origin of those events is mechanical (i.e., some object contacting the hydrophone) or electrical internal noise in the ULS system.

Figures 34 and 35 illustrate the case of outliers caused by flow noise. Figures 34 show the spectrograms corresponding to June 19 (28 dB outlier in the 13 Hz band) and Figure 35 shows the spectrograms for September 6 2022 (28 dB outlier in the 10 Hz band). In both examples there is what appears to be significantly higher flow noise in frame A compared to Frame B at frequencies <30 Hz.

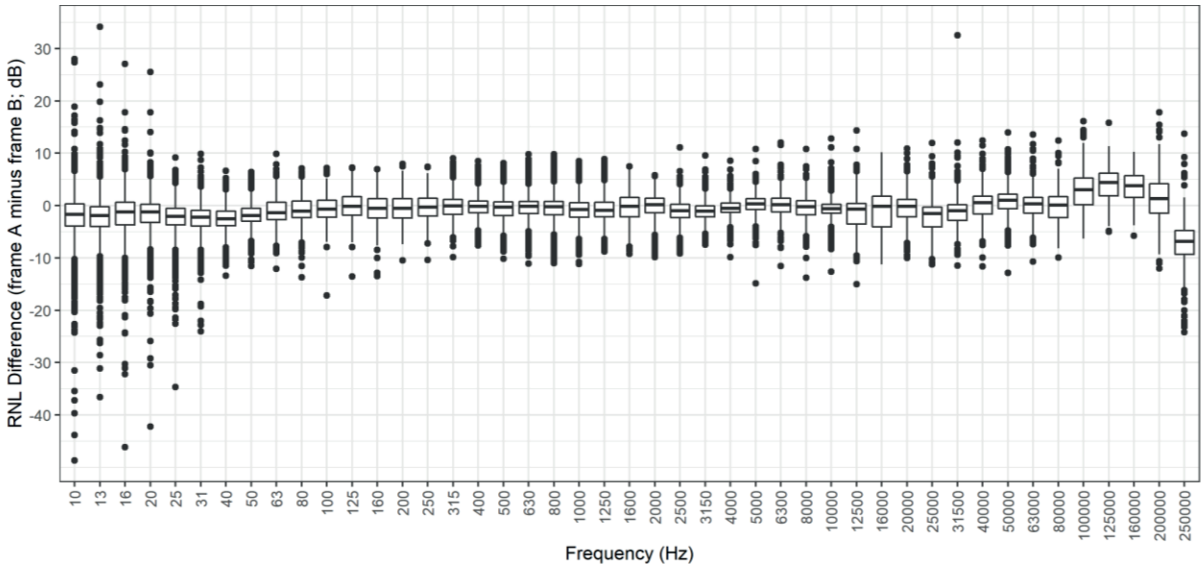

Figure 30. Differences between decidecade radiated noise level (RNL) for the same vessel transit through Boundary Pass as measured by Frames A and B in 2022 (Deployment 2,4722 measurements). A positive difference means source levels were higher on Frame A; a negative difference means source levels were higher on Frame B.

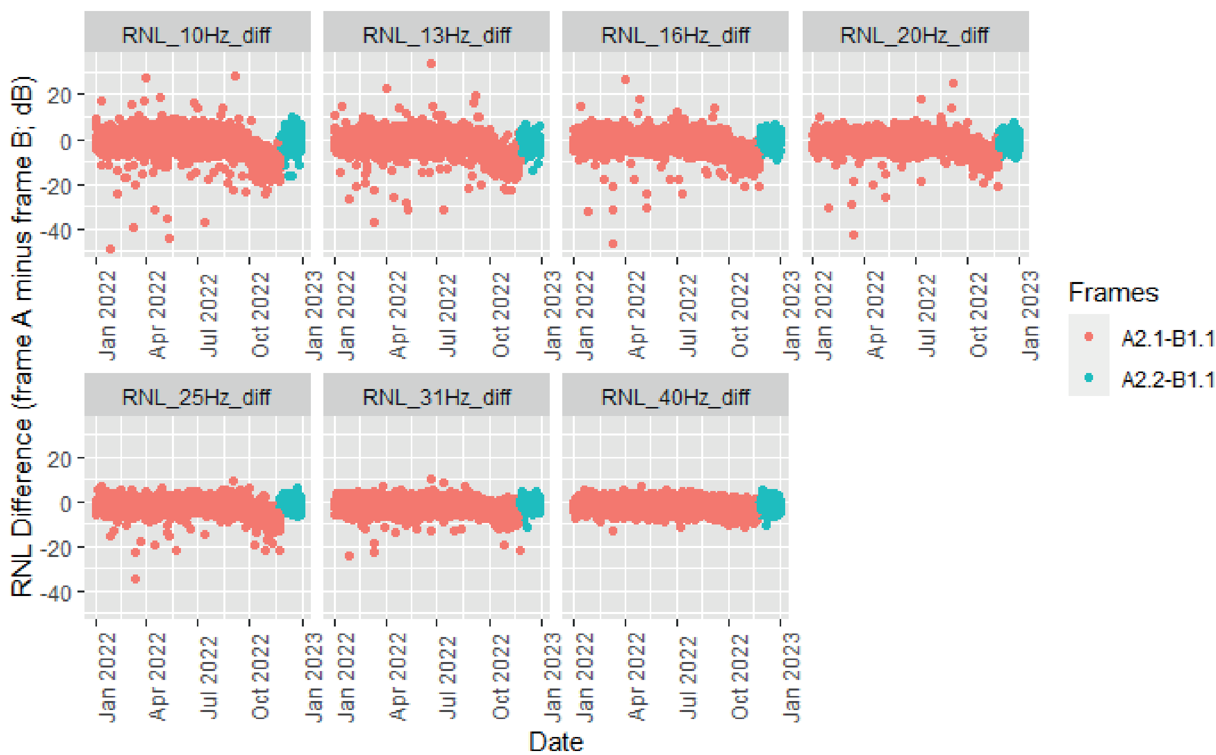

Figure 31. Time history of differences between decidecade radiated noise level (RNL) for the same vessel transit through Boundary Pass as measured by Frames A and B in 2022 (Deployment 2,4722 measurements). A positive difference means source levels were higher on Frame A; a negative difference means source levels were higher on Frame B. Only bands with outliers larger than ±20 dB in Figure 30 are shown here.

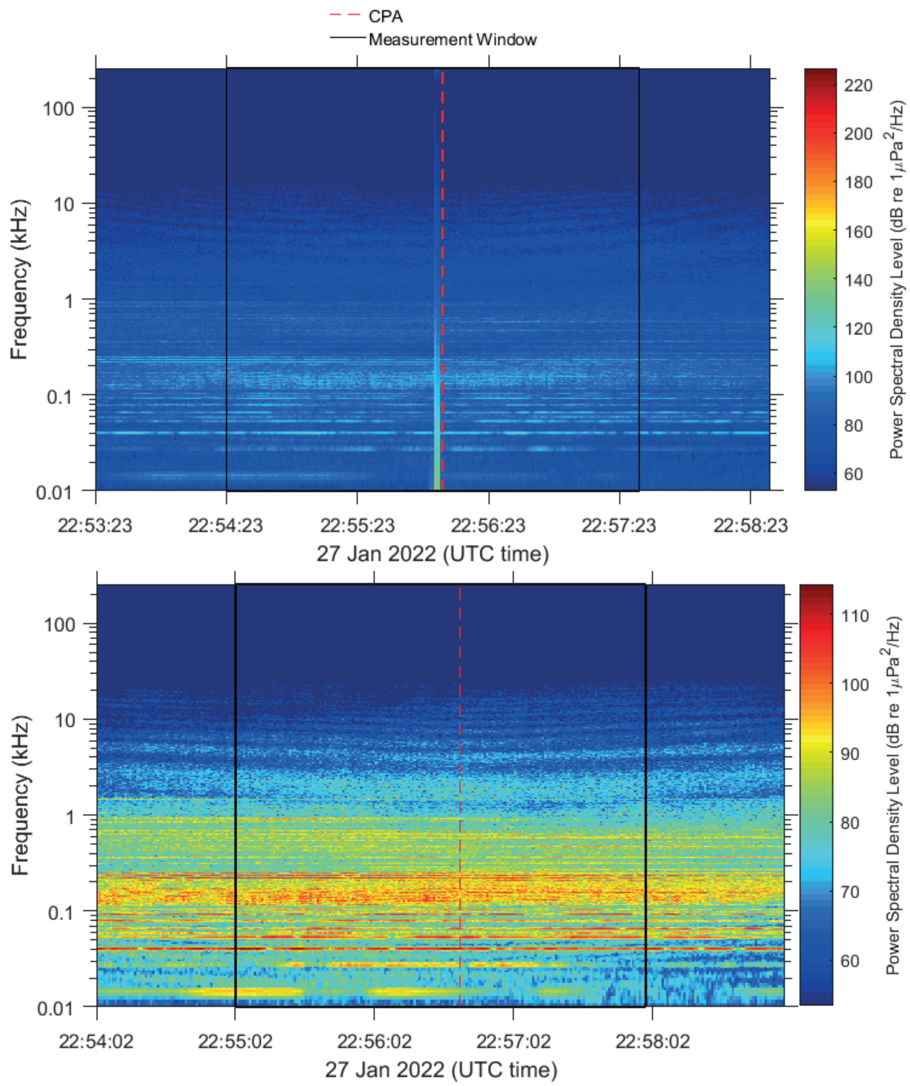

Figure 32 Spectrograms obtained on Jan 27 2022 on channels B.1.1 (top) and A.2.1(bottom): the noise event before CPA caused the -49 dB outlier observed in Figure 31 for the 10 Hz band, and it also affected other low frequency bands.

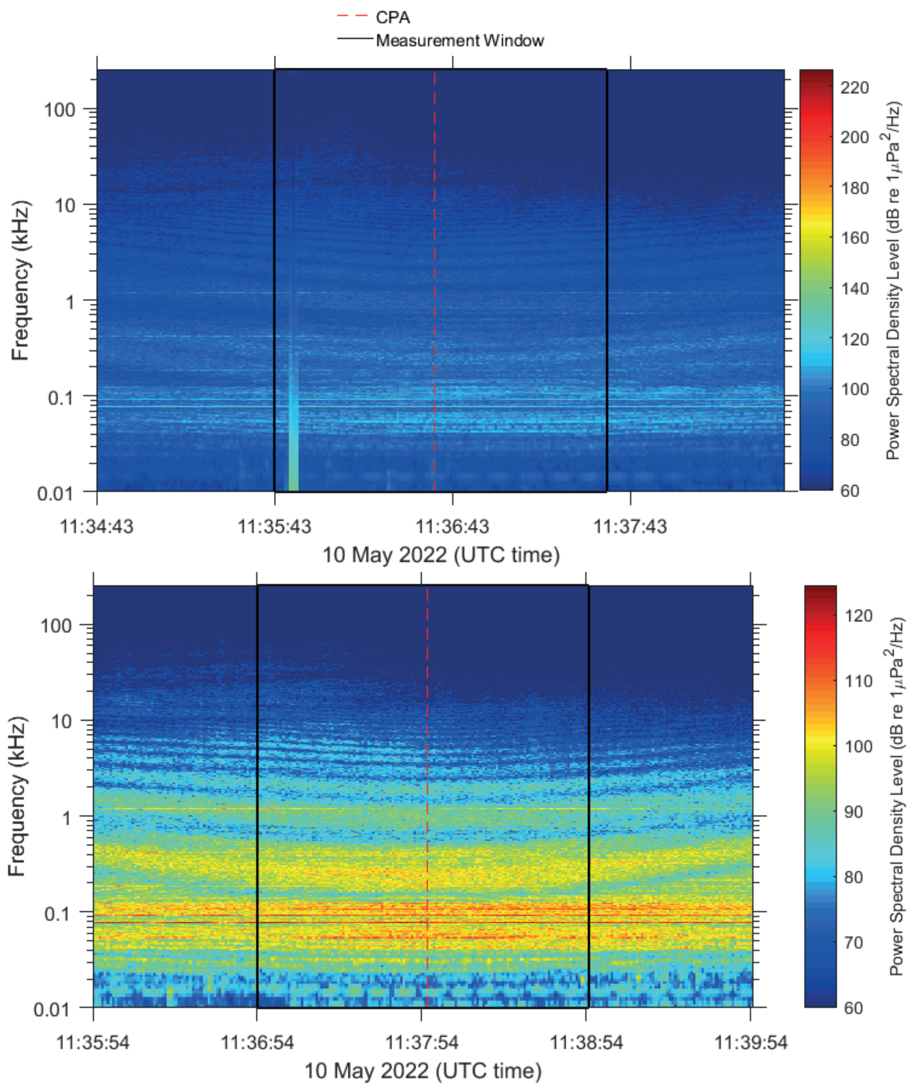

Figure 33 Spectrograms obtained on May 10 2022 on channels B.1.1 (top) and A.2.1(bottom): the noise event just past 11:35:43 caused the -44 dB observed in Figure 31 for the 10 Hz band, and it also affected other low frequency bands.

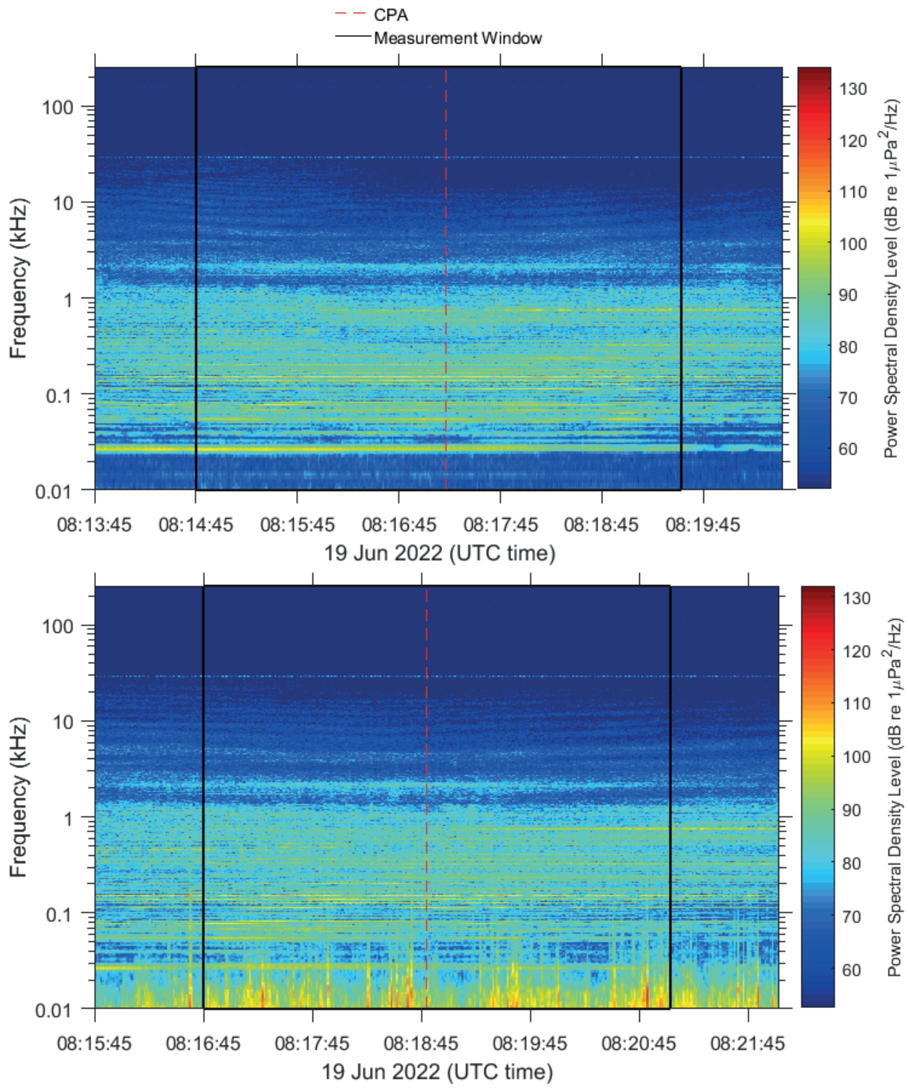

Figure 34 Spectrograms obtained on Jun 19 2022 on channels B.1.1 (top) and A.2.1(bottom): the spectrogram obtained from A.2.1 exhibits higher flow noise compared to B.1.1. This caused the 28 dB difference observed in Figure 31 for the 13 Hz band.

