Annual report – Boundary Pass acoustic monitoring

Year 3 (January to December 2021)

ECHO Program Summary

The Vancouver Fraser Port Authority (VFPA)-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 third annual report contains a comprehensive analysis of the measurement results for Year 3, from January to December 2021.

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 3 reporting period, one of the ULS multi-hydrophone arrays encountered a technical problem between June and October 2021. As a result, a single hydrophone recorder (AMAR) was deployed as a backup. The AMAR data were processed for ambient noise statistics to compare with ULS recordings but were not processed to detect marine mammals or for vessel source-level analysis. By October 9, 2021, both ULS arrays had been replaced with new systems. After the October ULS servicing operation, a power unit on one of the arrays became nonoperational, resulting in water current data (collected by an Acoustic Doppler Current Profiler, ADCP) being unavailable between October 2021 and May 2022. Water current data to evaluate speed through water for vessel measurements were derived from the WebTide prediction model during this time period.

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;
- Sound levels were generally consistent over time with two notable exceptions:
  - Higher percentile broadband (L5, L25) levels were lower from July through September, likely due to lower vessel noise from commercial vessels participating in the ECHO Program's 2021 Haro Strait and Boundary Pass voluntary slowdown.
  - Lower percentiles broadband (L75, L95) levels were elevated at frequencies above 10 kHz after the ULS servicing operation. The observed increase in the lower percentile levels beginning in late October may be related to high wind and rain.
- Ambient noise level statistics calculated from different hydrophones simultaneously showed good agreement at mid frequencies. However, some differences were observed at low frequencies (below ~100 Hz) and high frequencies (above ~10 kHz).
- There are differences in sound pressure levels between hydrophone channels at very high frequency (100–256 kHz) due to each hydrophone's characteristic noise floor.

Marine Mammal Detections

- Over 24,300 marine fauna detections (fish sounds and cetacean vocalizations) were recorded in the 12-month study period. Fish sounds were detected most frequently (45%), with detections occurring during all months of the year except February.
- Killer whale vocalizations were detected on 57 days, in all months except June. SRKW vocalizations were absent from May until the August and peaked in September, while Transient/Bigg's vocalizations were present every month except June.
- Humpback whale vocalizations were detected on 34 days over 8 months, with detections peaking in November. No Pacific white-sided dolphins were detected.

Vessel Source Levels

- A total of 10,709 source level measurements of 1,777 unique vessels were collected during the study period. Of these, approximately 74% (7,884 measurements) passed manual quality control checks.
- For accepted source level measurements, 1,866 correspond to unique transits measured at only one ULS array, while there were 3,009 transits for which duplicate measurements were accepted at both ULS arrays.
- The maximum accepted radiated noise level (RNL) measurement was 205.4 dB re 1 μPa m for a container ship.
- The minimum accepted radiated noise level measurement was 161.3 dB re 1 μPa m for a ferry transit.
- Bulkers made up approximately 53% of all accepted measurements, while container ships accounted for approximately 23% of the measurements during the study period.
- The mean difference in source level measurements between the two arrays was 0.3 dB (measurements January to June 2021), and 1.0 dB (measurements October to December 2021) indicating good agreement between the two arrays.

Conclusions and next steps

Acoustic measurements were made using at least one ULS array every day in 2021 and two recorders (either two ULS arrays or an array and an AMAR) on 339 of 365 days in 2021. 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 third annual Boundary Pass report, detections and classifications of marine mammal vocalizations have been expanded to include specific killer whale ecotypes, allowing for identification of Southern Resident killer whale detections.

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 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 third annual report supporting the long-term Boundary Pass ULS monitoring program, currently funded through March 2023.

Annual Report of Boundary Pass Acoustic Monitoring

Year 3, January to December 2021

JASCO Applied Sciences (Canada) Ltd

18 March 2022

Submitted to:

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Contract 19-0280

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P001507-001
Document 02684
Version 2.0

Suggested citation:

Houweling, A.E., E.E. Maxner, C.H. Grooms, Z. Li, J.L. Wladichuk, J.E. Quijano, and G.A. Warner. 2022. Annual Report of Boundary Pass Acoustic Monitoring: Year 3, January to December 2021. Document 02684, Version 2.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority.

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Executive Summary

Vancouver Fraser Port Authority (VFPA) has entered an agreement with Transport Canada to manage the analysis of a large underwater acoustic data set being 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 2021 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 12 Dec 2018 and will continue to at least 31 Mar 2023. Details of the data collection and analysis from 12 Dec 2018 to 31 Dec 2020 are described in two previous annual reports (Warner and Frouin-Mouy 2020, Cusano et al. 2021). This third annual report contains analysis of data acquired between 1 Jan and 31 Dec 2021. 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 time period analyzed in this third report were collected using two types of recorders: for the ULS, the recorders are 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] During this collection period, a technical problem prevented Frame B from collecting data from 17 Jun 2021 to 7 Oct 2021. The second type of recorder, deployed as a backup from 7 Jul 2021 to 3 Oct 2021 near the location of the still-operating Frame A, is a JASCO AMAR G4 (single hydrophone channel). The acquired AMAR data were processed for ambient noise statistics to compare with ULS recordings but were not processed to detect marine mammals or for vessel source levels. By 9 Oct 2021, both ULS frames had been replaced with new systems, which have been in continuous operation since.

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 speed at the ULS frames. Current speed is required in this analysis to estimate vessel speed through water, as well as to identify time periods of high flow noise, which have been observed when current speed exceeds 0.5 m/s. In this report, we present monthly sound pressure level statistics that include periods of high flow noise, and compare it to statistics that exclude those periods.

Part of this investigation involved comparing the sound levels obtained from different recorders to assess consistency. This comparison was carried out before and after ULS servicing (i.e., Frame A versus B), as well as during the period of a technical problem with Frame B (i.e., Frame A versus AMAR). In all cases, there was generally good agreement between data, with small differences observed at specific frequency bands, as follows.

Prior to servicing, the most evident differences between the ULS frames occurred in the decidecade frequency bands 160 kHz (due to acoustic contamination from the ADCP) and 250 kHz (likely due to differences in noise floors between hydrophones in the two frames). During relatively quiet times (when

[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).

vessels were absent), sound levels between the ULS frames exhibited slight differences at frequencies at or below 40 Hz. Such differences were significantly reduced during louder times (when vessels were present within 6 km of the hydrophone).

After servicing, differences between measurements at the two ULS frames were found at low frequencies (bands centred between 20 and 80 Hz). Similar to the period prior to servicing, these differences were significantly smaller during loud times than quiet times. Differences at mid to high frequencies (bands centred at frequencies greater than 8 kHz) were also found after servicing, and they are thought to be caused by the performance characteristics of the hydrophones in Frame A (HTI brand) and Frame B (GTI brand).

Sound levels processed from the Frame A data and the AMAR also showed consistency in most bands. The main differences occurred at bands centred below 80 Hz, for which the AMAR data exhibited higher sound levels than those from the ULS. For example, in the 10 Hz decidecade band (which is commonly affected by flow noise), ~100% of SPLs measured at Frame A1 were below 100 dB re 1 μPa, while only ~60% of the SPLs measured at the AMAR were below 100 dB re 1 μPa. The remaining 40% of AMAR measurements were above 100 dB re 1 μP, likely driven by higher current-induced flow noise which would have a stronger effect on the AMAR due to its mooring-style deployment design. Similar effects have been observed in previous years (Cusano et al. 2021).

Long-term ambient sound levels exhibit some monthly variability but were generally constant over time. A reduction of monthly variability was observed when time periods with current speeds greater than 0.5 m/s were omitted. Two exceptions were identified for this fairly constant temporal behavior in ambient sound levels. The first exception is that the higher percentile broadband levels (L_5, L_{25}) were lower in July to September, which is likely due to lower vessel noise from slower commercial vessels participating in the ECHO program's 2021 Haro Strait and Boundary Pass voluntary slowdown. The second exception was an increase of sound levels in the 10–100 kHz and 100–256 kHz band levels after the ULS servicing operation in early October 2021. We believe this is caused by the higher high-frequency noise floor of the Frame B1 hydrophone after servicing. On a daily scale, sound levels were largely determined by the tidal cycle, and they did not show a strong weekday/weekend difference. The sound levels on Christmas Day (25 Dec 2021) and New Years Day (1 Jan 2022) were noticeably lower than those on the preceding or following days, due to a decrease in vessel traffic (also noted in previous years).

In this study 24,355 manually validated marine fauna detections were found in the acoustic data during the 12 month data collection period for this report. Most (45%) of these detections were of fish sounds, which were detected in most months. The remaining marine fauna detections were from killer whale vocalizations (38%) and humpback whale vocalizations (17%). No Pacific white-sided dolphin vocalizations were detected. Killer whale ecotypes were determined and reported for all 2021 data.