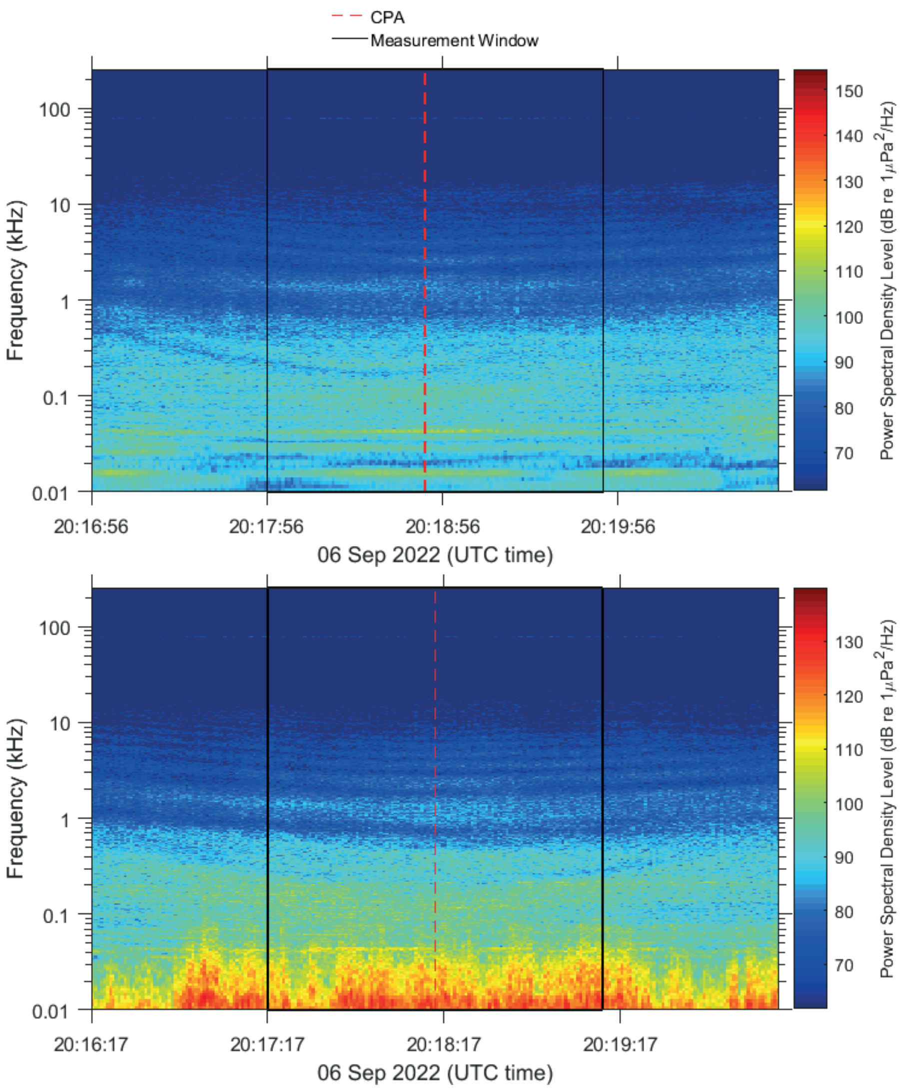

Figure 35 Spectrograms obtained on Sep 6 2022 on channels B.1.1 (top) and A.2.1(bottom): the spectrogram obtained from A.2.1 exhibits higher flow noise compared to B.1.1. This caused the 28 dB difference observed in Figure 31 for the 10 Hz band.

3.3.3. Average Source Levels by Vessel Category

Figure 36 shows the number of unique vessels measured by vessel category for each month. Note that the Bulker category also includes the AIS transmission vessel category “Cargo”, which is sometimes referred to as “General Cargo”. Appendix D contains tables of the number of accepted measurements and the acceptance rates. Table 5 lists RNL statistics by vessel category for all accepted measurements during the study period. Note that each vessel transit through Boundary Pass can have zero, one, or two accepted measurements. Calculating RNL statistics by first averaging multiple measurements of the same transit does not substantially affect the overall RNL statistics and percents listed in Table 5, so those results are not shown here. The number of unique vessels with at least 1 accepted measurement shows that many vessels make multiple transits through Boundary Pass each year. Decidecade RNL for vessel categories with more than 50 accepted measurements during the study period are shown in Figure 37.

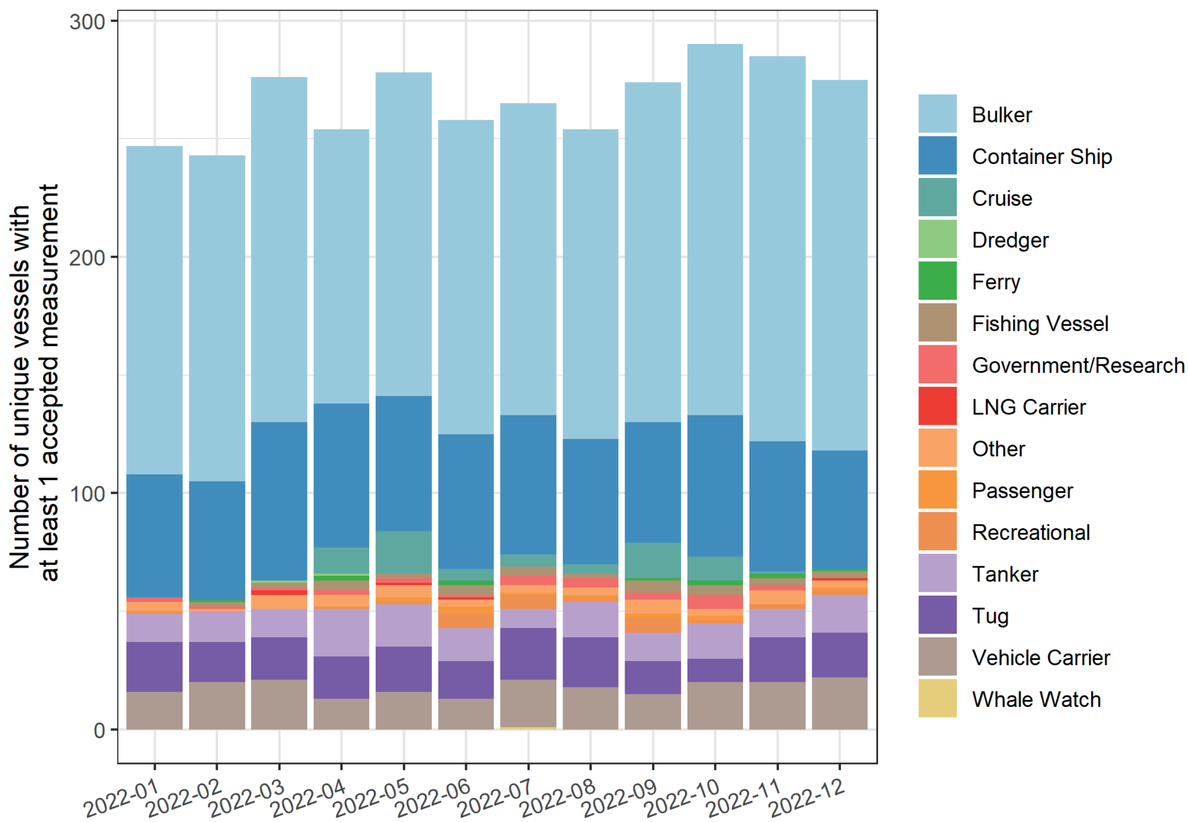

Figure 36. Stacked Bar Chart showing the number of unique vessels with at least 1 accepted source level measurement, by vessel category, that passed the automated and manual quality control checks as described in Appendix C for each calendar month.

Table 5. Summary of broadband radiated noise levels (RNL; dB re 1 µPa m) by vessel category.

Vessel class	Maximum RNL	Average RNL	Minimum RNL	Unique vessels with accepted measurement(s)	Accepted measurements	Fraction of accepted measurements (%)
Bulker <200 m	204.0	187.6	173.9	465	2041	20.8
Bulker ≥200 m	205.2	188.2	173.0	674	2834	28.8
Container Ship <200 m	200.7	187.2	178.2	24	227	2.3
Container Ship ≥200 m	205.6	191.4	178.2	220	1807	18.4
Dredger	187.7	187.3	187.0	1	3	0.0
Ferry ≥50 m	194.0	185.4	164.9	6	269	2.7
Fishing Vessel	190.0	179.6	166.9	12	99	1.0
Government/Research	189.3	177.9	159.4	11	74	0.8
LNG Carrier	196.3	192.4	187.3	4	10	0.1
Other	198.1	185.4	166.8	22	147	1.5
Passenger <100 m	178.0	172.2	162.3	8	30	0.3
Passenger ≥100 m	194.7	182.5	171.2	31	269	2.7
Recreational	190.6	172.3	151.4	22	56	0.6
Tanker	198.1	186.7	174.1	105	496	5.0
Tug <50 m	194.7	181.0	166.1	61	686	7.0
Tug ≥50 m	194.0	186.3	175.2	14	49	0.5
Vehicle Carrier	199.1	189.0	178.2	131	734	7.5
Whale watch	174.5	174.0	173.6	1	2	0.0
All vessels	**205.6**	**187.6**	**151.4**	**1812**	**9833**	**100.0**

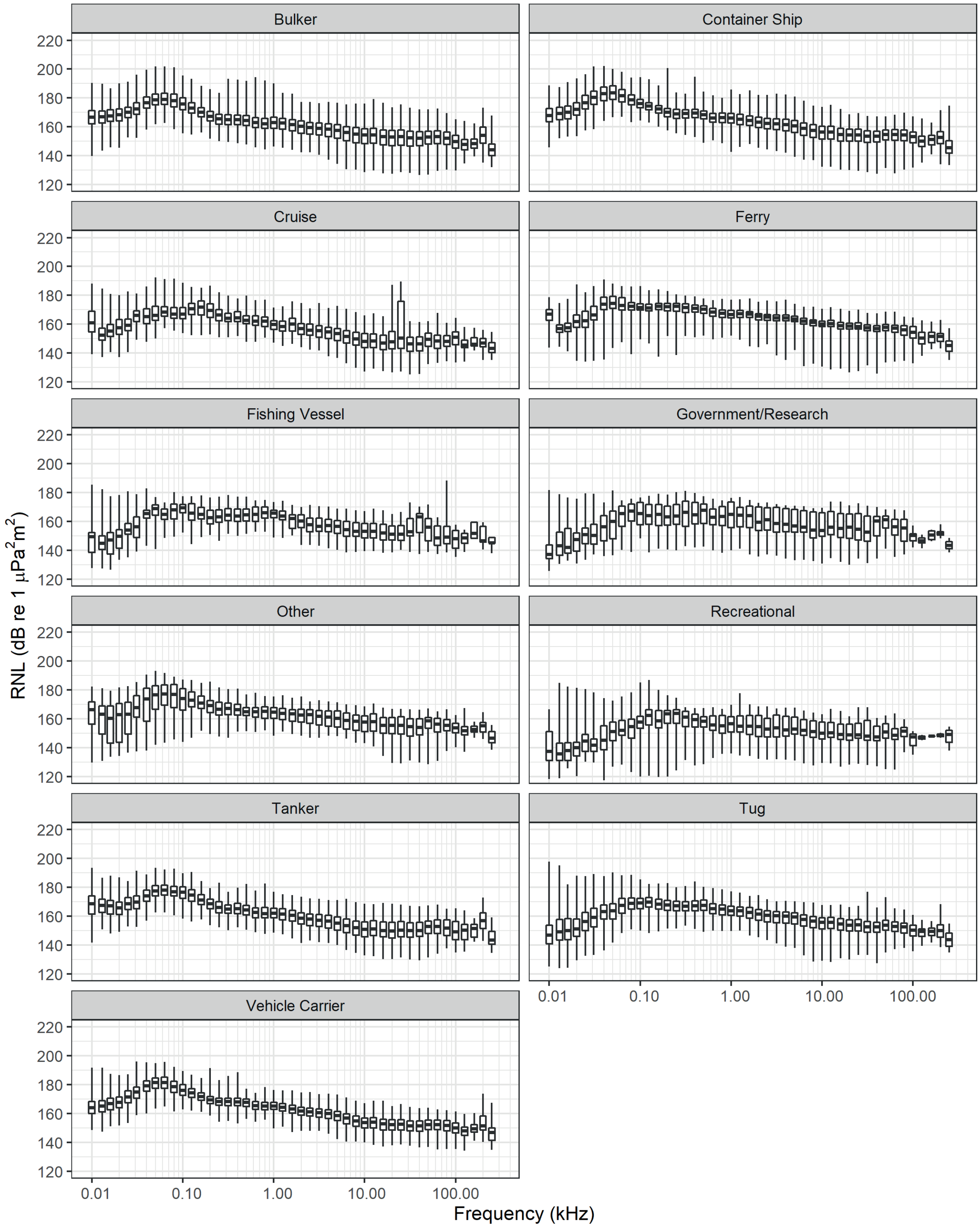

Figure 37. Box-and-whisker plots of radiated noise levels (RNL) for each ECHO vessel category with more than 50 accepted measurements during the study period (2022).

4. Discussion and Conclusion

In this report we have summarized the statistics of the ambient noise measurements for the period December 2018 to December 2022 (Section 3.1.2). Broadband levels (Figure 10) show variability of 18-20 dB between the 1st and 3rd quartiles for all months. Differences in the median ambient noise levels over time must be interpreted by keeping in mind the changes in recording equipment over the years. The highest broadband levels were measured using moored AMAR equipment (December 2018-June 2020), which was more affected by flow noise below 100 Hz compared to the cabled ULS units deployed after June 2020. The mooring design from February 2020 to mid June 2020 was particularly affected by this type of noise, yielding broadband ambient noise SPL ~12 dB higher compared to the previous period (Table 6). The first ULS deployment yielded the lowest median levels, followed by the second ULS deployment, which had median values ~3-5 dB higher than those of the first ULS deployment. The differences in monthly median values between deployments tend to reduce at higher frequencies. For example, at 100-1000 Hz the mean ambient noise was ~98-100 dB re 1 µPa (Table 6), except for the February-June 2020 mooring which at this frequency was still affected by flow noise, yielding median ambient noise ~107 dB re 1 µPa. At higher frequencies, differences between deployments tend to disappear, as shown in Figure 13.

Table 6. Summary of historical median SPL from December 2018 to December 2022.

Deployment period	Number of months	Broadband: Monthly median SPL (dB re 1 µPa)	Broadband: Average of monthly median SPLs (dB re 1 µPa)	100-1000 Hz: Monthly median SPL (dB re 1 µPa)	100-1000 Hz: Average of monthly median SPLs (dB re 1 µPa)
December 2018 to February 2020	14	113.6, 113.8, 116.9, 111.6, 114.9, 119.5, 117.0, 112.6, 112.2, 111.3, 108.7, 109.2, 110.6, 112.0	113.1	100.5, 101.2, 102.7, 98.6, 99.7, 104.4, 102.8, 101.5, 101.5, 99.1, 97.6, 99.3, 98.7, 99.7	100.5
February 2020 to June 2020	4	125.6, 124.6, 125.5,125.0	125.2	106.8, 106.0, 106.0, 108.2	106.8
June 2020 to October 2021	16	109.2, 103.5, 103.5, 103.8, 104.7, 105.0, 104.9, 104.5, 105.9, 104.4, 102.5, 104.3, 104.1, 102.9, 102.7, 103.2	104.3	99.4, 98.1, 99.0, 98.1, 99.2, 99.0, 98.1, 98.1, 99.9, 97.8, 96.7, 98.5,98.8, 98.2, 98.2, 98.2	98.4
October 2021 to December 2022	15	105.6, 105.4, 106.0, 105.4, 105.6, 106.0, 105.6, 107.2, 105.7, 105.4, 104.2, 103.6, 104.0, 105.7, 106.6	105.5	99.0, 97.5, 98.5, 96.7, 97.5, 97.8, 97.9, 99.9, 98.8, 99.6, 98.6, 98.0, 97.2, 98.8, 99.9	98.4

Acoustic measurements were made using two ULS recorders every day in 2022. Ambient noise level statistics calculated from different recorder hydrophones at simultaneous times showed good agreement at middle frequencies but were sometimes different at low frequencies (below ~100 Hz) and high frequencies (above ~10 kHz). During louder periods when vessels were present, sound level statistics at low frequencies from different recorder channels were in much better agreement. Minor differences at low frequencies seem to be caused by flow noise, while significant differences at low frequencies were caused by a gradual performance degradation in one of the ULS channels. At high frequencies, differences between channels were generally due to the characteristics of each hydrophone's noise floor and they have remained consistent since the beginning of operation of the ULS in June 2020. Each year from 2019 to 2022, a decrease in noise around July through October was likely due to lower vessel noise from slower commercial vessels participating in the ECHO Program Haro Strait and Boundary Pass voluntary vessel slowdown.

The marine mammal acoustic detection results presented in this report provide an index of acoustic occurrence for each species. Although they might be used to describe the relative abundance of a species across the study area, many factors influence the detectability of the targeted signals. Several marine mammal species, for example, produce sounds on a seasonal basis, e.g., courting calls during breeding months, leading to a large increase in acoustic detections for those times. While an acoustic detection does indicate presence, an absence of detections does not necessarily indicate an absence of animals; absences can be due to a lack of calling by individuals near the acoustic recorders, masking of signals by environmental or anthropogenic noise sources, or a combination of these factors.

Over 12,111 marine fauna detections were found in the acoustic data for the 12-month study period of 2022. Of all marine fauna, fish sounds were detected on the most frequent number of days in 2022 (23%), however fish were detected less frequently than in 2021 (45%), with detections occurring during all months of the year except March and May. Fish vocalizations appeared to increase in July, peaking in October, which may be associated with a late spawning of Pacific herring (*Clupea harengus pallasi*) (Haegele and Schweigert 1985) and possibly be linked to the large decrease seen in detections. No diurnal call pattern was observed for fish vocalizations. The remaining marine fauna detections were from humpback and killer whales.