Over 10,000 vessel source level measurements of 1777 unique vessels representing 13 vessel categories were analyzed with JASCO's ShipSound application for this analysis period (2021). Out of all these measurements, 7884 were accepted (1866 unique passes measured at only one ULS frame and 3009 duplicate passes measured at two ULS frames). Most measurements were of Bulker or Container ship categories. Most vessels transiting through Boundary Pass were measured on both ULS frames, that are separated by 300 m. These double measurements allowed investigation of consistency of measured RNL between the frames. For Deployment 1, the differences in RNL between Frames A and B (1 Jan 2022 to 17 Jun 2022) had a mean of −0.3 dB (with standard deviation of 1.3 dB), while for Deployment 2 (8 Oct 2022 to 31 Dec 2022) this mean was −1 dB (with standard deviation of 1.1 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 deployments of JASCO's calibrated Autonomous Multichannel Acoustic Recorders (AMAR 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 included two tetrahedral-shaped aluminum frames (Frames A and B), each frame supporting multiple hydrophone sensors, cabled to a shore station on Saturna Island.

In June 2021, Frame B stopped recording due to a component failure. This left only Frame A operating. While a ULS servicing operation was being planned, an AMAR G4 was deployed near the location of Frame A to act as a backup system. In October 2021, both ULS frames were replaced during the servicing operation. Both frames are still recording as of February 2022. 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 been occurring 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 2021, corresponding to the five autonomous recorder deployments and approximately 18 months of continuous ULS recordings, have been analyzed and reported for ambient noise statistics and marine mammal vocalizations in quarterly reports. 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, and the second annual report (Cusano et al. 2021), from October 2019 to December 2020. The present and third annual report contains a comprehensive analysis of the measurement results for Year 3, from January to December 2021.

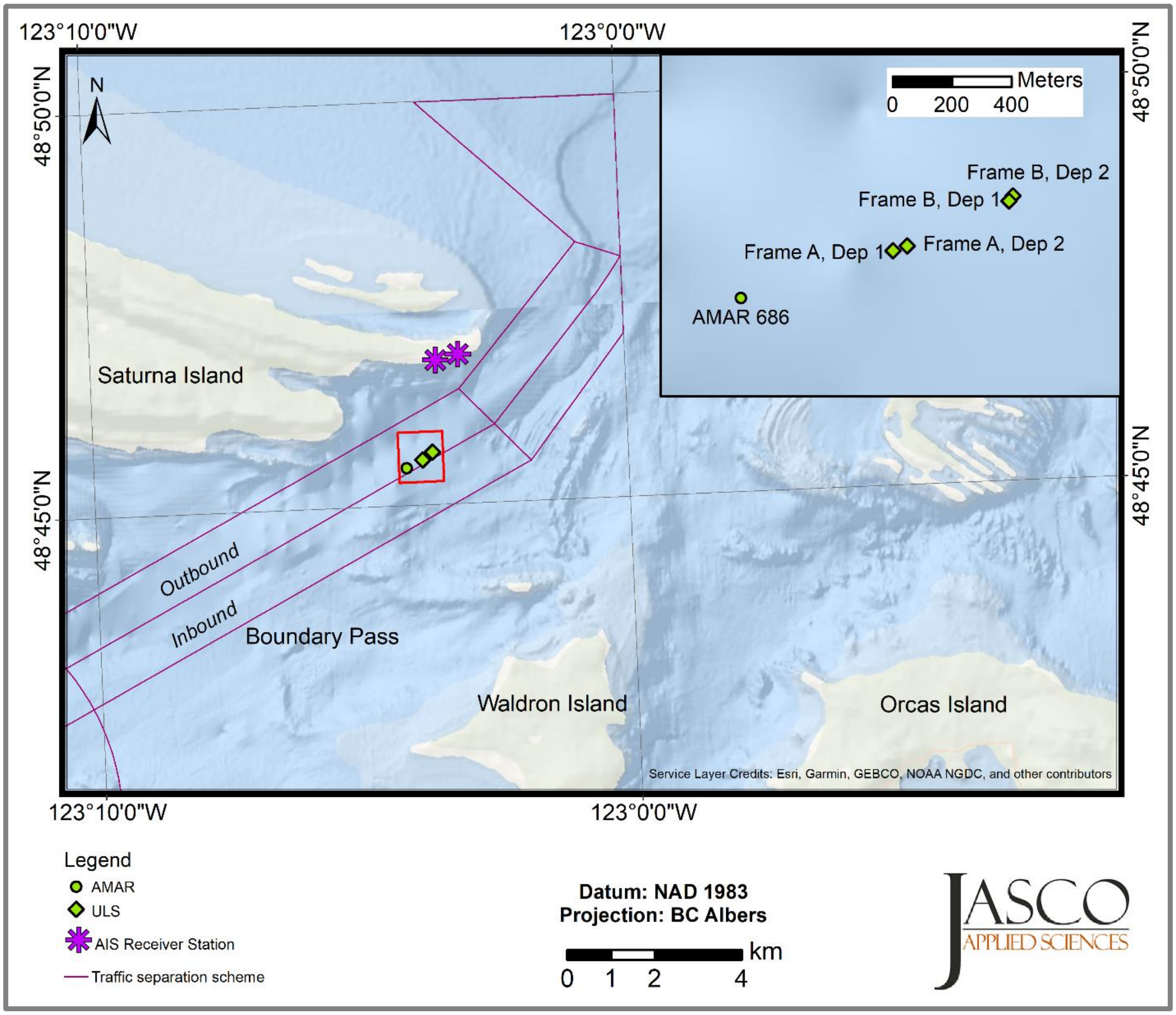

Figure 1. Map showing the locations of the data acquisition equipment in Boundary Pass. The locations of the Autonomous Multichannel Acoustic Recorder (AMAR 686) and the two deployments of the Underwater Listening Station (ULS) frames during Year 3 are shown on the inset map. The cabled Acoustic Doppler Current Profiler (ADCP) was mounted on Frame A. The vessel traffic lanes are shown as purple lines.

2. Methods

2.1. Data Acquisition

2.1.1. Acoustic Measurements

The primary acoustic measurements during the Year 3 reporting period were made at the ULS using two shore-cabled compact tetrahedral hydrophone arrays, which are referred to as Frames A and 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. In addition to the hydrophones arrays, Frame A also has a 150 kHz Teledyne Quartermaster Acoustic Doppler Current Profiler (ADCP) to measure the current speeds in the water column above.

On 17 Jun 2021, a component failure in Frame B caused that system to stop recording. After a few days of troubleshooting, it was determined that Frame B could not be restarted. While the ULS servicing operation was being planned, an Autonomous Multichannel Acoustic Recorder Generation 4 (AMAR G4) with one hydrophone was deployed nearby to provide a backup recording in case Frame A failed. The AMAR was deployed on 7 Jul and recorded until 3 Oct. Frame A continued recording throughout this time, so the AMAR data was not essential to the measurement program. Between 6 and 9 Oct, both ULS frames were replaced with new units during the servicing operation (Figure 2). The replacement ULS frames were operational after servicing, using Frames A2 and B1 to record data, and both continued to record data through the end of 2021.

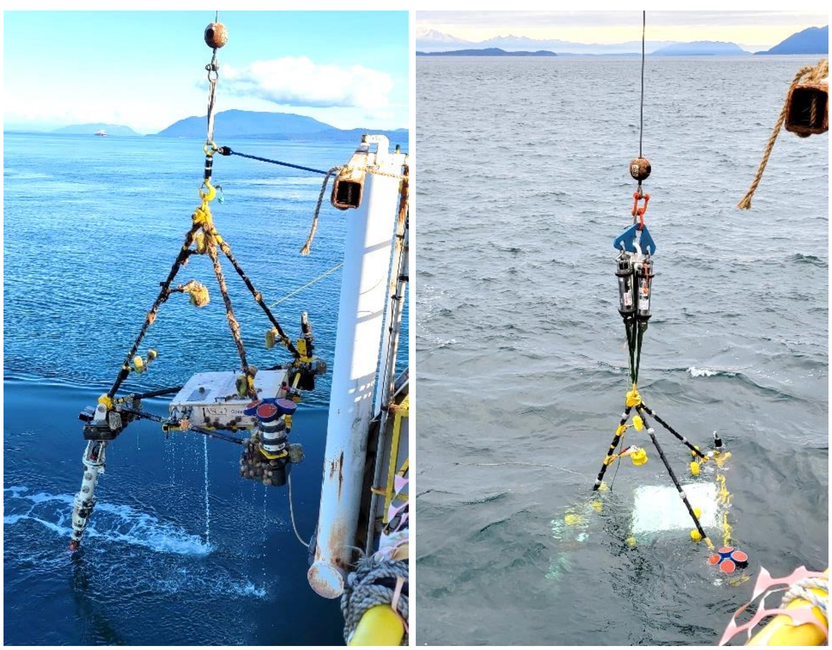

Figure 2. (Left) Retrieval of Underwater Listening Station (ULS) Frame A on 7 Oct 2021, and (right) deployment of the replacement Frame A on 8 Oct 2021.

All recorders (ULS frames and the AMAR) 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, and Figure 3 shows a visualization of the recording periods.

Table 1. Recorder deployment (Dep) locations and periods in 2021 (Year 3). The deployment locations are also shown in Figure 1 above.

Recorder	Latitude (N)	Longitude (W)	Water depth (m)	Active hydrophone array	Hydrophone model	Recording start	Recording end
Frame A, Dep 1*	48°45.55800'	123°3.87600'	193	Frame A1	GTI M36-V35-100	Jan 1 00:00	Oct 8 10:51
Frame B, Dep 1*	48°45.64800'	123°3.66600'	195	Frame B1	GTI M36-V35-100	Jan 1 00:00	Jun 17 11:46
AMAR 686	48°45.47220'	123°4.15200'	187	†	GTI M36-V35-100	Jul 7 10:46	Oct 3 00:06
Frame A, Dep 2	48°45.56672'	123°3.85010'	193	Frame A2	HTI 99-HF	Oct 8 10:54	Dec 31 23:59
Frame B, Dep 2	48°45.65731'	123°3.65912'	195	Frame B1	GTI M36-V35-100	Oct 7 11:53	Dec 31 23:59

* The ULS frames had been deployed and operating since June 2020.
† The AMAR had a single hydrophone.

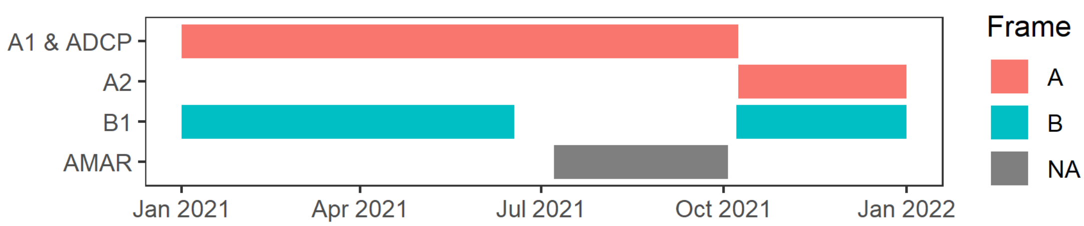

Figure 3. Recording periods of the ULS hydrophone arrays and the AMAR, both before and after the ULS servicing operation in October in which the ULS frames were replaced (see Table 1).

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 4). 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.

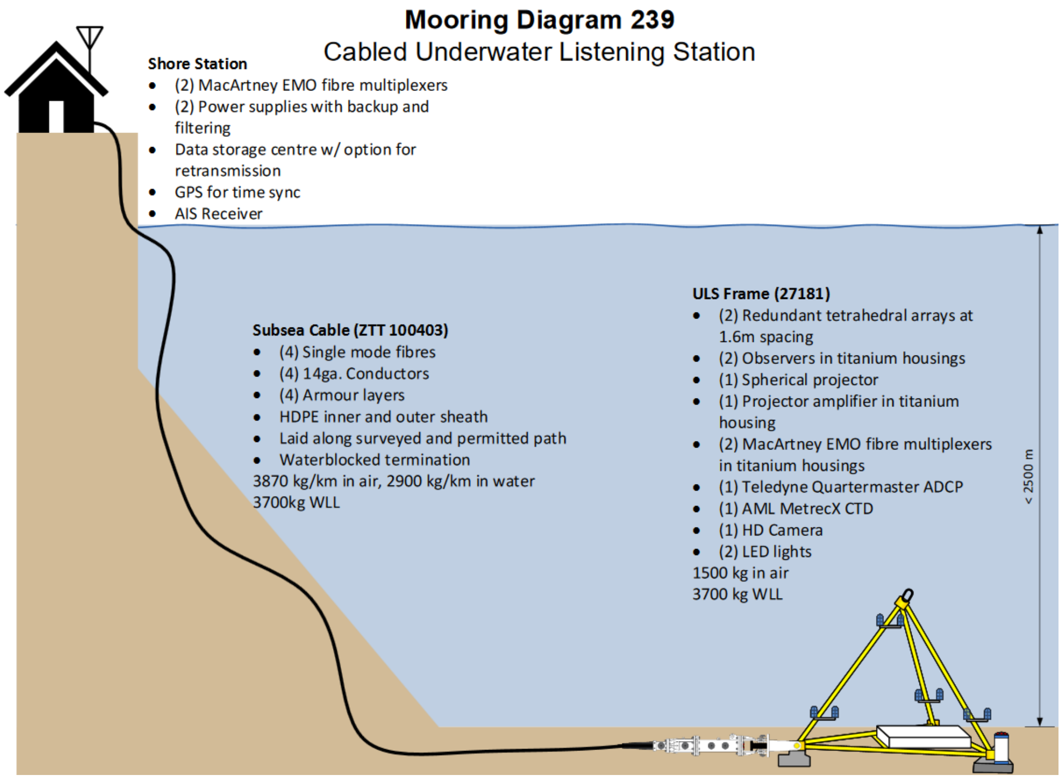

Figure 4. Boundary Pass Underwater Listening Station (ULS) mooring (JASCO mooring design 239). The Acoustic Doppler Current Profiler (ADCP), which was only present on Frame A, was mounted at the lower corner of the tetrahedral frame (depicted here as the white cylinder at the bottom right).

The AMAR mooring included a sacrificial anchor, tandem acoustic releases, flotation to orient the AMAR vertically and to support retrieval, and satellite beacons to reduce the likelihood of equipment loss. Figure 5 shows the G4 mooring design.

The AMAR was equipped with an M36-V35 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa nominal sensitivity). The AMAR recorded at 128,000 samples per second (10 Hz to 64 kHz recording bandwidth) with 24-bit resolution and 6 dB gain. The hydrophone was protected by a hydrophone cage, which was covered with a shroud to minimize noise artifacts from water flow. The AMAR recorded single-channel acoustic data from 7 Jul to 3 Oct 2021.

Immediately upon deploying the AMAR mooring, a GPS measurement was taken to record the tentative AMAR deployment position. Water currents cause moorings to drift horizontally as they descend to the seafloor during deployments. The recorders were accurately localized on the seabed by acquiring ranges to the acoustic releases at four locations and then triangulating. The estimated easting and northing accuracy after localization was approximately ±3 m.

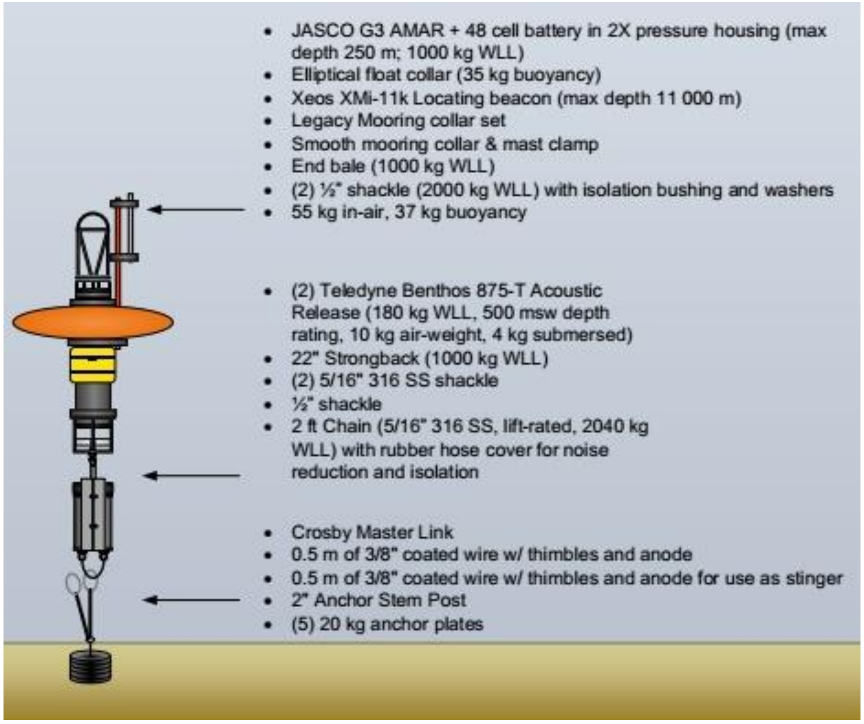

Figure 5. Boundary Pass mooring for the Autonomous Multichannel Acoustic Recorder (AMAR 686) (JASCO mooring design 202). The hydrophone was located 5.9 m above the seabed, inside the protective cage at the top of the AMAR.

The laboratory calibrations of the AMAR and ULS hydrophones at a single frequency were verified to within ±0.75 dB before deployment using a pistonphone Type 42AA precision sound source (G.R.A.S. Sound & Vibration A/S). The pistonphone calibrator produces a constant tone at 250 Hz at the hydrophone sensor. The level at which the AMAR/ULS records the reference tone yields the total pressure sensitivity for the instrument, i.e., the conversion factor between digital units and sound pressure. For the AMAR hydrophone, the calibration was also verified using the same procedure after retrieval. Verifying calibrations before and after deployment ensured that the sensitivity of the hydrophone did not change over the deployment period.

2.1.2. Water Current Measurements

Water current was measured using a Quartermaster Acoustic Doppler Current Profiler (ADCP; Teledyne) mounted on Frame A and integrated into the power supply (of Frame A1) and data cable of the ULS (see Figure 4). The ADCP was oriented vertically to measure water current profiles and operated at 150 kHz. The ADCP was deployed approximately 1 m above the seafloor and measured currents from near the seabed (~190 m depth) to near the surface.