Killer whale vocalizations (SRKW and Transient/Bigg’s) were detected 20.5% of days in 2022, with detections occurring during all months except December. SRKW vocalizations were also absent in June and November, while Transient/Bigg’s vocalizations were absent in September. SRKW and Transient/Bigg’s killer whale detections never overlapped in 2022. A slight diurnal trend was observed between ecotypes, with SRKW more vocally active in daylight and Transient/Bigg’s in darkness periods (see Figure 15). Transient/Bigg’s vocal behaviour may increase during darkness periods due to one of their known prey’s vocalization habits in the Salish Sea. Male harbour seal (*Phoca vitulina*) breeding roars are known to be eight times more vocal at night (Nikolich 2015) and consequently less alert to detecting Transient/Bigg’s vocalizations in darkness periods. The SRKW observations align with historical records, which suggests increased presence in the Salish Sea between July and September (DFO 2021). Overall, Transient/Bigg’s vocalizations were detected more frequently than SRKW vocalizations and detection counts more than doubled compared to 2021 (Houweling et al. 2022a).

BC waters are used by foraging and migrating humpback whales. They are seen year-round in BC waters but are most abundant from April to November. They are the most frequently sighted baleen whale during ship surveys and have recently been regularly sighted in the Salish Sea during summer and early fall (Ford et al. 2014). Visual humpback whale sightings reported from Vancouver Whale Watch increased from 2021 to 2022. Specifically, mother and calf humpback whale sightings increased, reporting growth from 21 (2021) to 34 (2022) unique pairs. However, humpback whale vocalizations were detected much frequently in 2022 (5% of days) compared to 2021 (9% of days). Detections peaked in fall and winter (September to December) and were not present in January, February, May, or August. This result may reveal less singing is occurring in Boundary Pass, however a diurnal pattern of humpback whale vocal behaviour was still observed here and has similarly been reported elsewhere. These results validate previous studies demonstrating nightly singing patterns observed during the onset of the winter breeding season off eastern Canada (Kowarski et al. 2019, Kowarski et al. 2021); Mexico (Cholewiak 2008); Brazil (Sousa-Lima and Clark 2008); and Angola (Cerchio et al. 2014). A new feature was added to PAMview in 2023 to classify song and non-song vocalizations, thus the amount of humpback whale song can be compared in future years and the importance of Boundary Pass as a singing ground can be explored.

Over 12,600 vessel source level measurements of 1,812 unique vessels were analyzed with JASCO's ShipSound application for Year 4 (2022). As in 2021, most vessels measured were either Bulker or Container ships. For a total of 9,833 accepted measurements, 4,722 correspond to vessels transiting through Boundary Pass that were measured twice (since two recorders were operating most of the time), while 389 measurements correspond to measurements at a single recorder. The overall measurement acceptance rates for Frames A and B were 77.0% and 78.8%, respectively, which is similar to the 77% rate before the ULS servicing in October 2021. The main reasons for measurement rejection were the presence of other vessels nearby and background noise contaminating the measurements. As observed in 2020-2021, the measurement acceptance rate was strongly related to the CPA distance, with closer measurements being more likely to be accepted.

Table 7 shows a summary of broadband RNL (maximum, average, and minimum values) for the vessel categories that have been reported since December 2018. In all analysis periods, the loudest vessel traffic are Bulkers (average RNL ~189 dB re 1 µPa m), Vehicle Carriers (average RNL ~189.5 dB re 1 µPa m), and Container Ships of length ≥200 m (average RNL ~192 dB re 1 µPa m), all of which have spectra dominated by noise in the 50-100 Hz band. Prior to January 2022 LNG carriers were classified as Tankers. However, since LNG carriers are likely to increase in the coming years they were included in 2022 as a new category, which reached an average broadband RNL of 192.4 dB re 1 µPa m (i.e., ~5-6 dB higher than the average for Tankers) comparable to the RNL for Container Ships. The quietest categories are Government/Research (average RNL 175-178 dB re 1 µPa m), Recreational (average RNL ~172-170 dB re 1 µPa m), Tug <50 m (average RNL ~181 dB re 1 µPa m), and Whale watch (average RNL 174 dB re 1 µPa m).

Table 7. Summary of historical broadband radiated noise levels (RNL; dB re 1 µPa m) by vessel category, from December 2018 to December 2022.

Vessel class	December 2018-October 2019			October 2019-December 2020			January-December 2021			January-December 2022		
	Maximum RNL	Average RNL	Minimum RNL	Maximum RNL	Average RNL	Minimum RNL	Maximum RNL	Average RNL	Minimum RNL	Maximum RNL	Average RNL	Minimum RNL
Bulker <200 m	202.9	188.4	175.0	202.5	188.3	169.5	202.7	187.8	173.5	204.0	187.6	173.9
Bulker ≥200 m	206.2	189.0	174.9	204.0	188.8	174.7	204.8	188.5	172.3	205.2	188.2	173.0
Container Ship <200 m	185.8	185.8	185.8	190.7	186.2	181.8	196.1	185.7	177.1	200.7	187.2	178.2
Container Ship ≥200 m	209.0	192.2	179.0	205.4	192.1	177.2	205.4	191.6	177.1	205.6	191.4	178.2
Dredger	186.1	186.0	185.8	186.7	184.6	181.2	185.2	183	181	187.7	187.3	187.0
Ferry ≥50 m	195.3	186.1	174.4	191.2	180.9	168.4	194.7	175.8	161.3	194.0	185.4	164.9
Fishing Vessel	191.9	181.3	174.8	189.3	180.8	170.7	187.9	180.2	164	190.0	179.6	166.9
Government/ Research	191.6	177.7	167.2	192.1	177.1	163.0	185.5	175.3	164	189.3	177.9	159.4
LNG Carrier	NA	NA	NA	NA	NA	NA	NA	NA	NA	196.3	192.4	187.3
Other	194.5	184.1	168.0	198.4	185.3	168.4	200.5	186	166.4	198.1	185.4	166.8
Passenger <100 m	185.6	177.1	167.4	192.6	182.6	171.6	177.7	171.5	163.9	178.0	172.2	162.3
Passenger ≥100 m	196.1	184.2	172.3	170.9	170.9	170.9	181.9	179.6	177.2	194.7	182.5	171.2
Recreational	194.2	177.9	161.1	188.9	175.1	165.1	193.6	179.3	172.7	190.6	172.3	151.4
Tanker	198.2	187.3	177.4	197.8	187.9	176.0	200.1	187.2	175.2	198.1	186.7	174.1
Tug <50 m	202.0	181.7	168.5	200.8	181.8	168.7	191	180.5	168.2	194.7	181.0	166.1
Tug ≥50 m	195.6	187.3	181.0	194.4	186.5	175.3	192.6	186.2	173.9	194.0	186.3	175.2
Vehicle Carrier	205.0	189.5	177.9	202.2	189.5	174.8	199.2	189.3	178.9	199.1	189.0	178.2
Whale watch	NA	NA	NA	NA	NA	NA	NA	NA	NA	174.5	174.0	173.6

Not applicable (NA) indicates that the vessel class was not reported in that period.

Broadband RNL calculated from the same vessel transit through Boundary Pass were slightly different depending on which ULS frame was used. RNL differed by -1.18 dB (on average), with Frame B measurements generally yielding slightly higher RNL compared to Frame A measurements. In the 2021 report (Houweling et al. 2022a), this mean difference between frames went from -0.3 dB before ULS servicing in October 2021, to -1 dB after servicing. At that time it was thought that the difference was due to the limited data post-servicing. However, this difference still remains after a full year of data collection in 2022, indicating that it is due to the characteristics of the two frames.

For individual decidecade bands, differences between radiated noise level (RNL) for the same vessel transit through at Frames A and B showed outliers in the order of ~20 dB for frequencies ≤31 Hz, with a few extreme cases in the order of ~50 dB found throughout the year. Investigation of a small sample of those outliers showed that they were caused by what appears to be differences in local flow noise conditions between the two frames, as well as to single impulsive noise events. The cause of those impulsive events is unknown, but it could be due to some drifting object contacting the hydrophone, or due to electrical internal noise in the ULS system. In general, these extreme outliers occur only sporadically and only affect low frequencies.

Acknowledgements

We thank David Osborne for allowing us to install our backup AIS logger at his home on Saturna Island. We also thank ITB for expert at sea support with cable laying and at sea service work. Extensive support from scientists, engineers, developers and IT experts at JASCO has allowed the overall system to collect and process very high quality acoustic data for close to 100% of the time since project inception – a major feat for a real-time oceanographic observatory of this type.

Glossary

1/3-octave

One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band

Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing centre frequency.

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

ambient noise

All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 (R2004)), 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.

background noise

Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI S1.1-1994 (R2004)). Ambient noise detected, measured, or recorded with a signal is part of the background noise.

bandwidth

The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI S1.13-2005 (R2010)).

box-and-whisker plot

A plot that illustrates the centre, spread, and overall range of data from a visual 5-number summary. The ends of the box are the upper and lower quartiles (25th and 75th percentiles). The horizontal line inside the box is the median (50th percentile). The whiskers extend outside the box to the highest and lowest observations.

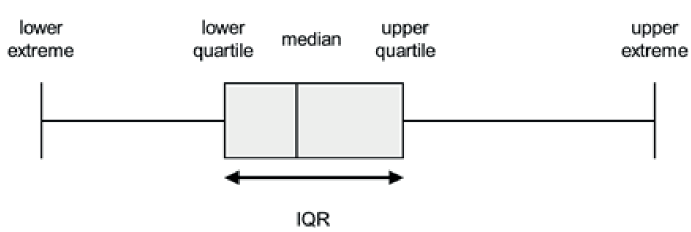

Figure 38. Diagram showing how quantiles are displayed on a box-and-whisker plot. IQR = interquartile range (i.e., the range between the 25th and 75th percentile).

broadband sound level

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

cetacean

Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade

One tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is "one-tenth decade". A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a "one-third octave".

decidecade band

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

decibel (dB)

One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 (R2004)).

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.

Global Positioning System (GPS)

A satellite-based navigation system providing accurate worldwide location and time information.

hertz (Hz)

A unit of frequency defined as one cycle per second.

hydrophone

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

impulsive sound

Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA 2013, ANSI S12.7-1986 (R2006)). For example, seismic airguns and impact pile driving.

L_{eq}

Equivalent continuous noise level

mean-square sound pressure spectral density

Distribution as a function of frequency of the mean-square sound pressure per unit bandwidth (usually 1 Hz) of a sound having a continuous spectrum (ANSI S1.1-1994 (R2004)). Unit: µPa^2/Hz.

median

The 50th percentile of a statistical distribution.

noise floor

System self-noise of the measurement system. In the context of a hydrophone, self-noise is generated by its electrical components without being exposed to an acoustic signal. The noise is electrical and non-acoustic but can be expressed as a noise-equivalent sound pressure level. The noise floor is the minimum level that a system can measure.

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.

percentile level, exceedance

The sound level exceeded *n* % of the time during a measurement.

power spectrum density

Generic term, formally defined as power in W/Hz, but sometimes loosely used to refer to the spectral density of other parameters such as square pressure or time-integrated square pressure.

pressure, acoustic

The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

pressure, hydrostatic

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

rms

root-mean-square.

sound

A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound pressure level (SPL)

The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 (R2004)).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 μPa) and the unit for SPL is dB re 1 μPa^2:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90 % sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile

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

source level (SL)

The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 μPa^2·m^2 (pressure level) or dB re 1 μPa^2·s·m (exposure level).

spectral density level

The decibel level (10·$\log_{10}$) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re 1 μPa^2/Hz and dB re 1 μPa^2·s/Hz, respectively.

spectrogram

A visual representation of acoustic amplitude compared with time and frequency.

spectrum

An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

synodic month

The time period between consecutive lunar phases. The long-term average synodic lunar month period is 29 days, 12 hours, and 44 minutes.

transmission loss (TL)

The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss.

Literature Cited

[ANSI] American National Standards Institute. 12.64-2009 (R2014). *Grade C – Survey Method - Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements*.

[ANSI] American National Standards Institute. S1.1-1994 (R2004). *American National Standard: Acoustical Terminology*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIS11994R2004.

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.13-2005 (R2010). *American National Standard: Measurement of Sound Pressure Levels in Air*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS1132005R2010.

[ANSI] American National Standards Institute. S12.7-1986 (R2006). *American National Standard: Methods for Measurements of Impulsive Noise*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIS121986R2006.

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S12.64-2009. *American National Standard: Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS12642009Part.

[DFO] Fisheries and Oceans Canada (Pacific Region). 2021. *Identification of Areas for Mitigation of Vessel-Related Threats to Survival and Recovery for Southern Resident Killer Whales*. Canadian Science Advisory Secretariat Science Advisory Report 2021/025. 11 p. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2021/2021_025-eng.pdf.

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

[ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. https://www.iso.org/standard/62406.html.

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

[NRC] National Research Council (US). 2003. *Ocean Noise and Marine Mammals*. National Research Council (US), Ocean Studies Board, Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals. The National Academies Press, Washington, DC, USA. https://doi.org/10.17226/10564.

Belanger, C.P. and E.E. Maxner. 2023. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections October to December 2022*. Document 02967, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Breiman, L. 2001. Random Forests. *Machine Learning* 45(1): 5-32. https://doi.org/10.1023/A:1010933404324.

Cerchio, S., S. Strindberg, T. Collins, C. Bennett, and H. Rosenbaum. 2014. Seismic Surveys Negatively Affect Humpback Whale Singing Activity off Northern Angola. *PLOS ONE* 9(3): e86464. https://doi.org/10.1371/journal.pone.0086464.

Cholewiak, D.M. 2008. *Evaluating the role of song in the humpback whale (Megaptera novaeangliae) breeding system with respect to intra-sexual interactions*. PhD Thesis. Cornell University. http://hdl.handle.net/1813/11206.

Cusano, D.A., G.A. Warner, H. Frouin-Mouy, and Z. Li. 2021. *Annual Report of Boundary Pass Acoustic Monitoring: Year 2, October 2019 to December 2020*. Document 02323, Version 2.1. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Dewey, R., T. Dakin, X. Mouy, and I.R. Urazghildiiev. 2015. A regional hydrophone network: Monitor, detect and track. *Underwater Acoustics Conference and Exhibition*. 21-26 Jun 2015, Crete, Greece.

Ford, J.K.B., E.H. Stredulinsky, G.M. Ellis, J.W. Durban, and J.F. Pilkington. 2014. *Offshore Killer Whales in Canadian Pacific Waters: Distribution, Seasonality, Foraging Ecology, Population Status and Potential for Recovery*. Canadian Science Advisory Secretariat (CSAS) Research Document 2014/088. 55 p. https://waves-vagues.dfo-mpo.gc.ca/Library/359988.pdf.

Foreman, M.G.G., W.R. Crawford, J.Y. Cherniawsky, R.F. Henry, and M.R. Tarbottom. 2000. A high-resolution assimilating tidal model for the northeast Pacific Ocean. *Journal of Geophysical Research* 105(C12): 28629-28651. https://doi.org/10.1029/1999JC000122.

Fristrup, K.M. and W.A. Watkins. 1993. *Marine animal sound classification*. Report WHOI-94-13. Woods Hole Oceanographic Institution. 32 p. http://darchive.mblwhoilibrary.org:8080/bitstream/handle/1912/546/WHOI-94-13.pdf?sequence=1.

Gray, L.M. and D.S. Greeley. 1980. Source level model for propeller blade rate radiation for the world's merchant fleet. *Journal of the Acoustical Society of America* 67(2): 516-522. https://doi.org/10.1121/1.383916.

Grooms, C.H. and G.A. Warner. 2021. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from July to September 2021*. Document 02559, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Grooms, C.H. and G.A. Warner. 2022. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from October to December 2021*. Document 02639, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Haegele, C.W. and J.F. Schweigert. 1985. Distribution and Characteristics of Herring Spawning Grounds and Description of Spawning Behavior. *Canadian Journal of Fisheries and Aquatic Sciences* 42(S1): s39-s55. https://doi.org/10.1139/f85-261.

Houweling, A.E. and C.P. Belanger. 2022. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections July to September 2022*. Document 02884, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Houweling, A.E., E.E. Maxner, C.H. Grooms, Z. Li, J.L. Wladichuk, J.E. Quijano, and G.A. Warner. 2022a. *Annual Report of Boundary Pass Acoustic Monitoring: Year 3, January to December 2021*. Document 02684, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority.

Houweling, A.E., E.E. Maxner, and J.L. Wladichuk. 2022b. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from October to December 2021*. Document 02636, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Institute of Ocean Sciences. 2015. WebTide Northeast Pacific Data (v0.7). Bedford Institute of Oceanography. http://www.bio.gc.ca/science/research-recherche/ocean/webtide/nepacific-nepacifique-en.php (Accessed 16 Jan 2019).

Kowarski, K., S. Cerchio, H. Whitehead, and H.B. Moors-Murphy. 2021. Where, when, and why do western North Atlantic humpback whales begin to sing? *Bioacoustics*: 1-20. https://doi.org/10.1080/09524622.2021.1972838.

Kowarski, K.A., H.B. Moors-Murphy, E.E. Maxner, and S. Cerchio. 2019. Western North Atlantic humpback whale fall and spring acoustic repertoire: Insight into onset and cessation of singing behavior. *Journal of the Acoustical Society of America* 145(4): 2305-2316. https://doi.org/10.1121/1.5095404.

Mellinger, D.K. and J.W. Bradbury. 2007. Acoustic measurement of marine mammal sounds in noisy environments. *2nd International Conference on Underwater Acoustic Measurements: Technologies and Results*. Heraklion, Greece. pp. 273-280. ftp://ftp.pmel.noaa.gov/newport/mellinger/papers/Mellinger+Bradbury07-BioacousticMeasurementInNoise-UAM,Crete.pdf.

Moloney, J., C.A. Hillis, X. Mouy, I.R. Urazghildiiev, and T. Dakin. 2014. Autonomous Multichannel Acoustic Recorders on the VENUS Ocean Observatory. *OCEANS 2014*. 14-19 Sep 2014. IEEE, St. John's, NL, Canada. pp. 1-6. https://doi.org/10.1109/OCEANS.2014.7003201.

Mouy, X., J. Ford, J. Pilkington, K. Kanes, A. Riera, T. Dakin, and P.-A. Mouy. 2015. Automatic Marine Mammal Monitoring off British Columbia, Canada. *7th International DCLDE Workshop*. 13-16 Jul 2015, La Jolla, CA, USA.

Nikolich, K.A. 2015. The Vocal Breeding Behaviour of Harbour Seals (Phoca vitulina) in Georgia Strait, Canada: Temporal Patterns and Vocal Repertoire.

Sousa-Lima, R.S. and C.W. Clark. 2008. Modeling the effect of boat traffic on the fluctuation of humpback whale singing activity in the Abrolhos National Marine Park, Brazil. *Canadian Acoustics* 36(1): 174-181. https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2008.

Warner, G.A. and H. Frouin-Mouy. 2020. *Annual Report of Boundary Pass Acoustic Monitoring: Year 1, December 2018 to October 2019*. Document 02020, Version 2.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Wenz, G.M. 1962. Acoustic Ambient Noise in the Ocean: Spectra and Sources. *Journal of the Acoustical Society of America* 34(12): 1936-1956. https://doi.org/10.1121/1.1909155.

Zammit, K.E. and G.A. Warner. 2021a. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from April to June 2021*. Document 02469, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Zammit, K.E. and G.A. Warner. 2021b. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from January to March 2021*. Document 02399,Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Appendix A. Example Ambient Noise Report for One Month

A.1. Introduction

JASCO Applied Sciences was contracted to the Vancouver Fraser Port Authority (VFPA) to analyze underwater sound in Boundary Pass as part of VFPA's Enhancing Cetacean Habitat and Observation (ECHO) program. Acoustic data were collected using JASCO's cabled underwater listening station (ULS), which has been operating since 10 Jun 2020 and is sampling at 512 kHz at two ULS frames (A and B).

This report contains analysis of data collected from 1 Apr to 30 Jun 2022. For this report, we analyzed ULS data from frame B.

A.2. Report Schedule

The analysis was conducted over calendar month periods from April to July 2022. Table 8 lists the report schedule for the Boundary Pass data.

Table 8. Periods analyzed for this report.

Month start	Month end	Weeks reported
1 Apr 2022 00:00 PDT	1 May 2022 00:00 PDT	Sun 3 Apr to Sat 9 Apr Sun 10 Apr to Sat 16 Apr Sun 17 Apr to Sat 23 Apr Sun 24 Apr to Sat 30 Apr
1 May 2022 00:00 PDT	1 Jun 2021 00:00 PDT	Sun 1 May to Sat 7 May Sun 8 May to Sat 14 May Sun 15 May to Sat 21 May Sun 22 May to Sat 28 May Sun 29 May to Sat 4 Jun
1 Jun 2021 00:00 PDT	1 Jul 2022 00:00 PDT	Sun 5 Jun to Sat 11 Jun Sun 12 Jun to Sat 18 Jun Sun 19 Jun to Sat 25 Jun Sun 26 Jun to Sat 2 Jul

A.3. Ambient Noise Data Processing Methods

Location Name: **Boundary Pass**

Analysis Period: **1 Apr to 30 Jun 2022**

Table 9. Underwater Listening Station (ULS) location and period used for analysis.

ULS	Hydrophone	Start date/time	End date/time	Latitude	Longitude	Water depth (m)
B1	GTI M36-V35-100	2022 Apr 1 00:00	2022 Jun 31 23:59	48° 45.65731' N	123° 3.65912' W	195

The results for this period are presented in seven formats:

1. **Combined plot of ambient sound pressure level (SPL) versus time and spectrogram**: The broadband and decade band results represent SPL in 1-hour intervals over the analysis period. The results are presented in six frequency bands: 10–256,000 Hz (broadband), 10–100 Hz, 100–1,000 Hz, 1000–10,000 Hz, 10–100 kHz, and 100–256 kHz.
2. **Decidecade-band and spectral level statistics**: The spectral results are computed in 1-minute periods as averages of 1-second Hanning-windowed spectra with 50% overlap. The 1-minute averages are displayed at 5th, 25th, 50th, 75th, and 95th percentile levels, referred to as L_5, L_{25}, L_{50}, L_{75}, and L_{95}. By ANSI standard, L_5 is the sound level exceeded just 5% of the time and is therefore greater than L_{95}. The L_{50} is commonly referred to as the median. The frequency range displayed spans the acoustic bandwidth of the recording. The decidecade levels are calculated similarly to the spectral levels, except the 1-minute spectra are first integrated within the decidecade-bands with centre frequencies between 10 Hz and 200 kHz, which are then displayed at 5th, 25th, 50th, 75th, and 95th percentile levels. The mean band and spectral levels are also shown. For comparison, the upper and lower limits of prevailing ambient noise (NRC 2003, adopted from Wenz 1962), are also shown in the figures and are denoted L_{Wenz}.
3. **Decidecade-band levels**: A tabular presentation of the decidecade-band and broadband results.
4. **Daily rhythm plot**: The data from the analysis period are examined in 10-minute steps throughout one day (i.e., from 0:00–0:10, 0:10–0:20, …, 23:50–24:00). The ten 1-minute bins in each 10-minute step are grouped with the same ten one-minute bins each day for all days of the month. This group of 1-minute samples is then analyzed and its median value calculated. For example, in a 30-day month, the daily L_{50} for 12:00–12:10 is the median of the ten 1-minute samples each day for all 30 days (therefore from 300 one-minute samples). Plotting the daily cadences can reveal patterns associated with human activity such as ferries or other regularly scheduled vessel passages.
5. **Weekly rhythm plot**: Similar to the daily rhythm plot, the data are examined in 30-minute steps over a week. The 30 one-minute samples in each step are combined over multiple weeks, so over 4 weeks there are 120 samples. The samples are analyzed for median values. Plotting the weekly cadences can reveal patterns associated with human activity that vary on a weekly schedule, such as work week versus weekend differences.
6. **SPL box plot**: A summary of the broadband and decade-band statistics of SPL (1 minute) over the synodical month analysis period. A table of values accompanies each plot.
7. **Weekly band level plots**: Similar to the monthly ambient SPL versus time, the broadband and decade-band results represent SPL in 1-hour intervals over a calendar week, according to the methods specified for underwater ambient noise measurements by the ECHO program guidelines.

Wind and near-seafloor current speeds are also plotted following the acoustic data in each monthly section of the report. Hourly wind speeds were obtained from the Environment Canada station “Saturna Island CS”. During time periods when wind speeds from the Saturna station were unavailable, data from the Environment Canada station “Kelp Reefs” were used instead. At times, weather data from both stations were not available, and we could not identify another weather station close enough to the ULS to provide relevant wind speed data.

Near-seafloor current speeds are typically obtained from an Acoustic Doppler Current Profiler (ADCP). However, due to an equipment failure, current estimates for this monitoring period were estimated from the WebTide Tidal Prediction Model (v 0.7.1).

A.4. Results: April 2022

A.4.1. Ambient Sound Pressure Level versus Time

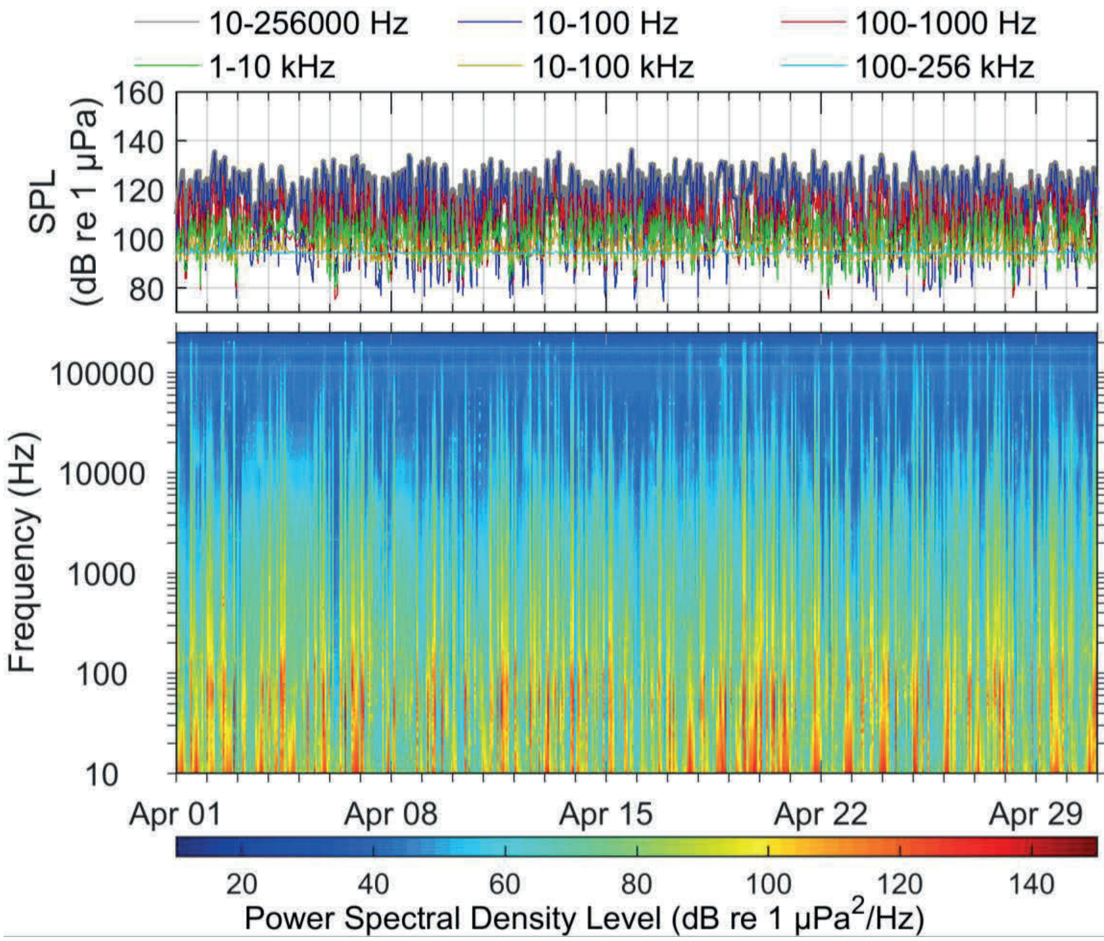

Figure A-1. April 2022: Broadband, decade band sound pressure level (SPL) versus time, and spectrogram through the analysis period. The elevated noise levels and data gaps around 6–9 Oct were due to the ULS servicing vessels and the servicing operation.

A.4.2. Spectral Levels and decidecade Band Levels

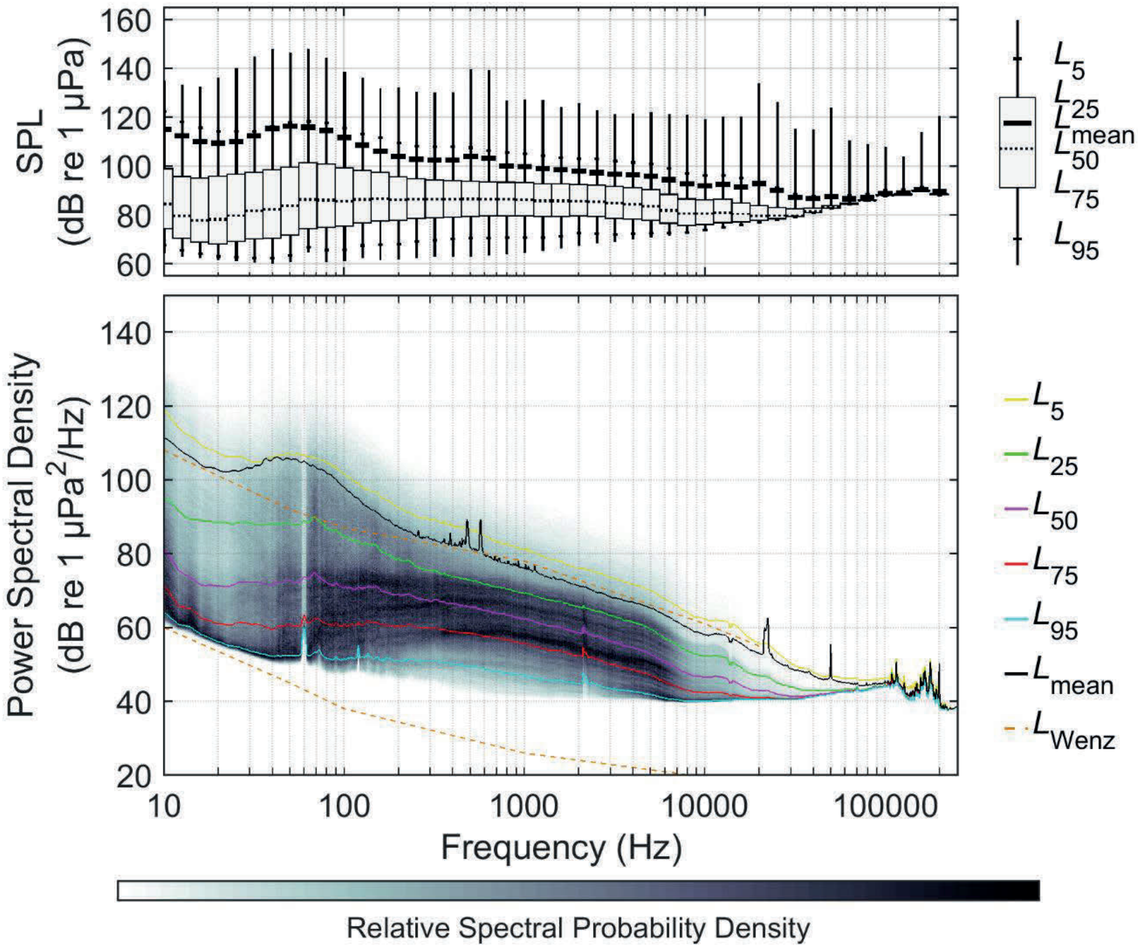

Figure A-2. April 2022: (Top) Percentiles and mean decidecade band sound pressure level (SPL; 1 minute) over the analysis period. (Bottom) Percentiles and mean power spectral density levels over the same time period.

A.4.3. Table of Broadband and 1/3-Octave SPL Values

Table A-1. April 2022: Broadband and decidecade-band sound levels (dB re 1 µPa) for the 95th, 75th, 50th, 25th, and 5th percentiles. Levels correspond to 1-minute sound pressure level (SPL).