In May, a USB adapter in the shore station for the ADCP failed, resulting in a two-week data gap. After the October ULS servicing operation, power circuit 1 on Frame A became nonoperational a few hours after deployment so ADCP current measurements have been unavailable since that time. Table 2 summarizes the available ADCP data. An autonomous ADCP will be deployed near the ULS in late April or early May 2022 to measure water currents throughout the water column. The ADCP will be retrieved in fall 2022. It is uncertain if another autonomous ADCP will be deployed after that time, or if the ULS-mounted ADCP can be fixed remotely, or if the ULS-mounted ADCP will be fixed during the next servicing operation (dates have not been determined yet).

Table 2. Acoustic Doppler Current Profiler (ADCP) recorder location (on Frame A) and recording periods during Year 3 (2021).

ADCP serial number	Centre frequency (kHz)	Latitude	Longitude	Water depth (m)	Start	End
24647	150	48°45.55800' N	123°3.87600' W	193	2021 Jan 01 00:00	2021 May 6 16:36
					2021 May 20 07:41	2021 Oct 7 06:07

The WebTide Tidal Prediction Model (v0.7.1) (Foreman et al. 2000, Institute of Ocean Sciences 2015) was used to fill the data gaps when the ADCP was not operational. The WebTide model predicts current speeds in the north-south and east-west directions as a function of time and location. The model does not explicitly state at which depth the current predictions correspond to. To investigate the accuracy of the WebTide model, we compared the ADCP measurements from the first ULS deployment to the model. The WebTide model was found to agree fairly well with measured currents near the surface but did not agree as well with measured currents near the seafloor. Accurate seafloor current speeds are useful for filtering out time periods when flow noise can substantially contaminate sound level measurements, which has been observed when the speed exceeds 0.5 m/s (Warner et al. 2021).

ADCP-measured seafloor current speed (magnitude) was found to be correlated with WebTide currents in the northeast direction. Figure 6 shows the magnitude of the measured seafloor current speed vs. WebTide current in the NE/SW direction. Often, measured current speed exceeded 0.5 m/s when the NE WebTide current exceeded 0.5 m/s. Using this criterion as a proxy for predicting when seafloor current speeds exceeded 0.5 m/s resulted in a correct prediction 87% of the time, with a 5% false positive rate (currents were predicted to be greater than 0.5 m/s but they weren't) and 8% false negative rate (currents were predicted to be less than 0.5 m/s but they weren't).

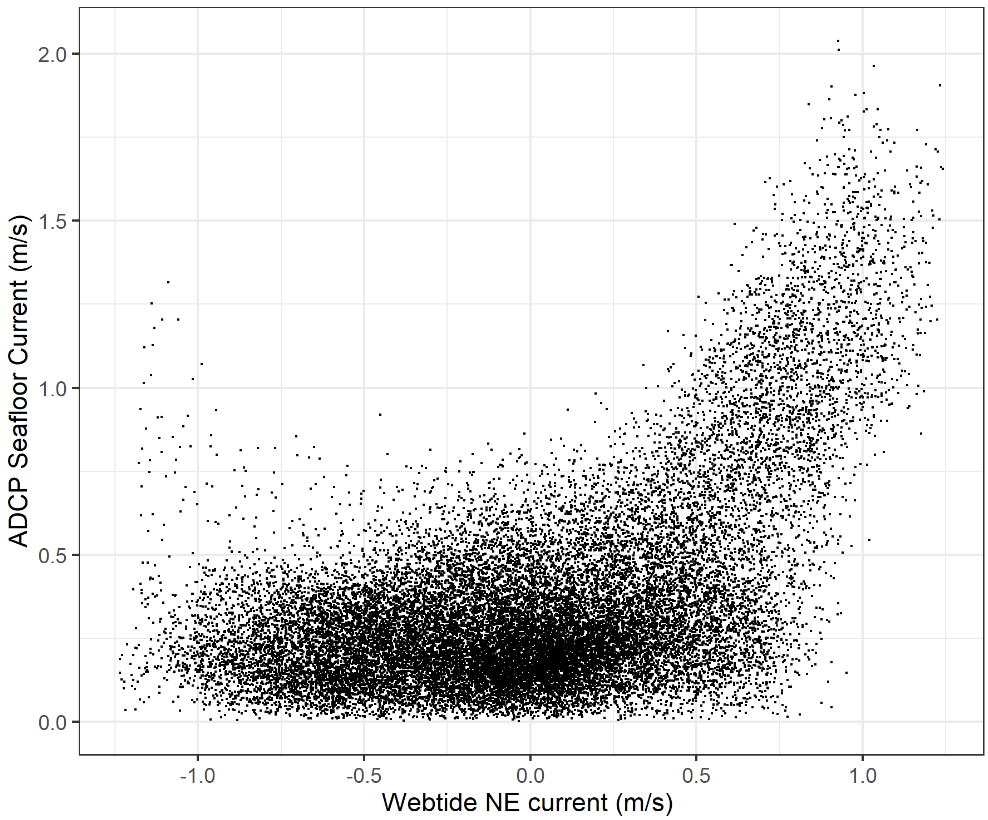

Figure 6. Magnitude of the ADCP-measured seafloor current speed plotted against WebTide-predicted current speed in the NE/SW direction. Positive WebTide current speeds indicate water travelling in the NE direction; negative WebTide current speeds indicate water travelling in the SW direction.

2.1.3. Vessel Traffic Logging

Automatic Identification System (AIS) data were acquired by on-shore recording stations on Saturna Island (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 last year 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

Since there were multiple simultaneous hydrophone channels recording throughout the analysis period, we had to choose which channel to use as the primary data source to represent ambient sound levels in Boundary Pass. Due to changes to the recording equipment, the primary hydrophone channel changed throughout the analysis period as follows:

- January-June 2021: Frames A1 and B1 were operating. Data analysis was carried out using Frame A1 data because the sounds from the ADCP could be more easily filtered out from this data set.
- July-October 2021: Frame A1 and AMAR 686 were operating. Data from Frame A1 were used because the ULS data were acquired at a higher sample rate and were less susceptible to flow noise artefacts and mechanical noise from the mooring compared to the AMAR data.
- October-December 2021: Frames A2 and B1 were operating. Data from Frame B1 were used because the GTI hydrophones of Frame B1 had a lower noise floor than the HTI hydrophones of Frame A2.

Unless otherwise noted, ULS sound levels in this report are from Channel 1 (the top hydrophone) of the chosen active hydrophone array.

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 summarizes the results from the initial reports and investigates differences between sound levels measured on different hydrophone channels.

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 different ecotype populations of killer whales, so ecotype classification was done manually by an experienced analyst (J. Wladichuk) by listening to and viewing spectrograms of the automatically detected killer whale calls. This report includes a division of the killer whale detections into three ecotype classifications:

- Southern Resident killer whale (SRKW),
- Transient/Bigg's killer whale, and
- Unknown killer whale (UNKW)—not able to determine ecotype.

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 an experienced analyst, and false detections were identified and discarded. The verified detection results were presented in reports by calendar month (Maxner and Houweling 2021c, 2021b, 2021a, Houweling et al. 2022). 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 3 (2021).

Two different ULS frames (A and B) were used to collect acoustic data in Boundary Pass during Year 3. The large majority of calls were detected on both frames since the frames were relatively close to each other (~300 m apart). To prevent double counting detections, only one of the frame's acoustic data was used for analysis at a time. For selected time periods, however, acoustic detections were compared between the two frames to validate the detection numbers. Acoustic data presented in this report are from Channel 1 of Frame A exclusively, with the exception of detections used for killer whale ecotype analysis (Table 3).

Table 3. Time periods in which each underwater listening station (ULS) array was used for killer whale ecotype analysis in 2021.

Start	End	ULS array
Jan 1	Apr 27	Frame B1
Apr 28	Nov 15	Frames A1 and A2
Nov 16	Dec 31	Frame B1

We are presently satisfied with the killer whale detector even though it does have a fairly high false positive rate in the presence of certain types of vessel noise, such as when the engine/propeller speed change rapidly. The detector has performed accurately in most instances of visual killer whale detections made from Saturna Island, and made many more detections where visual identifications were not made. Tests with the Fisheries and Oceans Canada (DFO) killer whale projector made detections up to 5 kilometers distance. The few instances of false positives that are due to humpback calls occur when humpbacks are singing at high frequencies, usually in late fall, and those can be identified manually by viewing spectrograms while simultaneously listening to the humpback calls. We do not think this finding on its own requires retraining the detectors, though the data will be included in the next training round to improve the differentiation between high frequency humpback calls and killer whale calls. Due to the very similar features of these particular humpback songs compared to killer whale whistles, the chance of capturing all killer whale calls with no false positives is unlikely. The primary improvements will likely be the avoidance of false detections triggered by vessel sounds, as well as noise from a nearby moorings' ringing chain. When using the detectors for research purposes, false positives are favored as no calls want to be missed. In a commercial use, less sensitive detectors may be favored.