Frequency (Hz)	L_{95}	L_{75}	L_{50}	L_{25}	L_5
Broadband	97	99.4	104.7	116.2	129.5
10	67.55	74.5	84.47	98.86	122.35
12.6	65.4	70.51	79.65	95.72	118.02
15.8	64.24	68.9	77.72	95.07	115.61
20	62.99	68.1	78.2	95.78	114.12
25.1	62.52	69.09	79.89	96.54	114.23
31.6	62.25	70.2	81.62	97.46	114.14
39.8	62.33	70.44	82.34	98.57	116.29
50.1	63.42	71.87	83.8	99.42	117.95
63.1	66.8	74.44	86.28	101.41	118.23
79.4	65.61	74.94	86.03	100.8	117.59
100	65.76	75.48	85.55	99.38	115.56
125.9	67.45	76.85	86.3	98.22	113.11
158.5	67.74	77.57	86.76	97.48	111.6
199.5	68.2	77.83	86.22	95.64	109.5
251.2	69.11	78.5	86.37	94.84	108.23
316.2	69.72	78.95	86.42	94.36	107.87
398.1	70.13	79.01	86.53	93.91	107.92
501.2	70.4	79.36	86.54	93.8	107.52
631	70.42	79.54	86.33	93.43	106.44
794.3	70.62	79.67	86.35	93.36	105.48
1000	70.73	79.56	86.21	93.12	105.11
1258.9	70.68	79.26	85.78	92.74	104.17

Frequency (Hz)	L_{95}	L_{75}	L_{50}	L_{25}	L_5
1584.9	71.19	79.3	85.77	92.7	103.55
1995.3	72.45	79.56	85.68	92.44	102.91
2511.9	72.33	79.26	85.35	92.26	102.84
3162.3	72.07	78.62	84.77	91.72	102.02
3981.1	72.36	78.26	84.24	91.2	101.49
5011.9	72.48	77.7	83.44	90.24	100.74
6309.6	72.44	76.6	81.84	88.39	98.94
7943.3	72.85	75.81	80.42	86.56	96.94
10000	73.8	76.1	80.36	86.13	96.04
12589.3	74.95	76.88	81.03	86.49	96.15
15848.9	76.06	77.13	80.18	84.95	95.06
19952.6	77.11	77.68	79.7	83.77	92.89
25118.9	78.12	78.45	79.83	82.99	91.25
31622.8	79.23	79.38	80.09	82.38	88.63
39810.7	80.95	81.03	81.38	82.74	87.75
50118.7	82.71	82.75	82.94	83.78	87.79
63095.7	84.39	84.42	84.51	84.93	87.96
79432.8	85.85	85.88	85.93	86.15	88.53
100000	87.84	88.02	88.1	88.21	89.95
125892.5	88.22	88.32	88.41	88.57	90.28
158489.3	89.74	89.85	89.94	90.07	91.36
199526.2	88	88.34	88.48	88.57	89.15

A.4.4. Daily Rhythm Plot

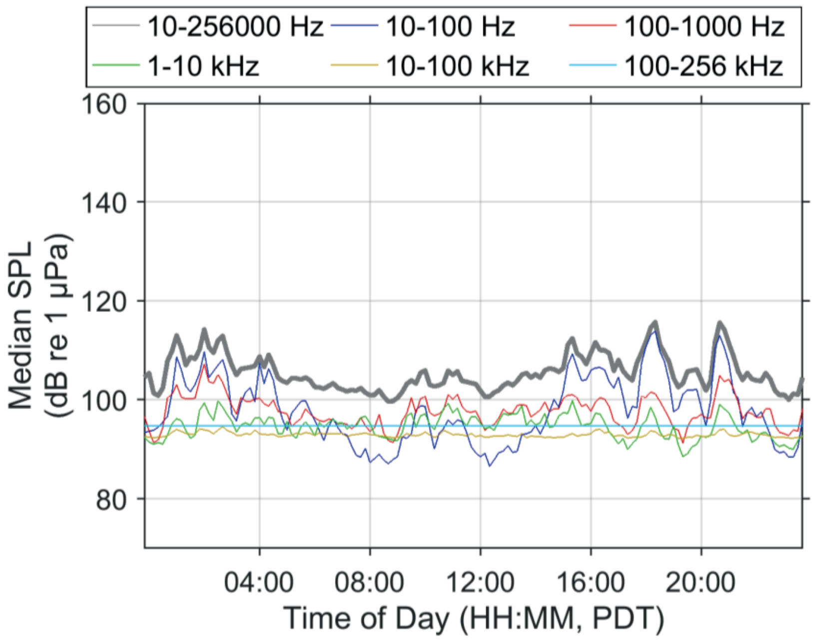

Figure A-3. April 2022: Median 1-minute sound pressure level (SPL) versus time of day (10 min resolution) over the analysis period.

A.4.5. Weekly Rhythm Plot

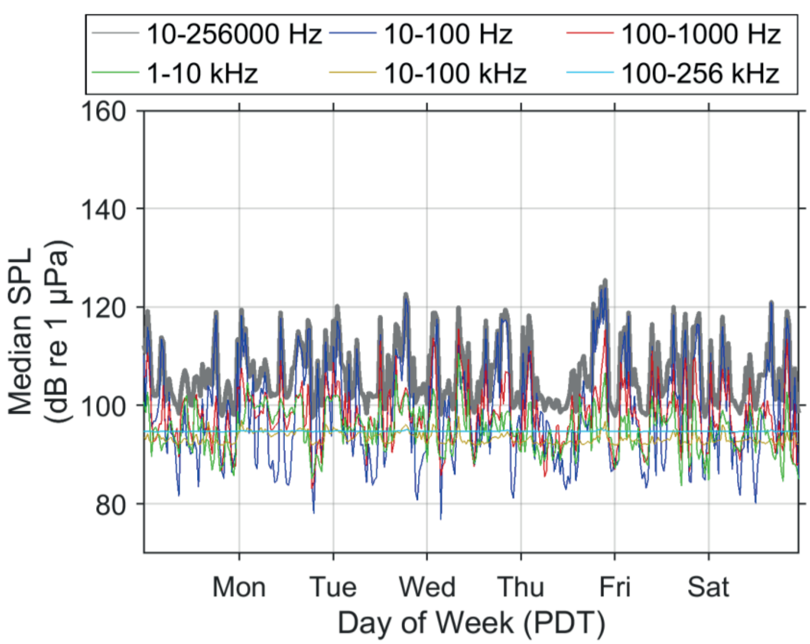

Figure A-4. April 2022: Median 1-minute sound pressure level (SPL) versus day of week (30 min resolution) over the analysis period.

A.4.6. SPL Box Plot

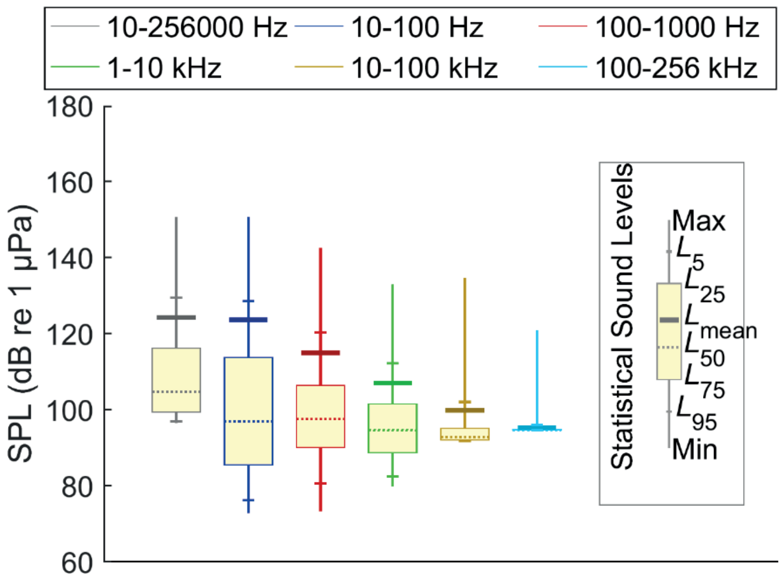

Figure A-5. April 2022: Broadband and decade-band sound pressure level (SPL; 1 minute) statistics over the analysis period.

A.4.7. Table of Values

Table A-2. April 2022: Sound pressure level (SPL; 1 minute) statistics (dB re 1 µPa) used to generate the SPL box plot in Figure A-5.

Sound level statistic	10–256000 Hz	10–100 Hz	100–1000 Hz	1000–10000 Hz	10–100 kHz	100–256 kHz
Min	96.6	72.8	73.2	79.8	91.8	94.3
L_{95}	97	76.2	80.7	82.4	91.8	94.6
L_{75}	99.4	85.4	90.1	88.7	92	94.7
L_{50}	104.7	97	97.6	94.7	92.9	94.7
L_{25}	116.2	113.7	106.4	101.5	95.1	94.8
L_{5}	129.5	128.6	120.3	112.2	102.1	96.1
Max	150.7	150.7	142.5	132.9	134.7	120.9
Mean	124.3	123.6	114.9	107	99.8	95.3

A.4.8. Weekly Band Levels

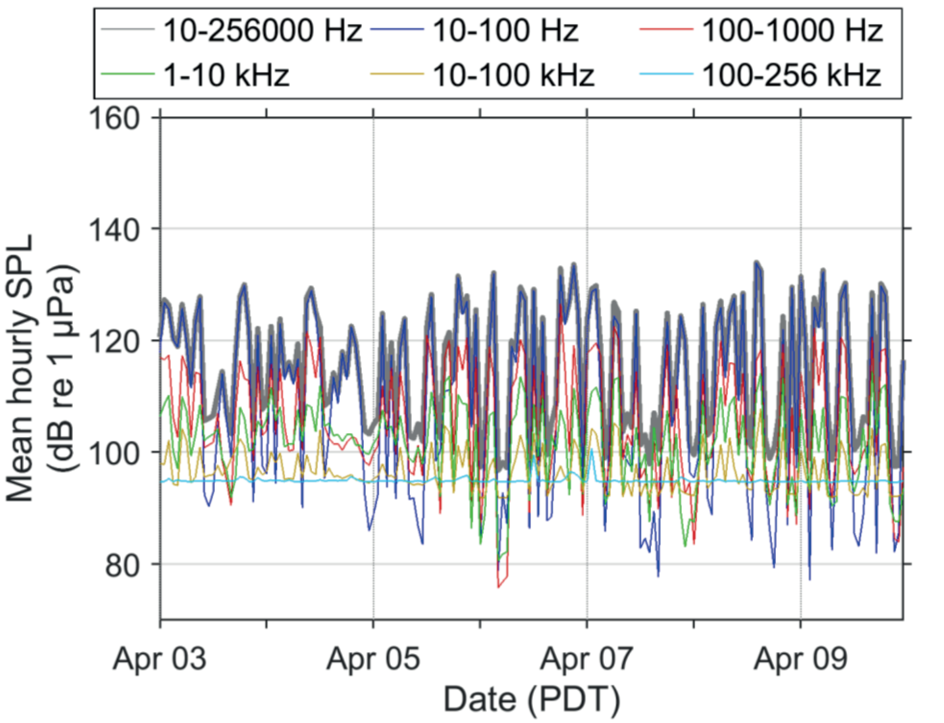

Figure A-6. 3–9 Apr 2022: Weekly broadband and decade band sound pressure level (SPL) versus time.

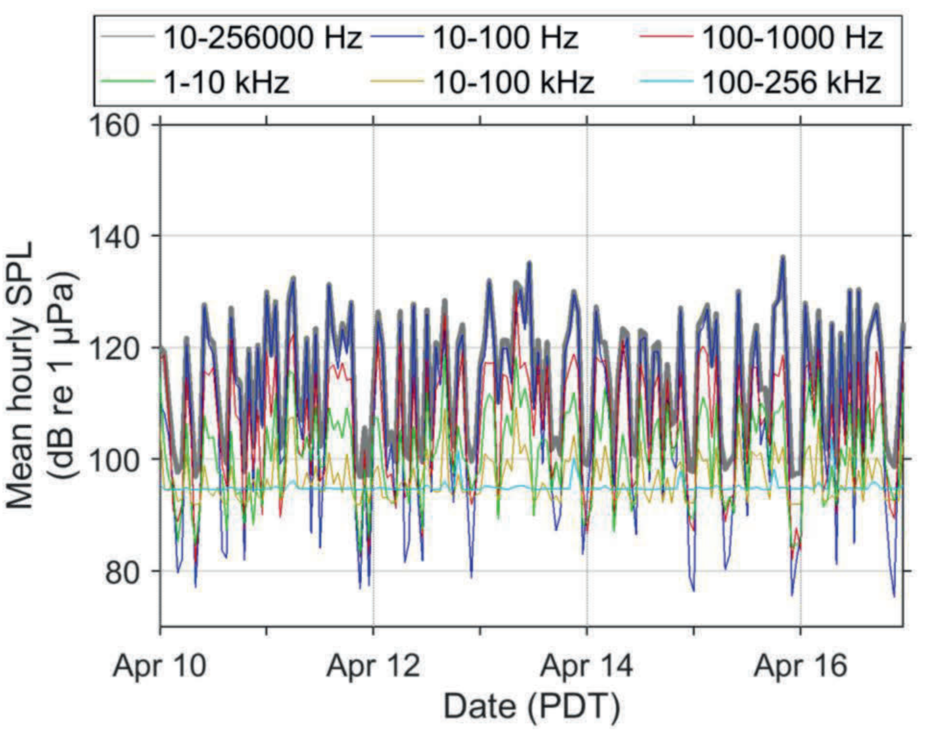

Figure A-7. 10–16 Apr 2022: Weekly broadband and decade band sound pressure level (SPL) versus time.

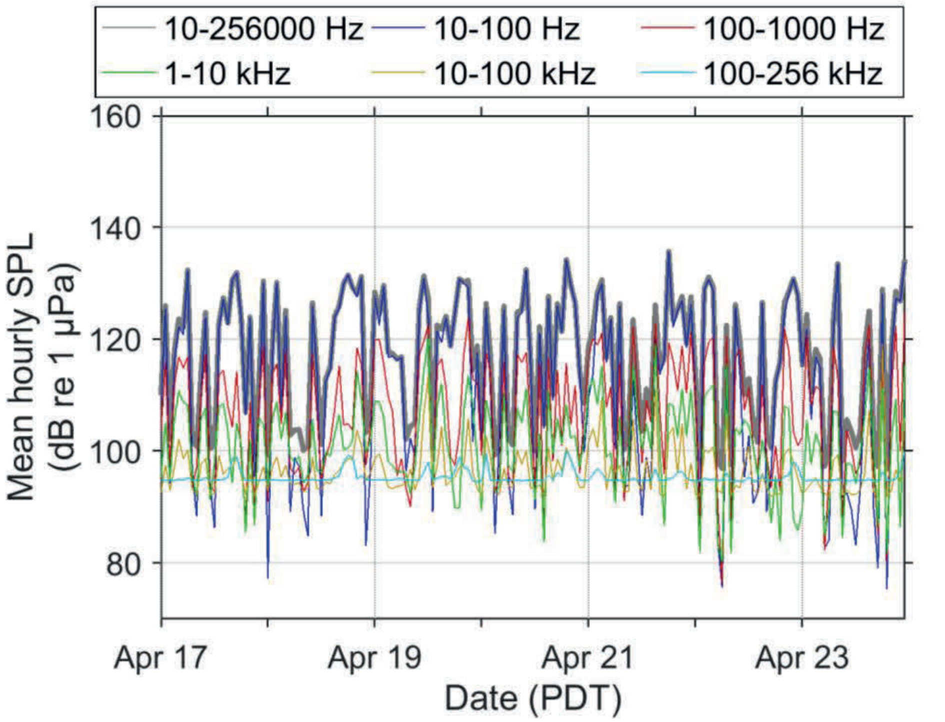

Figure A-8. 17–23 Apr 2022: Weekly broadband and decade band sound pressure level (SPL) versus time.

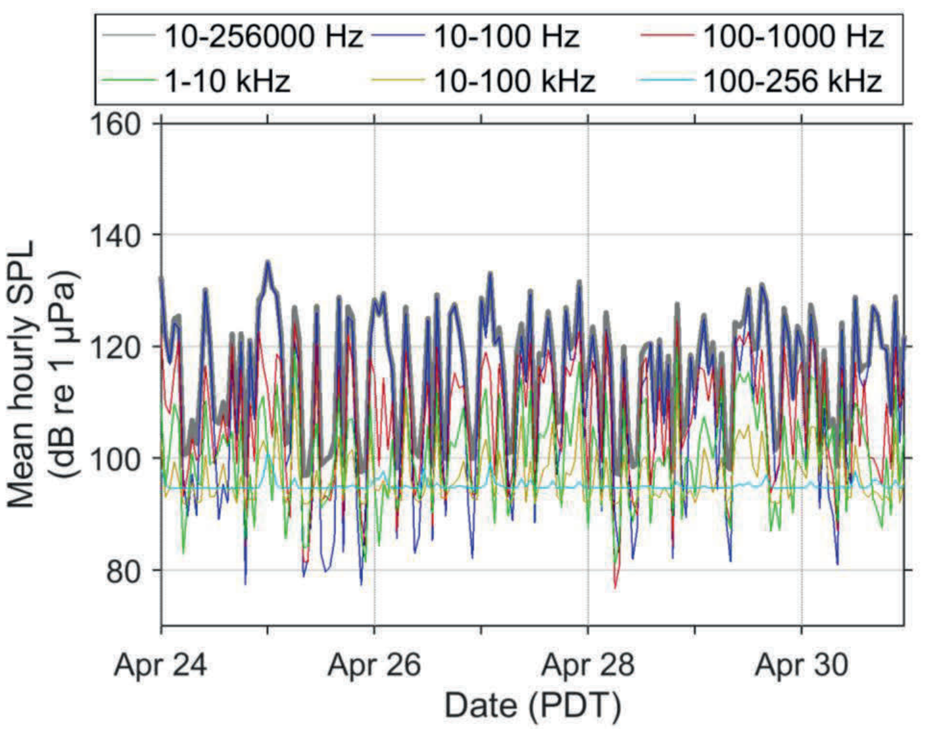

Figure A-9. 24–30 Apr 2022: Weekly broadband and decade band sound pressure level (SPL) versus time.