Throughout the manual validation process for the 1 Oct to 31 Dec 2021 Report, experienced acoustic analysts found that some humpback whale vocalizations were misclassified by the killer whale detector (Table 4). These detections were therefore rejected for the killer whale detector and manually added to the humpback whale results. However, the presence-absence graphs showing the monthly and hourly occurrence in this report where not adjusted, as it would require significant reprocessing time.

Table 4. Humpback whale vocalizations misclassified as killer whale vocalizations in 2021.

Start	End	Misclassified calls
Oct 12 12:42	Oct 12 13:10	30
Oct 15 08:23	Oct 15 10:55	77
Nov 9 23:13	Nov 9 23:17	17
Nov 10 00:08	Nov 10 10:22	203
Nov 13 10:53	Nov 13 11:47	342
Nov 17 04:59	Nov 17 05:21	62
Nov 19 06:13	Nov 19 07:07	88
Nov 20 03:47	Nov 20 12:22	968
Dec 24 02:04	Dec 24 02:58	59
Dec 25 04:41	Dec 25 05:51	29
Dec 29 22:16	Dec 29 22:19	17

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 1 of each ULS frame were processed. 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 initial ambient noise reports submitted to VFPA throughout the year. The results below investigate differences between sound levels measured simultaneously on hydrophone channels of different recorders, and the variability in ambient noise levels over time.

3.1.1. Comparison of Sound Levels Between Recorder Channels

There were three "overlap" periods during 2021 when multiple recorders were operating:

1. 1 Jan to 17 Jun, with Frame A1 and B1 (first ULS deployment),
2. 7 Jul to 3 Oct, with Frame A1 (first ULS deployment) and AMAR 686, and
3. 8 Oct to 31 Dec, with Frame A2 and B1 (second ULS deployment).

These recorders were all operating within approximately 300 m of each other and the relatively minor environmental differences between deployment locations are not expected to influence sound levels. Analyzing data acquired at the same time by different recorder channels is useful for interpreting non-acoustic noise (e.g., system, current-induced, or mooring noise) and for ensuring the hydrophone calibrations are consistent. As an example, Figure 7 shows the SPL over selected bands measured in Frame B1.1-B1.4 (4 channels) and Frame A2.1 (1 channel), on 17 Oct 2021. Similar trends were observed for other days. The following characteristics can be observed:

- The SPL is generally dominated by energy in the 10–100 Hz and the 100–1000 Hz bands. There is an excellent agreement between channels for the 100–1000 Hz band. For the 10–100 Hz band, the agreement between channels is very good around sharp SPL peaks (i.e., narrow peaks higher than 100 dB re 1 µPa, likely caused by transiting vessels).
- The agreement between the 4 (co-located) Frame B1 channels to the measurements in Frame A2.1 (obtained ~300 m from Frame B1) provides confidence on the system's calibration and performance.
- For the 10–100 Hz band, there are time periods of higher variability between the channels, usually when the SPL is below 100 dB re 1 µPa (e.g., at 3:00, 6:00, 12:00, and 16:30). It is observed that this is not a problem with the system's calibration, since there are other instances of low SPL that exhibit excellent agreement between channels (e.g., at 9:00 and at 15:00). We think that the instances of high variability are due to flow noise, which may impact each hydrophone with slightly different strength based on their position in the ULS frame.
- Since current measurements were not available for this analysis period, the hypothesis of flow noise affecting (mostly) the 10–100 Hz band is still an ongoing investigation. To support this hypothesis, we noticed that in many cases the events that exhibit high inter-channel variability occur during changes from low-to-high or from high-to-low tide[2]. Our investigation will determine whether tide could be used as a reliable proxy to indicate time periods with high flow noise caused by internal currents.
- At high frequency (100–256 kHz) there are large differences in SPL between channels. The plot suggests that the differences are caused by the characteristic noise floor of each hydrophone. Data recorded in Frame B1.4 was noticeably higher than other channels.

[2] Tide predictions obtained from https://tides.gc.ca/ for Narvaez Bay (Station 07345).

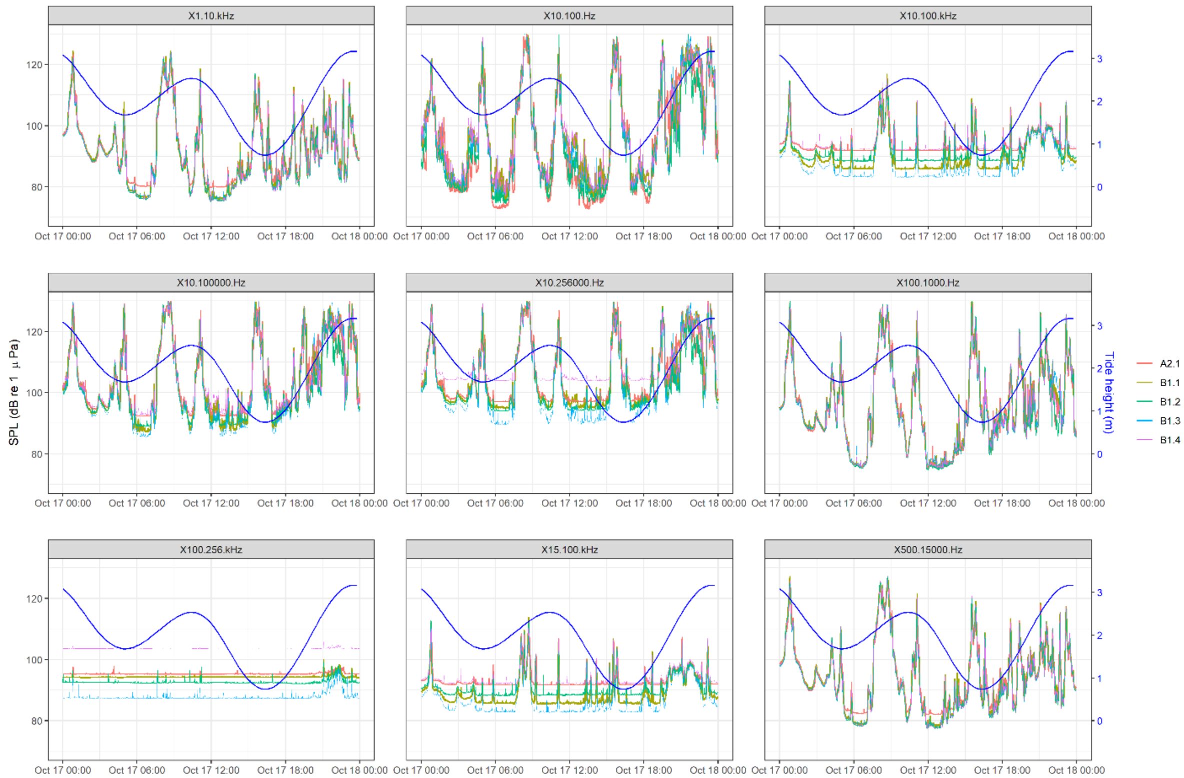

Figure 7. Comparison of per-band SPL measured simultaneously in Frame B1.1-B1.4 (4 channels), and Frame A2.1 (1 channel), on 17 Oct 2021. The tide height at Narvaez Bay is shown in blue (notice the corresponding blue vertical scale to the right).

Another way to verify the agreement between recorder channels, this time considering data from longer periods, is by comparing the cumulative density functions (CDFs) of the measured SPL. Figure 8 shows the decidecade band level CDFs from the first overlap period. The top hydrophone (Channel 1) of each active ULS hydrophone array was analyzed here. Both ULS frames used their array of GTI hydrophones during this period. To show the differences during quieter times, the data in Figure 8 were filtered to exclude minutes during which AIS-broadcasting vessels were within 6 km of the hydrophone or when current speeds were greater than 0.5 m/s.

The main differences between the ULS frames were limited to decidecade frequency bands centred at 20, 25, 31, 160,000, and 250,000 Hz. Sound levels in the 160 kHz band were higher for Frame B1.1 data because they included sounds from the 150 kHz pulses of the ADCP. Data for Frame A1.1 did not have ADCP noise because time periods with ADCP sounds were removed prior to analysis. ADCP noise was relatively simple to detect for Frame A1.1 because it saturated the recorder channels. It could be possible to remove data with ADCP noise from the Frame B1.1 data but would require applying a more sophisticated detector. In the 256 kHz band, sound levels were slightly higher for Frame A1.1 data than for Frame B1.1 data. This difference is likely due to differences in noise floors between the two specific hydrophones.

Figure 9 shows the CDFs for louder periods, for which AIS-broadcasting vessels were within 6 km of the hydrophone (and current speeds were less than 0.5 m/s). During these louder periods, the low-frequency levels were in much better agreement and the differences in high-frequency levels were approximately the same as for periods without AIS-broadcasting vessels (Figure 8). The better agreement at low frequencies when vessels were present suggests differences during quiet times were not due to a calibration issue.

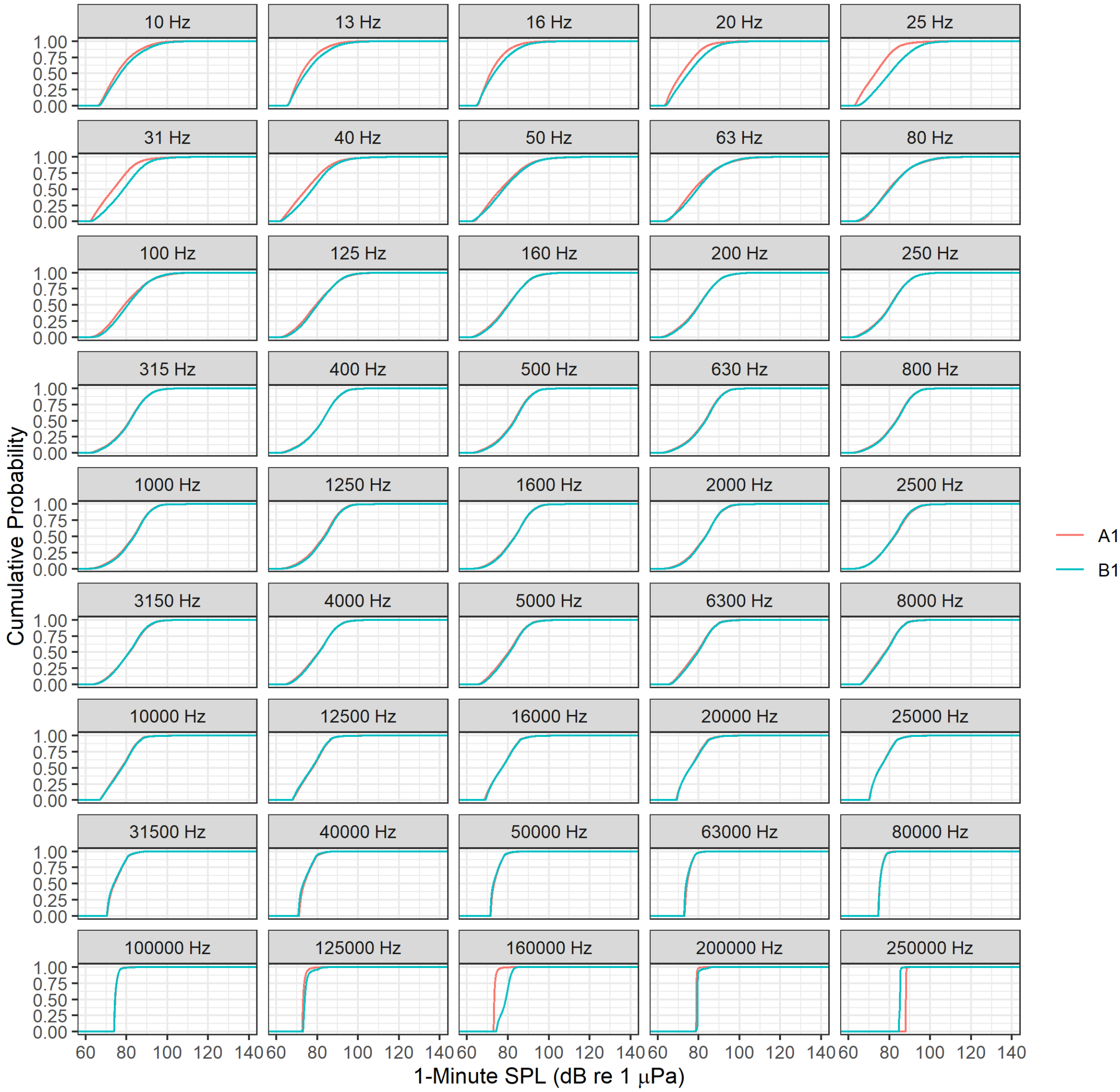

Figure 8. 1 Jan to 17 Jun 2021, during quiet periods: Cumulative density functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A1.1 and B1.1; 123 746 min). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

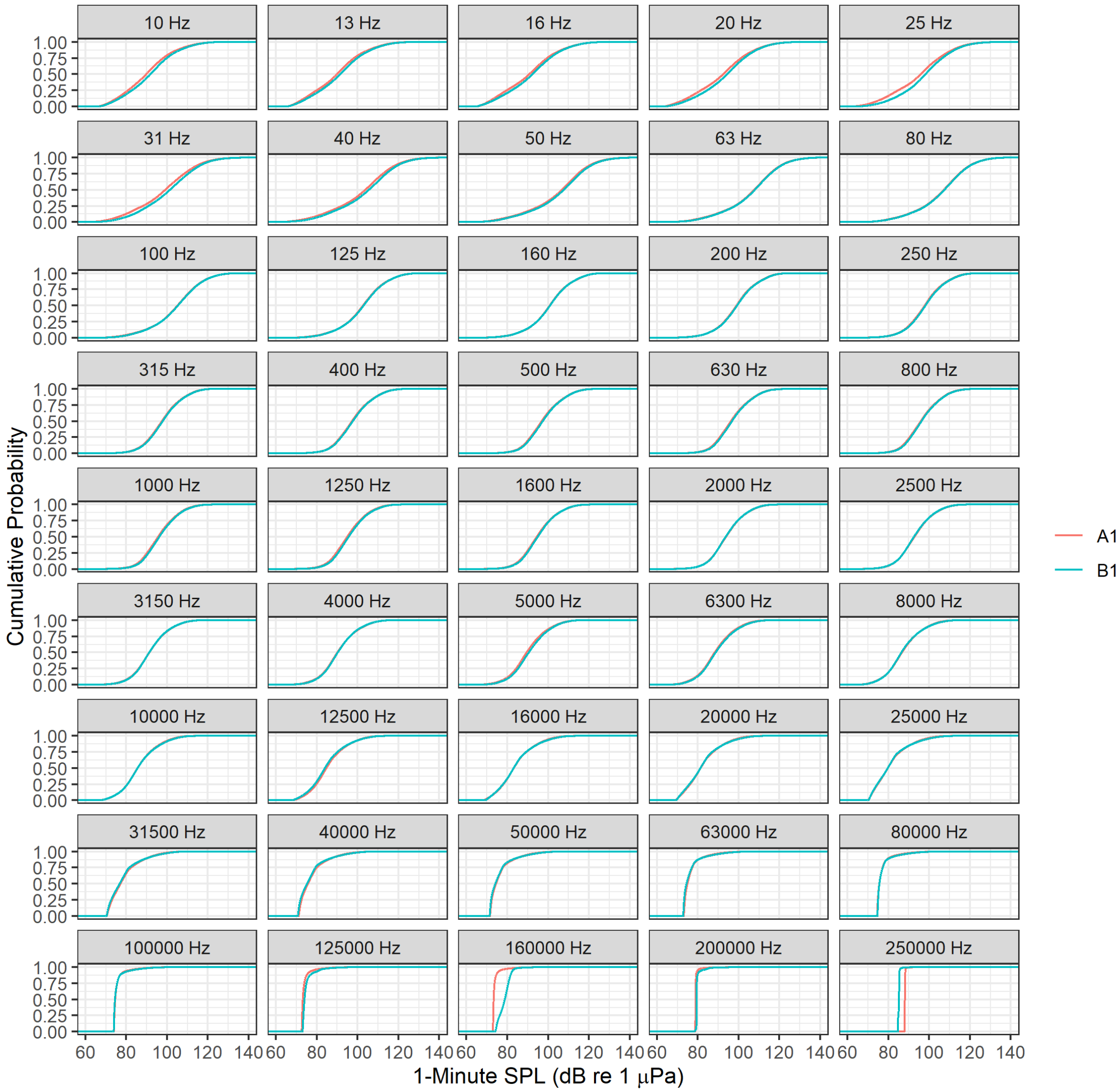

Figure 9. 1 Jan to 17 Jun 2021, during loud periods: Cumulative density functions of decidecade band sound levels measured by simultaneously recording instruments (Frames A1.1 and B1.1; 65 394 min). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.

Figure 10 shows the decidecade band level CDFs from the second overlap period. Both recorders used GTI hydrophones during this time. To show the differences during quieter times, the data in Figure 10 were filtered to exclude minutes where AIS-broadcasting vessels were within 6 km of the hydrophone or when current speeds were greater than 0.5 m/s. The differences between the AMAR and Frame A1.1 data were greatest in the decidecade bands centred below 80 Hz. At these frequencies, sound levels from the AMAR were much higher than those from the ULS. We suspect this is because of higher low-frequency noise caused by low-speed currents which can deflect the AMAR mooring (in contrast to the ULS, which has a rigid frame that does not allow the hydrophones to move). The higher levels in the 63 kHz band from Frame A1.1 are mostly due to the ULS recording sound levels in the entire band (53–71 kHz) whereas the AMAR only recording sounds in part of the band (53–64 kHz). Low frequency sound levels were in better agreement during louder periods (when AIS-enabled vessels were within 6 km of the hydrophones, Figure 11).