A.4.9. Hourly Wind Speed

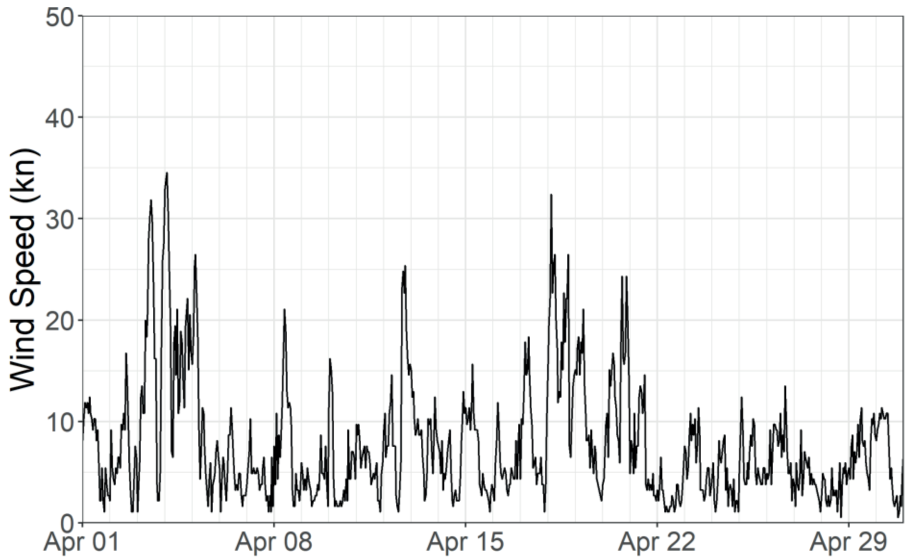

Figure A-10. April 2022: Hourly wind speed.

A.4.10. Near-seafloor Current Speed

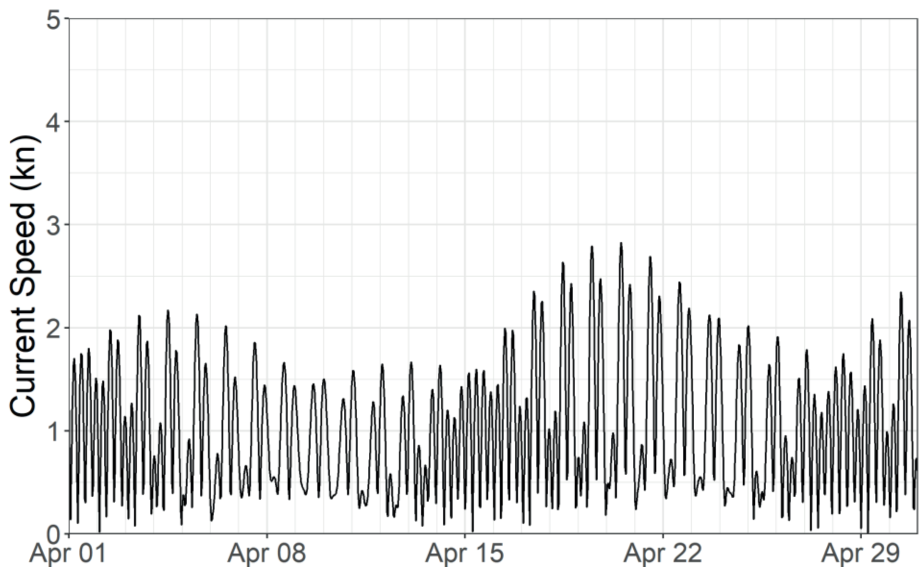

Figure A-11. April 2022: WebTide current speed.

Appendix B. Example Marine Mammal Detection Report for One Month

B.1. Introduction

JASCO Applied Sciences was contracted to the Vancouver Fraser Port Authority (VFPA) to analyze underwater sound in Boundary Pass as part of VFPA's Enhancing Cetacean Habitat and Observations (ECHO) program. Acoustic data were collected using JASCO's cabled underwater listening station (ULS), which has been operating since 10 Jun 2020 and is sampling at 512 kHz.

The acoustic data were processed to detect marine fauna sounds. This report presents the results of data collected from 1 to 31 Jul 2022, 1 to 31 Aug 2022, and 1 to 30 Sep 2022. The data are presented in the following three formats:

- Pie charts of the counts and proportion of validated automatic vocalization detections by species. The automated detector was used to detect killer whale (Orcinus orca) vocalizations, humpback whale (Megaptera novaeangliae) vocalizations, Pacific white-sided dolphin (Lagenorhynchus obliquidens) vocalizations, and fish sounds.
- Graphs showing the daily and hourly occurrence for each species. All graphs are in astronomical noon time for longitude unless otherwise indicated.
- Graphs showing the number of validated detection counts per day for each species. All graphs are in astronomical noon time for longitude unless otherwise indicated.
- Spectrograms showing how animal-vocalization frequencies varied in time.

B.2. Methods

B.2.1. Acoustic Data

Table B-1 lists the ULS deployment coordinates and recording start/end times used for analysis. For this period, we report the highest number of killer whale, Pacific white-sided dolphin, and fish detections per day from ULS A2 or B1, and the highest number of humpback whale detections from ULS A2.

Table B-1. Underwater Listening Station (ULS) location and period used for analysis.

ULS	Latitude	Longitude	Water depth (m)	Start date/time	End date/time
A2	48°45.56672' N	123°3.85010' W	193	2022 Jul 1 00:00	2022 Sep 30 23:59
B1	48°45.65731'N	123°3.65912'W	195	2022 Jul 1 00:00	2022 Sep 30 23:59

B.2.2. Detection Algorithm

An automated detector developed by JASCO was used to detect the vocalizations of killer whales, humpback whales, Pacific white-sided dolphins, and sounds from fish from acoustic recordings. The algorithm employed was similar to the one described in Moloney et al. (2014) and Dewey et al. (2015). Figure B-1 shows the various processing steps of the detector.

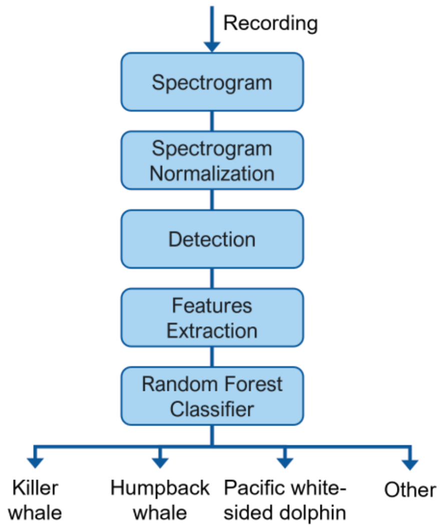

Figure B-1. The process for automatic detections of killer whales, humpback whales, Pacific white-sided dolphins, and fish sounds.

The algorithm first calculated the spectrogram and normalized it for each frequency band. Next, the spectrogram was segmented to detect acoustic events between 10 Hz and 8 kHz. For each event, a set of 40 features representing salient characteristics of the spectrogram were extracted, several of which were calculated following Fristrup and Watkins (1993) and Mellinger and Bradbury (2007). The features were based on the spectrogram, frequency envelope, and amplitude envelope of the signal.

Extracted features were presented to a classifier to determine the class of the sound detected. The classification was performed using a random forest classifier (Breiman 2001), which was trained using several thousands of manually annotated vocalizations in recordings collected at different locations in British Columbia (Mouy et al. 2015). The random forest was defined with the following classes: “killer whale”, “humpback whale”, “Pacific white-sided dolphin”, “fish”, and “other”. Figure B-2 illustrates the key processing steps of the detector on a recording that contained killer whale vocalizations.

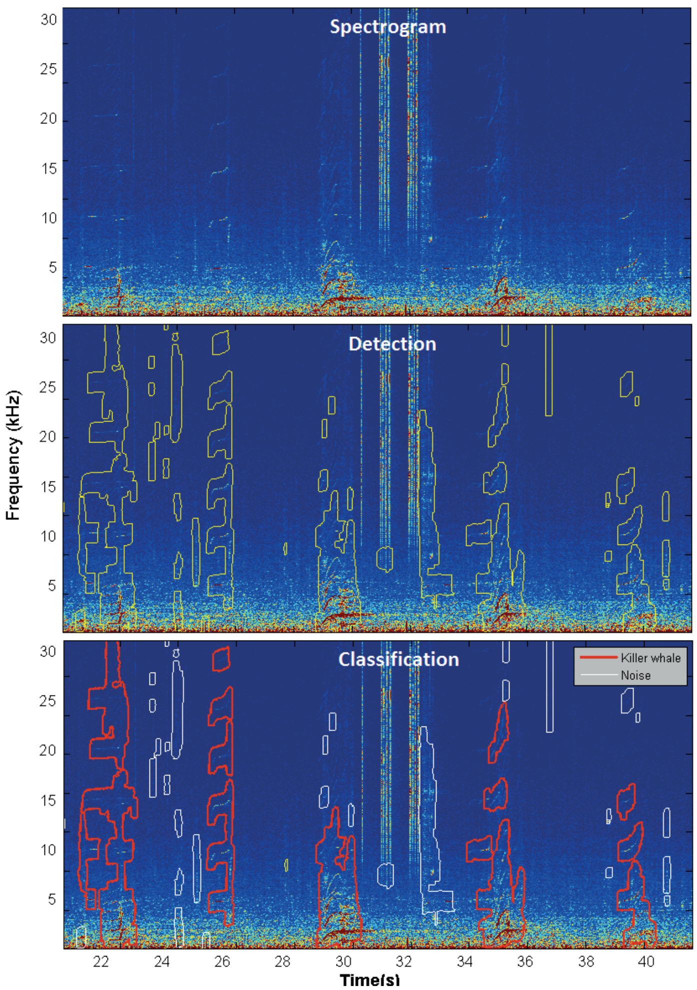

Figure B-2. Key processing steps of the detector. Top panel: Spectrogram with killer whale vocalizations. Middle panel: Acoustic events detected in the spectrogram. Bottom panel: Killer whale vocalizations classified using a random forest classifier.

All automated detections from killer whale vocalizations, humpback whale vocalizations, Pacific white-sided dolphin vocalizations, and fish sounds were manually verified by an experienced analyst using JASCO’s software PAMview. Only validated detections for these species are included in this report.

B.3. Results: 1 to 31 Aug 2022

B.3.1. Relative Vocalization Detections by Species

A total of 734 killer whale vocalizations (726=SRKW, 8=Bigg's, 0=UNKW) and 109 fish sounds were validated from the automated detectors at ULS A2 and B1 from 1 to 31 Aug 2022. There were no validated detections for humpback whale or Pacific white-sided dolphin vocalizations during this analysis period. Figure B-3 shows the proportion of detections for this period.

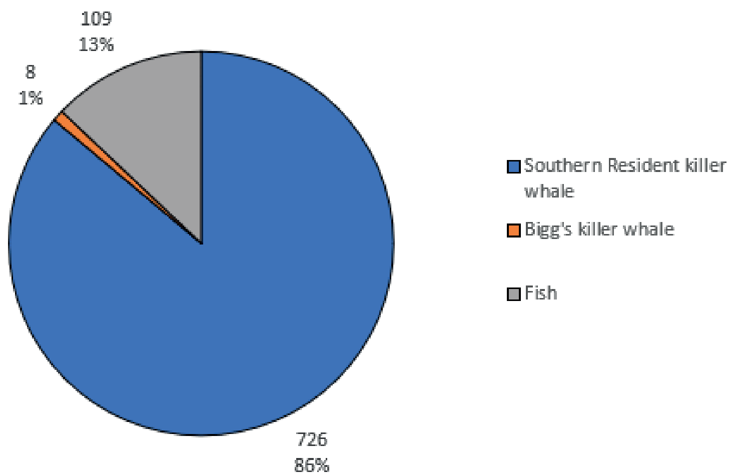

Figure B-3. 1 to 31 Aug 2022: Counts and proportion of vocalization detections per species.

B.3.2. Killer Whales

Figure B-4. 1 to 31 Aug 2022: Daily and hourly occurrence of killer whale vocalizations at ULS A2. Black blocks indicate validated detections, and grey areas indicate darkness period.

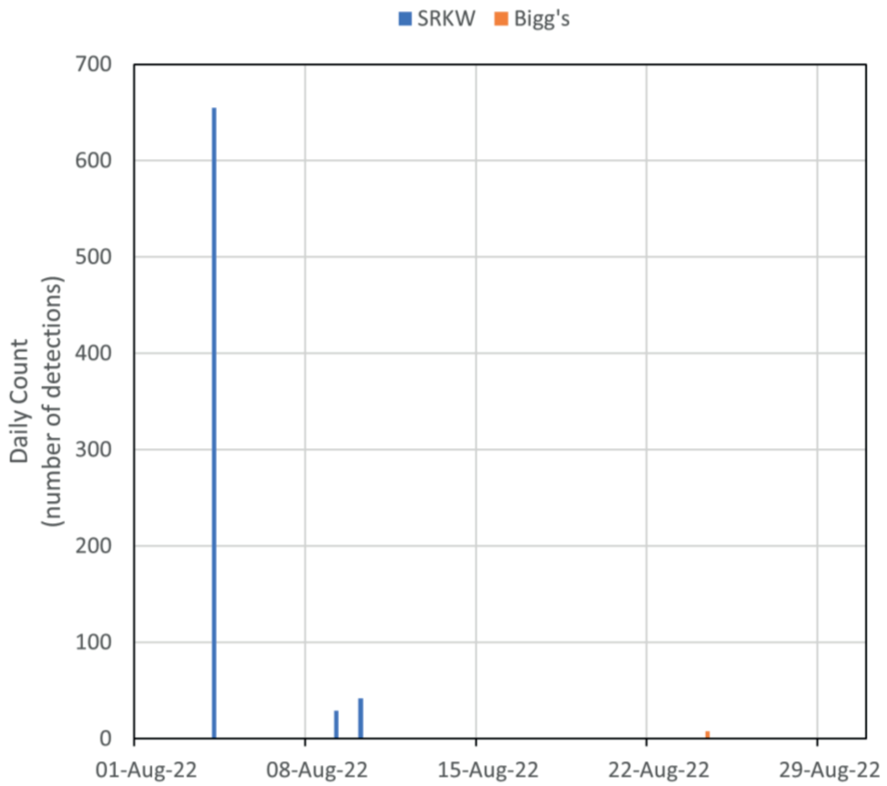

Figure B-5. 1 to 31 Aug 2022: Daily validated detection counts of Southern Resident Killer Whale (SRKW) and Bigg's vocalizations at ULS A2 and B1.

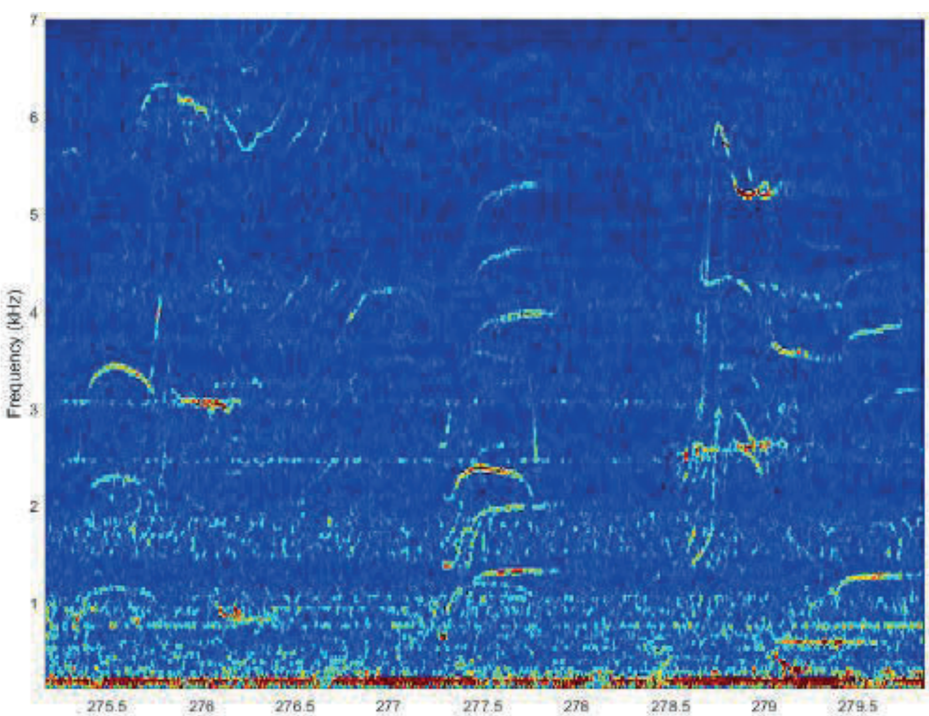

Figure B-6. 4 Aug 2022 (22:44 UTC): Spectrogram of Southern Resident killer whale (SRKW) vocalizations at ULS A2.

B.3.3. Humpback Whales

No humpback whale detections were validated on ULS A2 or B1 recordings during the analysis period.

B.3.4. Pacific White-sided Dolphins

No Pacific white-sided dolphin detections were validated on ULS A2 or B1 recordings during the analysis period.

B.3.5. Fish

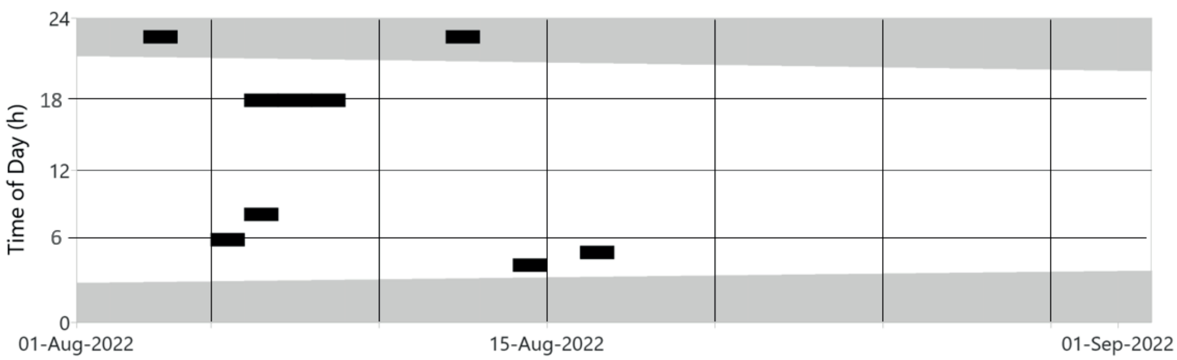

Figure B-7. 1 to 31 Aug 2022: Daily and hourly occurrence of fish sounds at ULS B1. Black blocks indicate validated detections, and grey areas indicate darkness period.

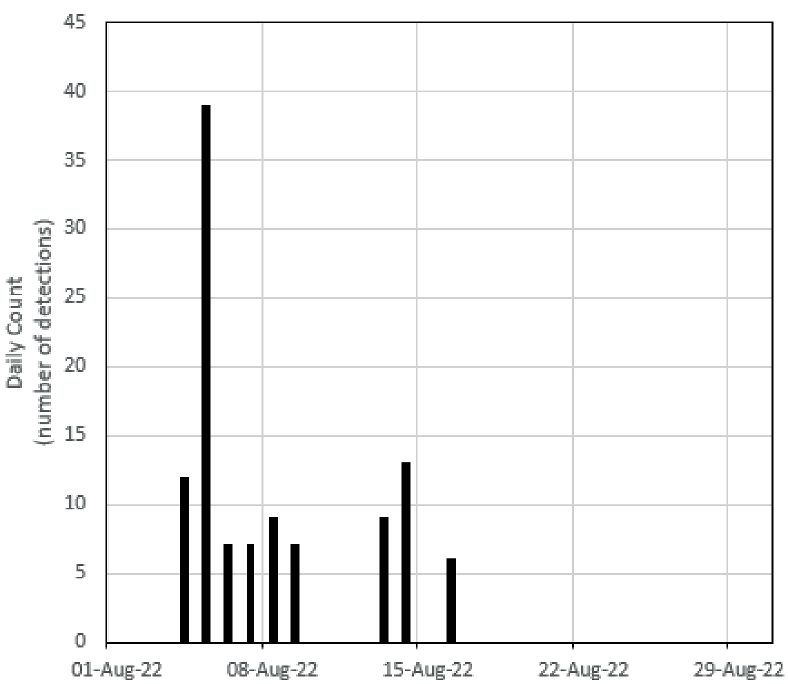

Figure B-8. 1 to 31 Aug 2022: Daily validated detection counts of fish sounds at ULS B1.

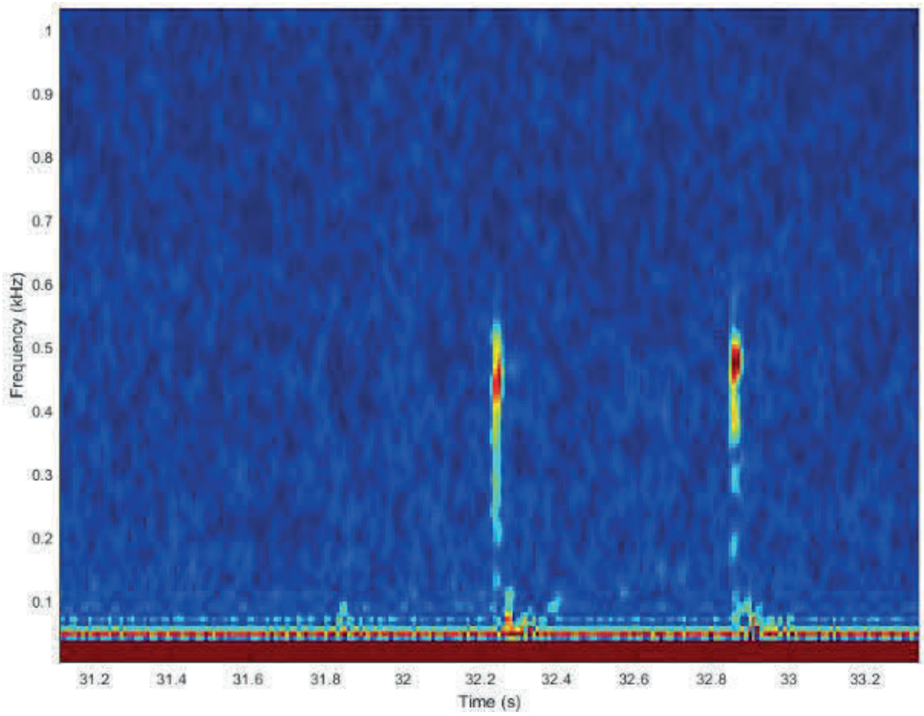

Figure B-9. 4 Aug 2022 (07:09 UTC): Spectrogram of fish knocks at ULS B1.

Appendix C. Summary of Vessel Source Level Methods

JASCO's ShipSound software monitors sound level measurements and AIS broadcasts from passing vessels. It identifies vessels that traverse a predefined transit area and then automatically extracts the corresponding acoustic data for analysis. To determine the timing and location of closest point of approach (CPA) of a vessel's acoustic centre, one of two algorithms can be selected: (1) use a vessel's broadcast speed together with a cepstral analysis of the Lloyd mirror pattern or (2) image symmetry detection by gradient polarity. ShipSound can analyze streaming data from a hydrophone in real time or, as in the case of the Boundary Pass autonomous listening stations, can analyze archival hydrophone data downloaded from autonomous recorders.

The ANSI/ASA S12.64 data window is defined by the period over which the acoustic centre is within ±30° of the CPA (ANSI/ASA S12.64-2009). ShipSound automatically determines the data window and processes a single acoustic channel in 1-second periods stepped in 0.5-second intervals (Figure C-1). Spectrum measurements are calculated using 1-second fast Fourier transforms, shaded using a Hanning window.

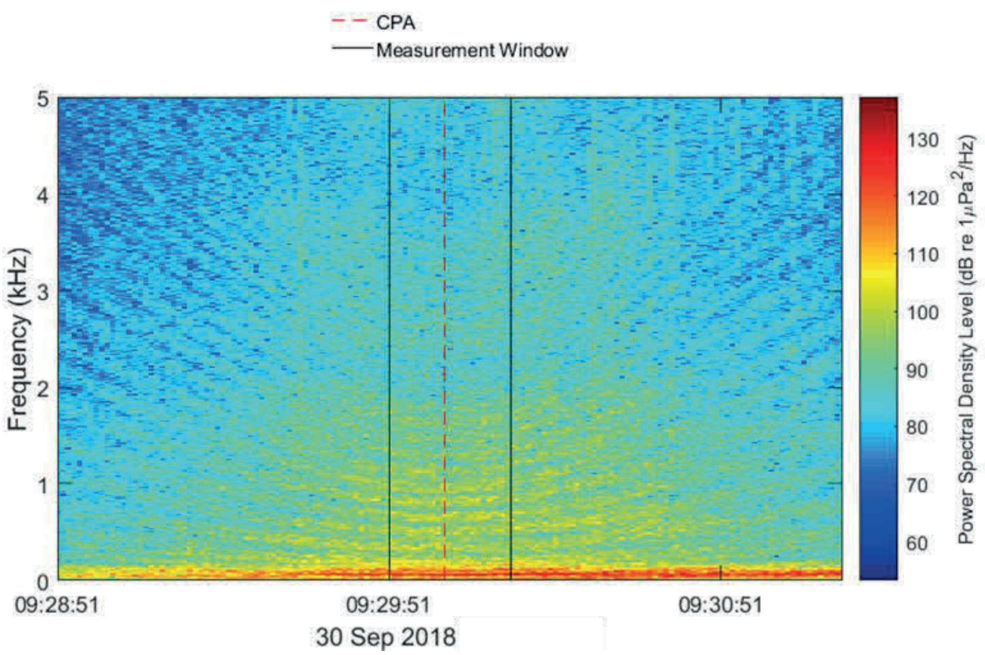

Figure C-1. Spectrogram of a single vessel measurement from ShipSound, showing the closest point of approach (CPA) time (dashed red line) and the measurement window (black box) used for calculating vessel source levels. The spectrogram shows the spectrum of the underwater sound pressure recorded on the AMAR versus time and frequency. Although acoustic data were characterized up to 64 kHz, the spectrogram is shown up to 5 kHz because the Lloyd mirror pattern is strongest at lower frequencies.

ShipSound calculates two metrics representing vessel noise emissions: Radiated Noise Level (RNL) and Monopole Source Level (MSL). RNL is equal to the measured sound pressure level, back-propagated according to the distance between a source and the hydrophone. The software applies the ANSI/ASA S12.64 Grade-A method for back-propagation distance: it determines instantaneous vessel range (R) in metres from the measurement hydrophone for each 1-second step within the data window. The RNL back propagation method of 20 x $\log_{10}(R)$ is applied to the spectra of each step separately. MSL is equal to the measured sound pressure level scaled according to a numerical acoustic transmission loss (TL) model that accounts for the effect of the local environment on sound propagation (i.e., sea-surface reflection, water column refraction and absorption, and bottom loss). MSL back-propagation is performed using predictions of the Parabolic Equation model RAM, modified to treat shear wave reflection losses, in decidecade-bands to 5 kHz, and an image reflectivity model at higher frequencies. MSL back-propagation requires a source depth, which is defined in ShipSound as a Gaussian distribution centred at the draft minus 0.85 of the propeller diameter (Gray and Greeley 1980). If the propeller diameter is unknown, it is calculated from the vessel draft as,

$$p = 0.3d/0.85,$$

where *p* is the propeller diameter (m), and *d* is the vessel draft (m). Thus, when the propeller diameter is unknown, the Gaussian is centred at 70 % of the vessel draft. RNL is the source level calculation method specified by the ANSI standard whereas most acoustic models used for assessing shipping noise effects on marine fauna use MSL.

Environmental conditions (wind speed and current speed) were also recorded for each measurement. Meteorological data for Boundary Pass were obtained from Environment Canada weather stations (see Section2.1.4). Ocean current measurements were obtained from ADCP measurements, or, when unavailable, the WebTide Tidal Prediction Model (v 0.7.1) (see Section 2.1.2). Ocean current data were used to calculate speed through water from speed over ground (SOG) information received via AIS for each vessel measurement.

PortListen includes a web-based user interface for accessing vessel and measurement information. A table view screen lets the user select and view multiple measurements by vessel criteria. This information, including broadband MSL and RNL source levels, can be exported as a spreadsheet. Vessel measurements are summarized in PDFs, presenting vessel and environment information, and the decidecade-band MSL and RNL source levels.

All source level measurements were subjected to two phases of quality control: an automated review of source and background levels that was performed on a decidecade-band basis, and a manual review of the overall measurement. For the first quality review phase, ShipSound calculated background noise in each frequency band from one-minute time periods before and after the vessel entered the measurement funnel. ShipSound accepted band source levels if they exceeded background levels by more than 10 dB, corrected them if they exceeded background levels by 3–10 dB, and rejected them if they were less than 3 dB above background. Adjusted and rejected levels were flagged in the database. Figure C-2 summarizes this approach. The overall vessel measurement was not necessarily rejected if some of the decidecade-band source levels were rejected during the automated quality review phase.

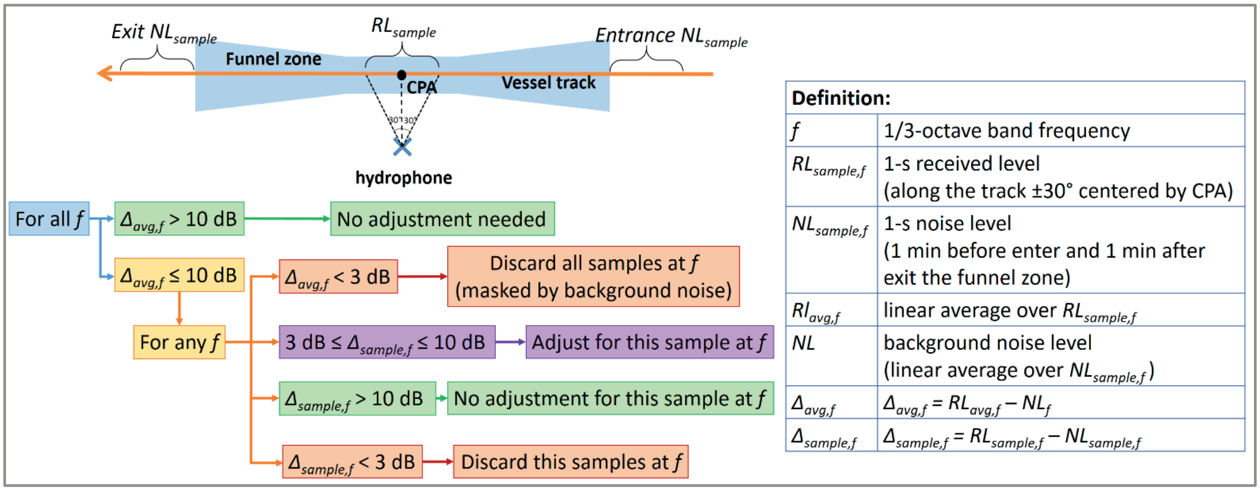

Figure C-2. Background noise comparison and adjustment process as part of the first (automated) phase of quality control.

For the second quality review phase, an experienced analyst used the web-based interface to manually review every measurement. An analyst could reject a measurement because it contained interference from other vessels, had high levels of background noise (i.e., a large number of rejected band source levels), or if a vessel did not have constant speed and a straight track inside the data window, or if the data clipped more than 6 seconds within the measurement data window.

Appendix D. Summary of Vessel Source Level Measurements

Table D-1 lists the total number of accepted vessel source level measurements during the analysis period. Table D-2 lists the vessel acceptance rate as a percent.

Table D-1. Number of accepted vessel source level measurements during Year 4 (January to December, 2022).

Vessel category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Bulker	394	417	442	342	399	391	385	373	416	455	443	418	**4875**
Container Ship	153	142	205	192	168	178	171	162	157	191	156	159	**2034**
Cruise	0	0	0	37	59	28	29	20	59	34	3	0	**269**
Dredger	0	0	1	2	0	0	0	0	0	0	0	0	**3**
Ferry	0	16	0	19	0	22	0	0	2	83	55	72	**269**
Fishing Vessel	0	6	4	7	6	13	16	6	14	9	6	12	**99**
Government/Research	3	2	2	5	4	2	10	8	8	19	11	0	**74**
High Speed Ferry	0	0	0	0	0	0	0	0	0	0	0	0	**0**
LNG Carrier	0	0	4	0	2	2	0	0	0	0	0	2	**10**
Other	14	2	25	16	19	8	10	8	19	5	13	8	**147**
Passenger	0	0	0	0	3	8	5	3	6	2	0	3	**30**
Recreational	1	0	0	1	2	12	10	4	17	2	3	4	**56**
Tanker	33	38	43	59	50	42	29	49	31	43	36	43	**496**
Tug	68	70	72	50	77	60	66	67	49	32	62	62	**735**
Vehicle Carrier	61	74	69	43	56	44	62	62	56	63	69	75	**734**
Whale Watch	0	0	0	0	0	0	2	0	0	0	0	0	**2**

Table D-2. Acceptance rate (percent) of vessel source level measurements during Year 4 (January to December, 2022). Cells with "NA" indicate there were no accepted or rejected measurements for the corresponding month and vessel category.

Vessel category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Bulker	81.9	85.5	82.2	82.6	84.5	85.0	80.0	80.6	77.5	80.4	79.2	82.9	**81.8**
Container Ship	84.1	84.5	84.0	91.9	76.4	87.3	83.0	83.5	81.8	95.0	73.6	85.5	**84.1**
Cruise	NA	NA	NA	84.1	84.3	82.4	80.6	76.9	86.8	73.9	75.0	NA	**82.0**
Dredger	NA	NA	100.0	100.0	NA	NA	NA	NA	NA	NA	NA	NA	**100.0**
Ferry	NA	66.7	NA	73.1	NA	75.9	NA	NA	100.0	87.4	85.9	85.7	**83.0**
Fishing Vessel	NA	60.0	66.7	70.0	50.0	72.2	88.9	50.0	82.4	75.0	75.0	85.7	**72.3**
Government/Research	75.0	100.0	40.0	41.7	100.0	25.0	37.0	66.7	50.0	59.4	42.3	0.0	**49.3**
High Speed Ferry	NA	NA	NA	NA	NA	NA	NA	0.0	NA	NA	NA	NA	**0.0**
LNG Carrier	NA	NA	100.0	NA	100.0	100.0	NA	NA	NA	NA	NA	100.0	**100.0**
Other	70.0	28.6	96.2	72.7	73.1	80.0	83.3	72.7	73.1	41.7	81.3	88.9	**74.6**
Passenger	NA	NA	NA	NA	25.0	50.0	71.4	50.0	66.7	20.0	NA	75.0	**46.9**
Recreational	50.0	NA	NA	20.0	20.0	70.6	34.5	50.0	58.6	40.0	9.7	66.7	**39.4**
Tanker	63.5	65.5	56.6	68.6	64.9	60.0	58.0	68.1	51.7	75.4	60.0	61.4	**62.9**
Tug	63.6	60.3	59.5	48.1	59.2	52.6	54.1	65.7	59.0	52.5	61.4	57.9	**58.0**
Vehicle Carrier	92.4	97.4	89.6	79.6	90.3	84.6	79.5	81.6	94.9	85.1	93.2	91.5	**88.4**
Whale Watch	NA	NA	NA	NA	NA	NA	100.0	NA	NA	0.0	NA	NA	**66.7**

Appendix E. Probability density functions (PDFs) of the measured SPL

The probability density functions (PDFs) in this section correspond to the CDFs (Figures 4-8) provided in Section 3.1. They are provided to facilitate comparisons between hydrophone channels, since in many cases the differences between CDFs described in Section 3.1 become more evident in the PDF representation.