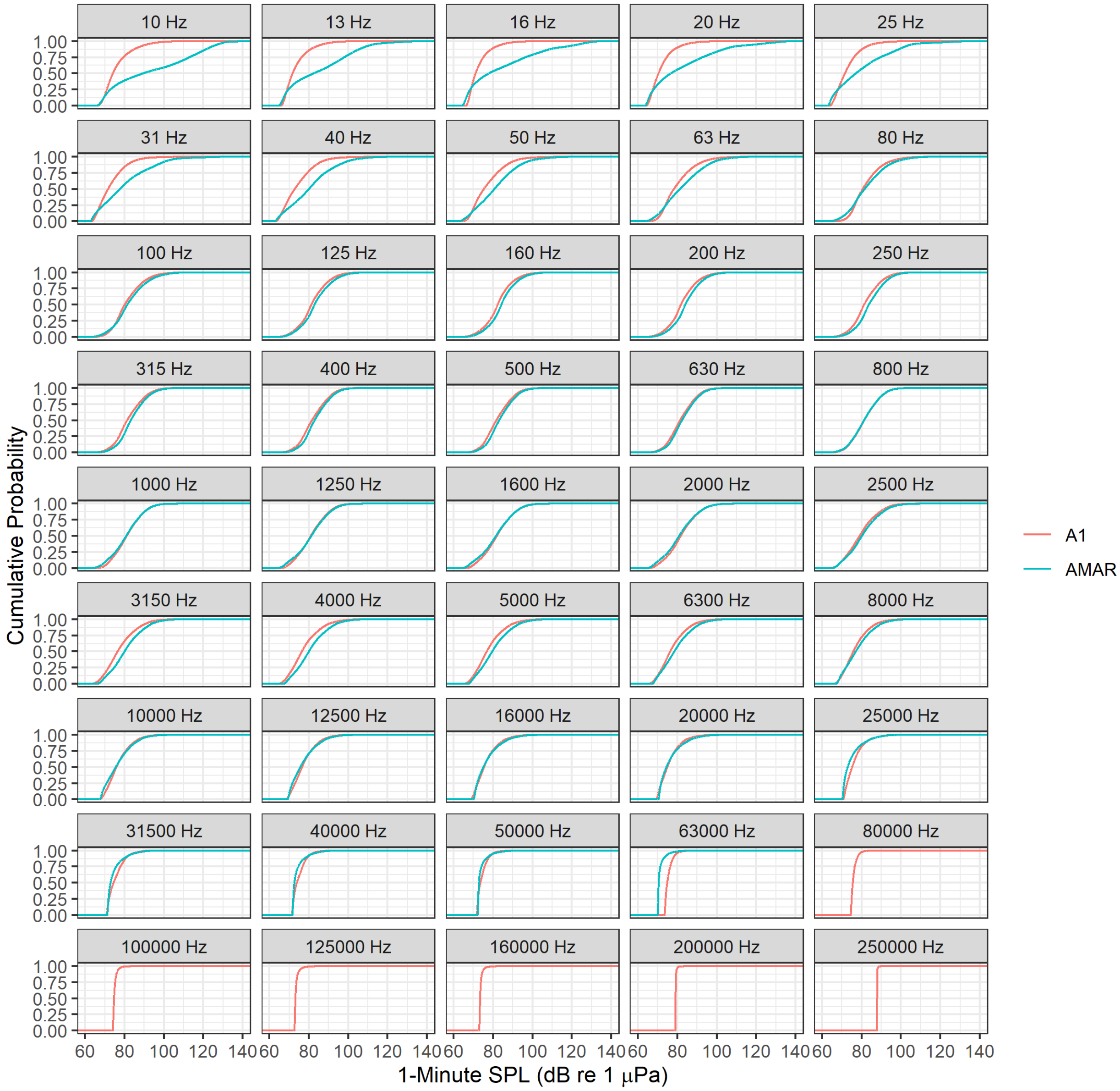

Figure 10. 7 Jul to 3 Oct 2021, during quiet periods: Cumulative density functions of decidecade band sound levels, measured by simultaneously recording instruments (Frame A1.1 and AMAR 686; 69 611 min). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band. AMAR measurements were limited to frequencies at or below 63 kHz; Underwater Listening Station (ULS) measurements spanned the displayed frequency range (10 Hz to 250 kHz).

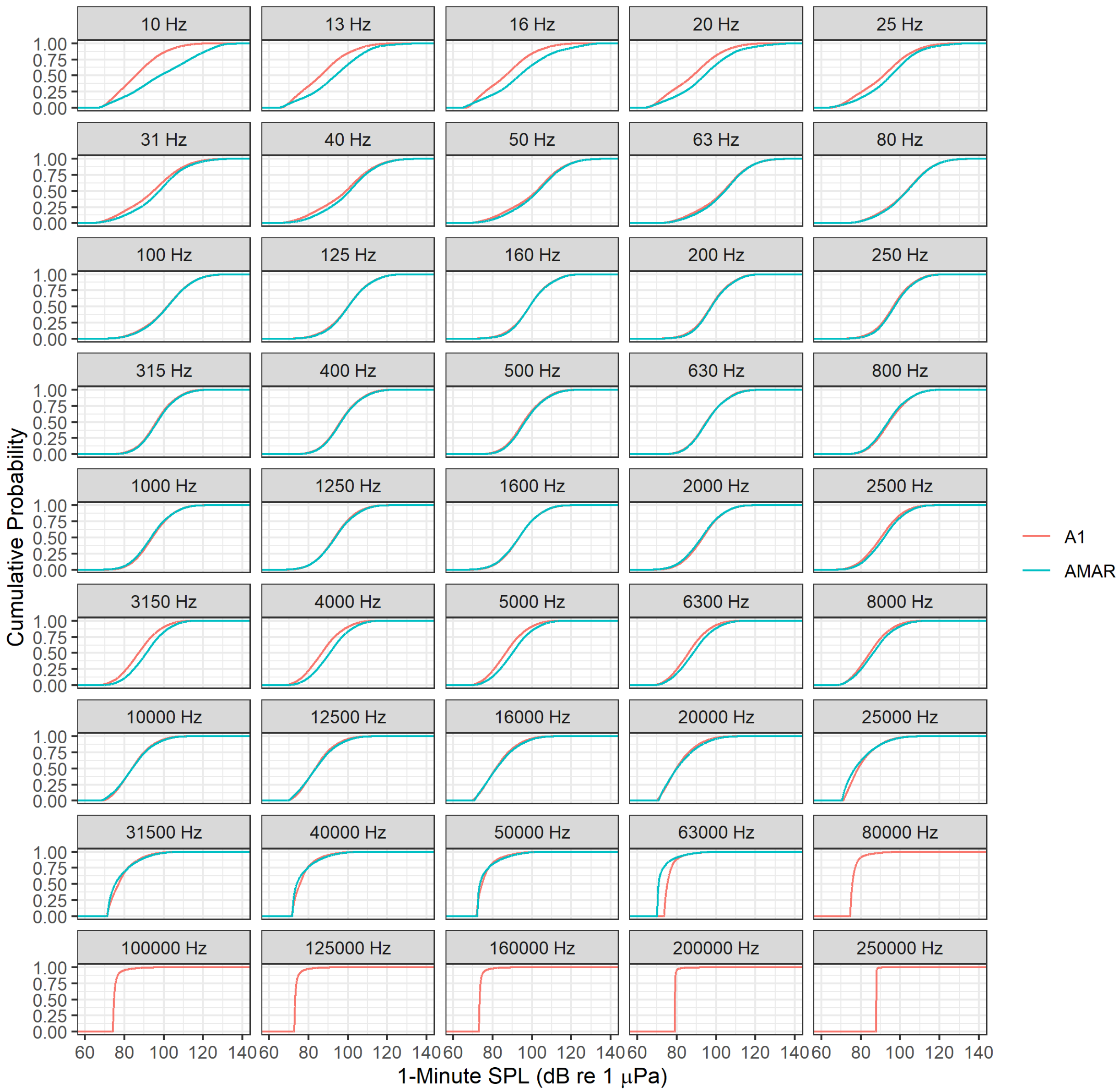

Figure 11. 7 Jul to 3 Oct 2021, during loud periods: Cumulative density functions of decidecade band sound levels, measured by simultaneously recording instruments (Frame A1.1 and AMAR 686; 43 016 min). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band. AMAR measurements were limited to frequencies at or below 63 kHz; Underwater Listening Station (ULS) measurements spanned the displayed frequency range (10 Hz to 250 kHz).

Figure 12 shows the decidecade band level CDFs from the third overlap period. The top hydrophones on the ULS frames were analyzed here. Frame A2 used HTI hydrophones and Frame B1 used GTI hydrophones during this period. To show the differences during quieter times, the data in Figure 12 were filtered to exclude minutes where AIS-broadcasting vessels were within 6 km of the hydrophone or when current speeds were greater than 0.5 m/s.

The main differences between the ULS frames were at low frequencies (bands centred between 20 and 80 Hz) and at high frequencies (bands centred at frequencies greater than 8 kHz). The differences at low frequencies were much lower during periods when AIS-enabled vessels were within 6 km of the hydrophones, suggesting the difference is not due to a calibration issue (Figure 13). Differences in the higher-frequency bands are due to different noise floors between hydrophones. Generally, the high-frequency noise floor is higher for HTI hydrophones than for GTI hydrophones.