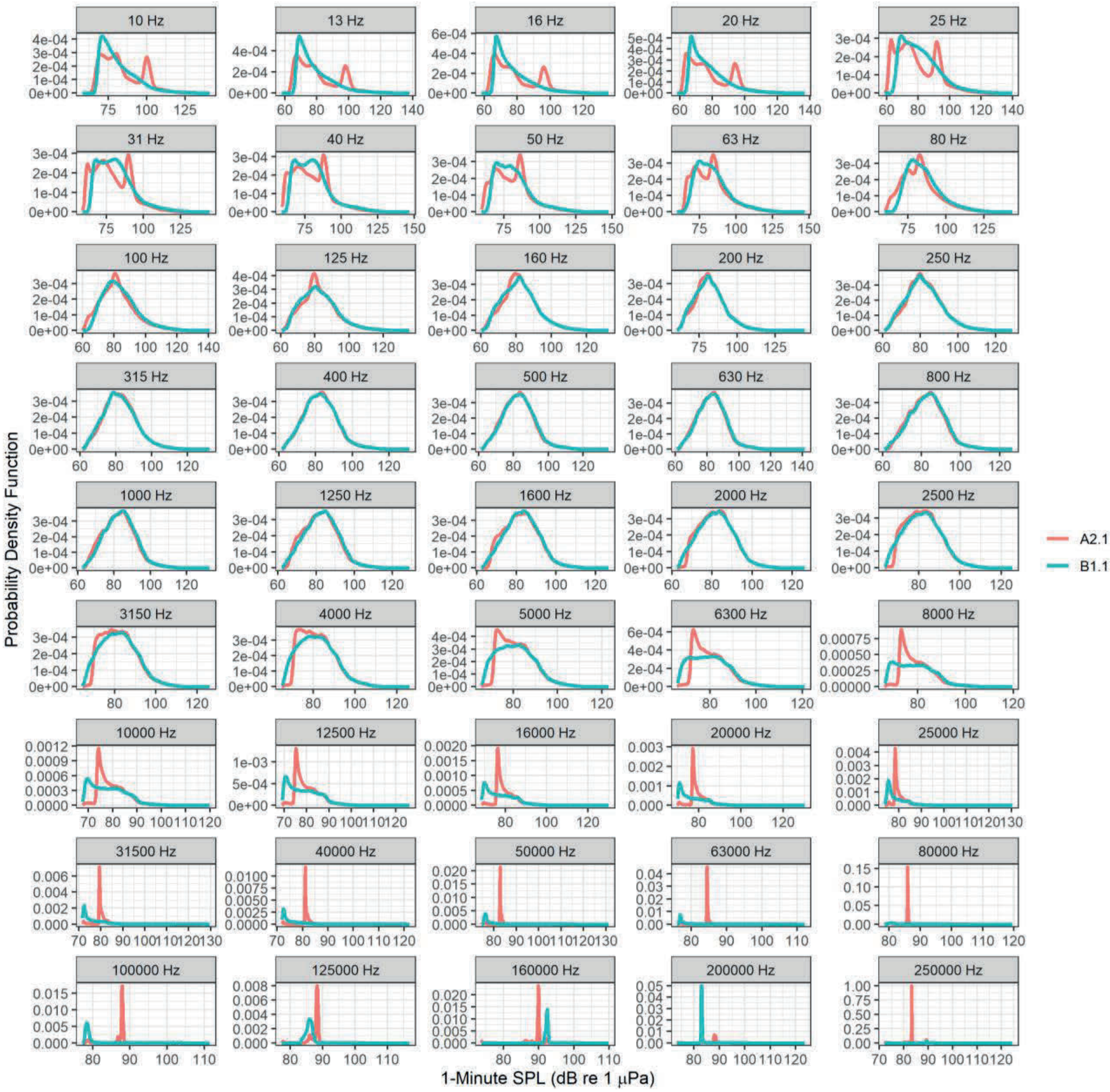

Figure E-1. 1 Jan to 1 Dec 2022, during quiet periods: Probability density functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.1 and B1.1). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.25 m/s. Panel headings indicate the centre frequency of the decidecade band.

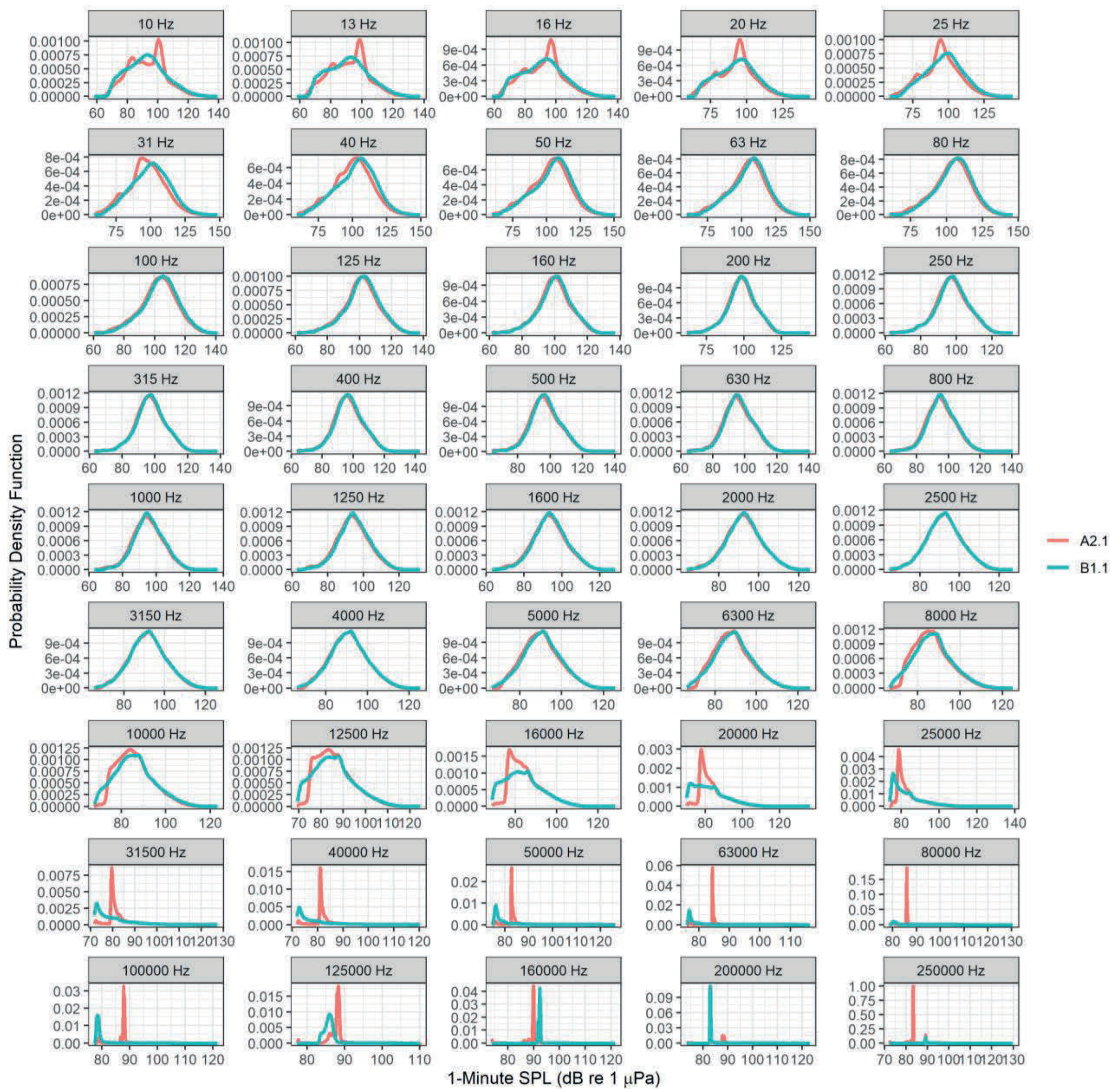

Figure E-2. 1 Jan to 1 Dec 2022, during loud periods: Probability density functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.1 and B1.1). Data were pre-filtered to exclude minutes when current speeds were greater than 0.25 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.

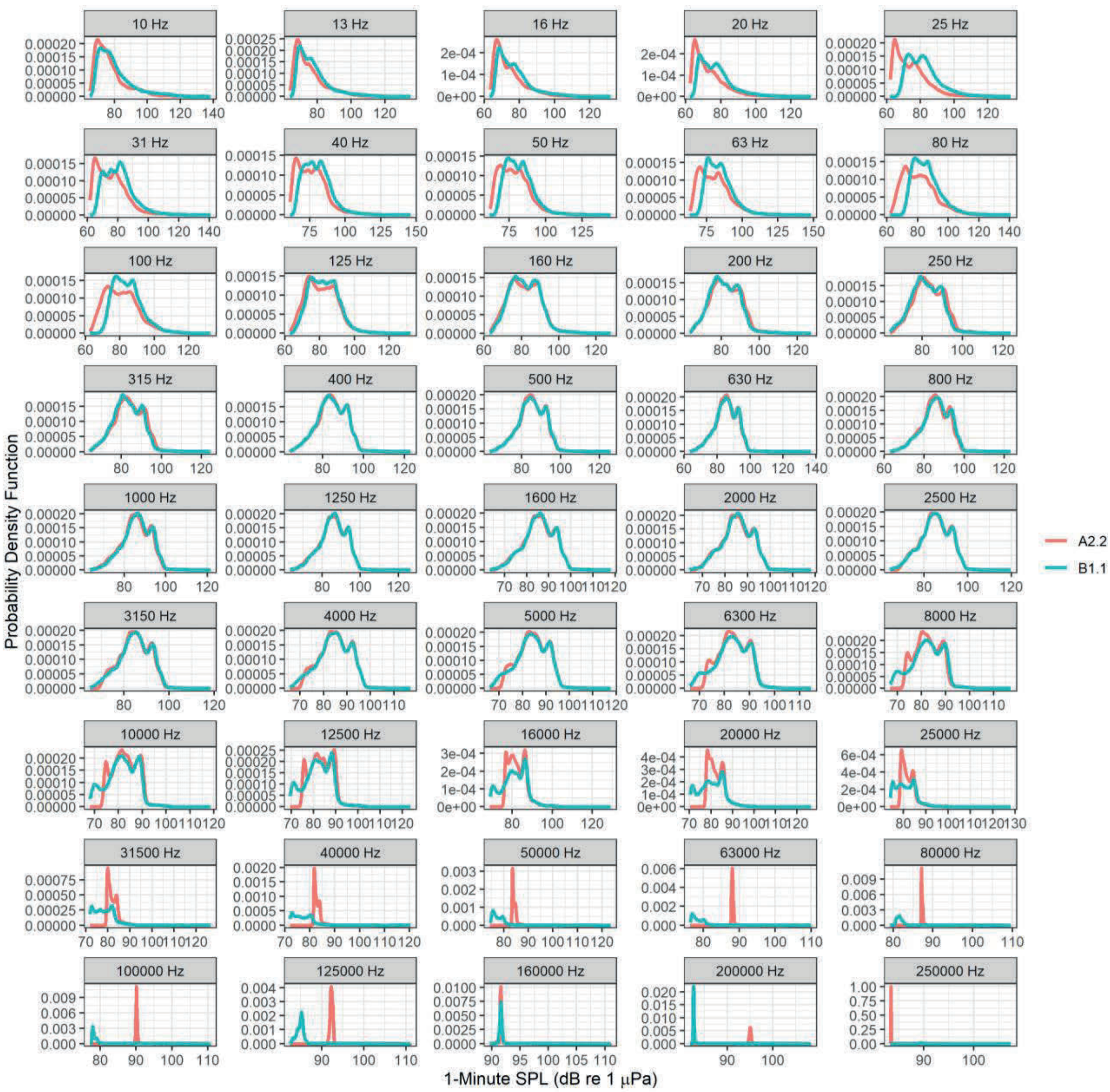

Figure E-3. 1 Dec to 31 Dec 2022, during quiet periods: Probability density functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.2 and B1.1). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.25 m/s. Panel headings indicate the centre frequency of the decidecade band.

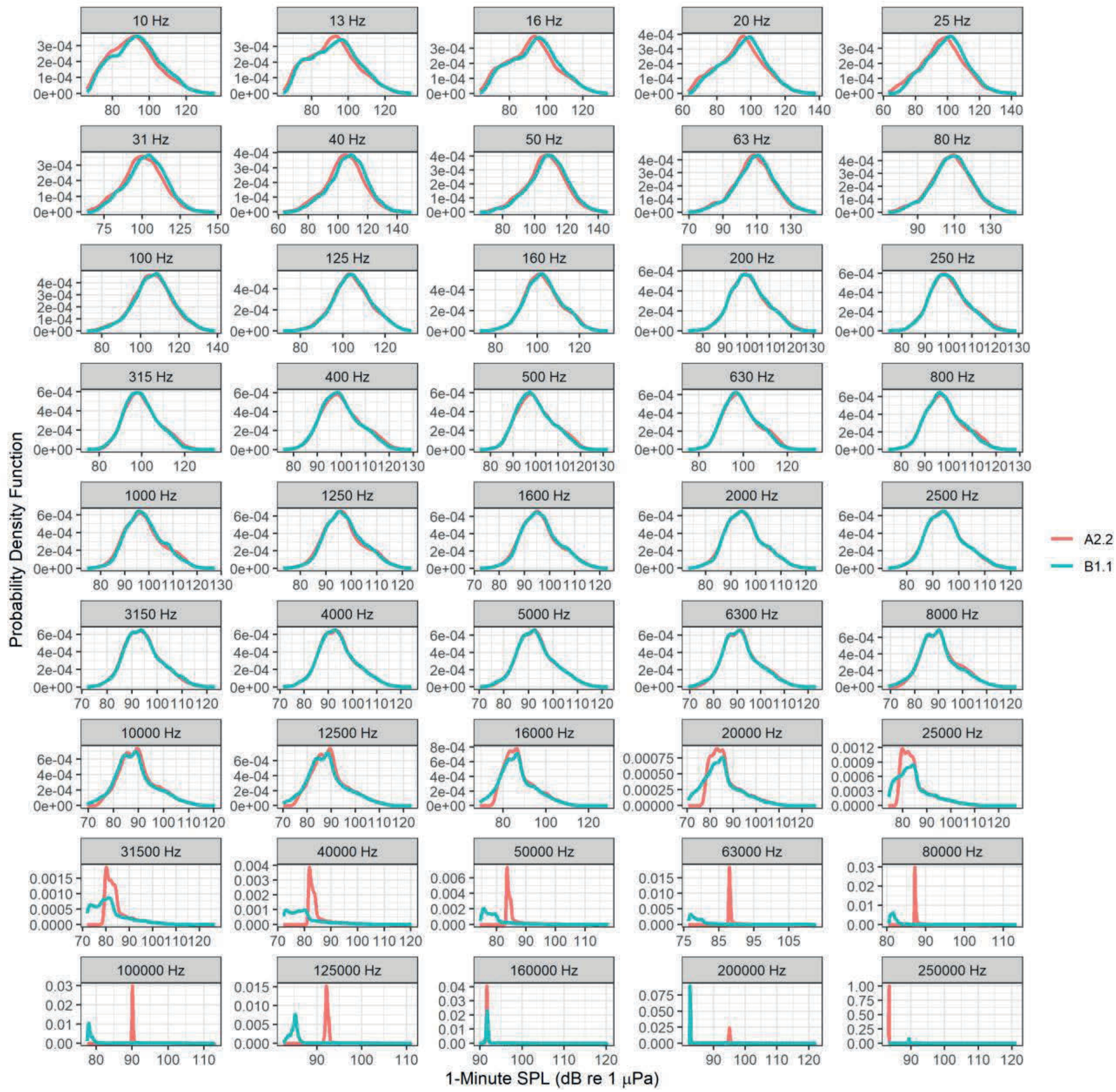

Figure E-4. 1 Dec to 31 Dec 2022, during loud periods: Probability density functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A2.2 and B1.1). Data were pre-filtered to exclude minutes when current speeds were greater than 0.25 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.