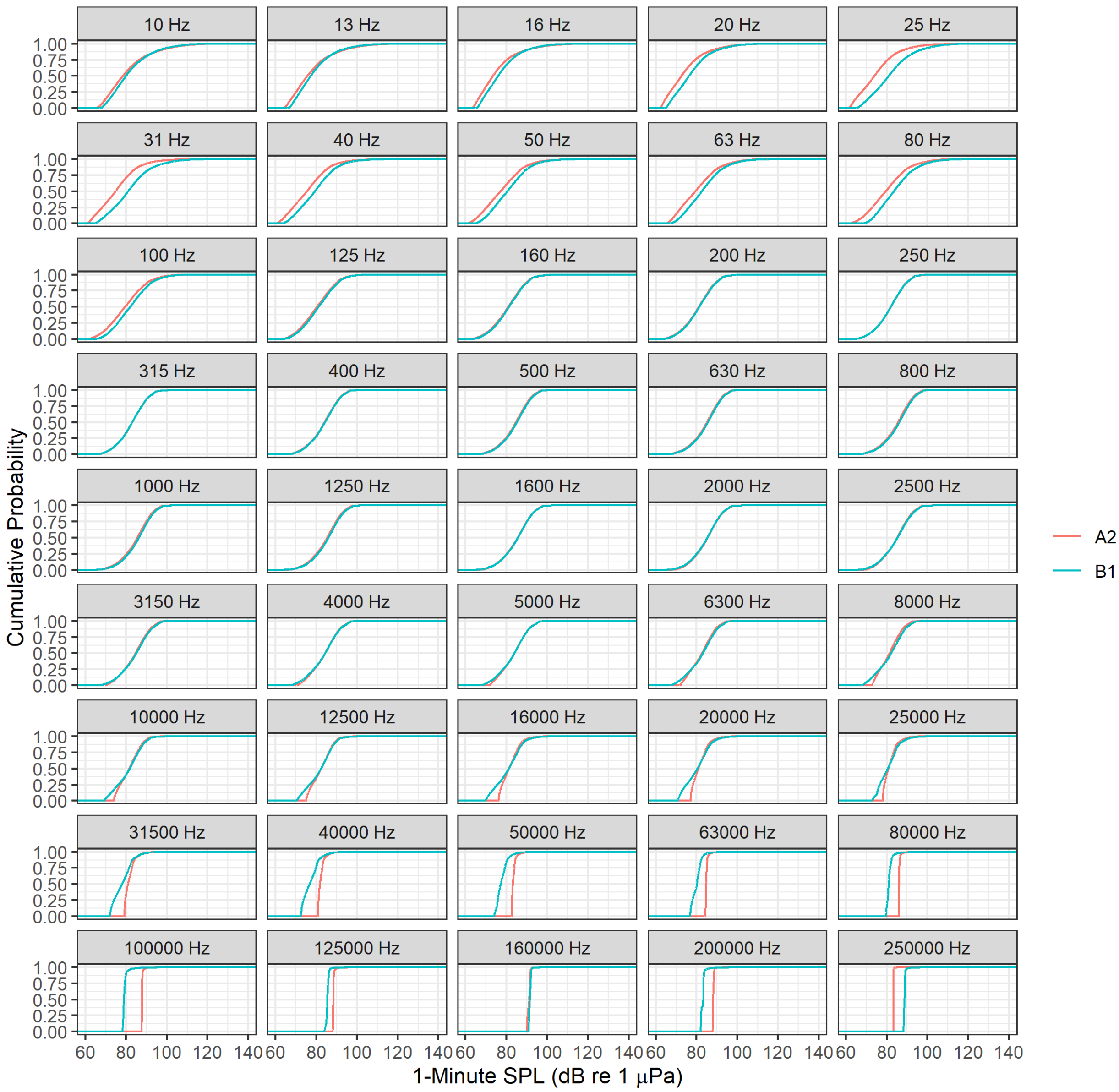

Figure 12. 8 Oct to 31 Dec 2021, during quiet periods: Cumulative density functions of decidecade band sound levels, measured by simultaneously recording instruments (Frames A2.1 and B1.1; 67 776 mins). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decidecade band.

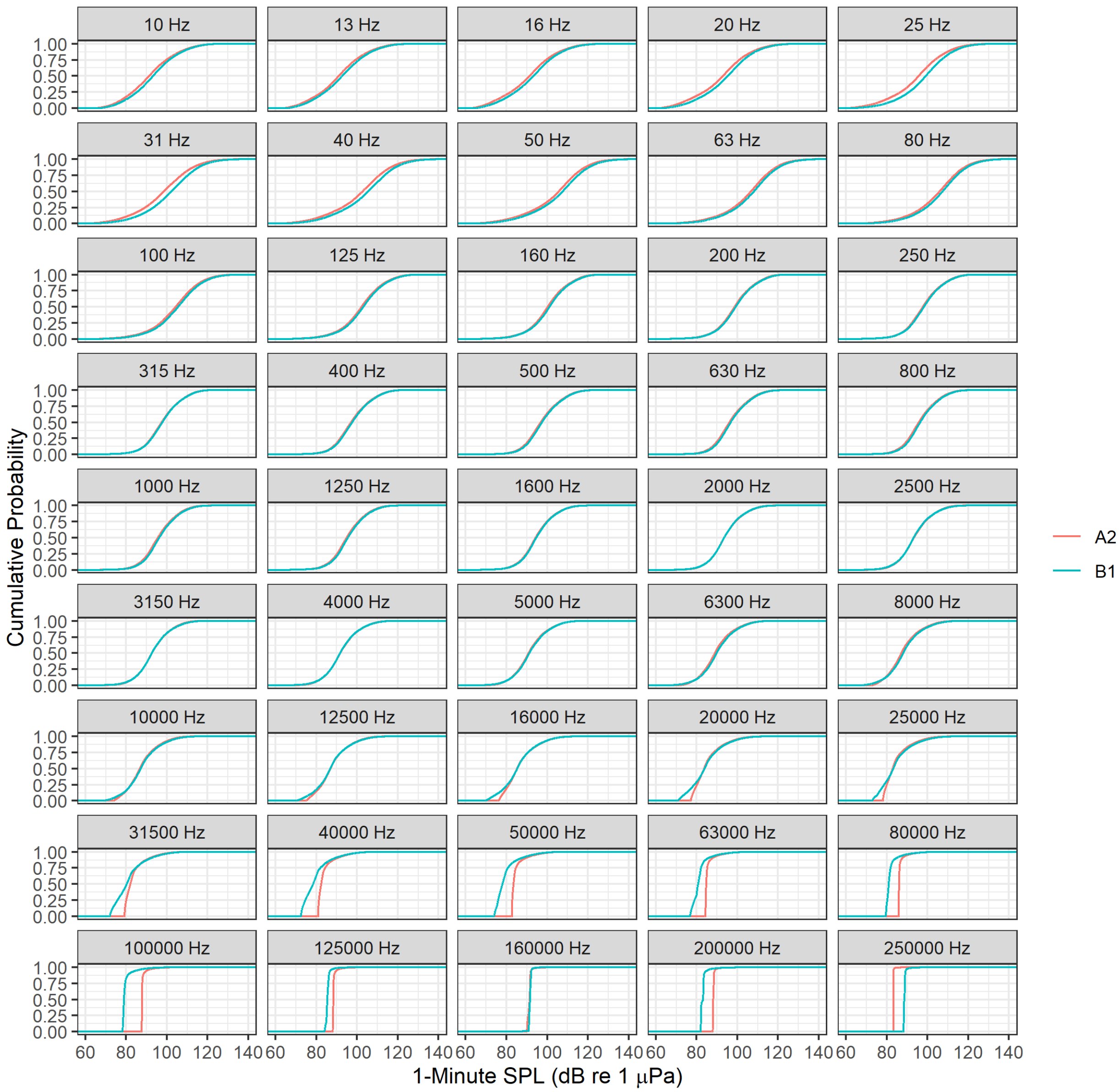

Figure 13. 8 Oct to 31 Dec 2021, during loud periods: Cumulative density functions of decidecade band sound levels, measured by simultaneously recording instruments (Frames A2.1 and B1.1; 32 782 min). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.

Although there was no overlap time for ULS recordings before and after the October servicing operation, during which the ULS frames were replaced, it is useful to compare CDFs from all measurements in 2021 to look at the noise floor differences. Figure 14 shows CDFs from all 5 recorder channels throughout the year during times when AIS-broadcasting vessels were within 6 km of the hydrophones. These plots show that at frequencies above 20 kHz, the noise floor of Frame B1.1 recordings after the servicing operation (B1_Dep2) was significantly higher than the noise floor of Frames A1.1 and B1.1 recordings before servicing (A1_Dep1 and B1_Dep1, respectively). All these recordings were made using GTI hydrophones. The noise floor of the HTI hydrophone from Frame A2.1 recordings after servicing (A2_Dep2) was higher than those of the GTI hydrophones.

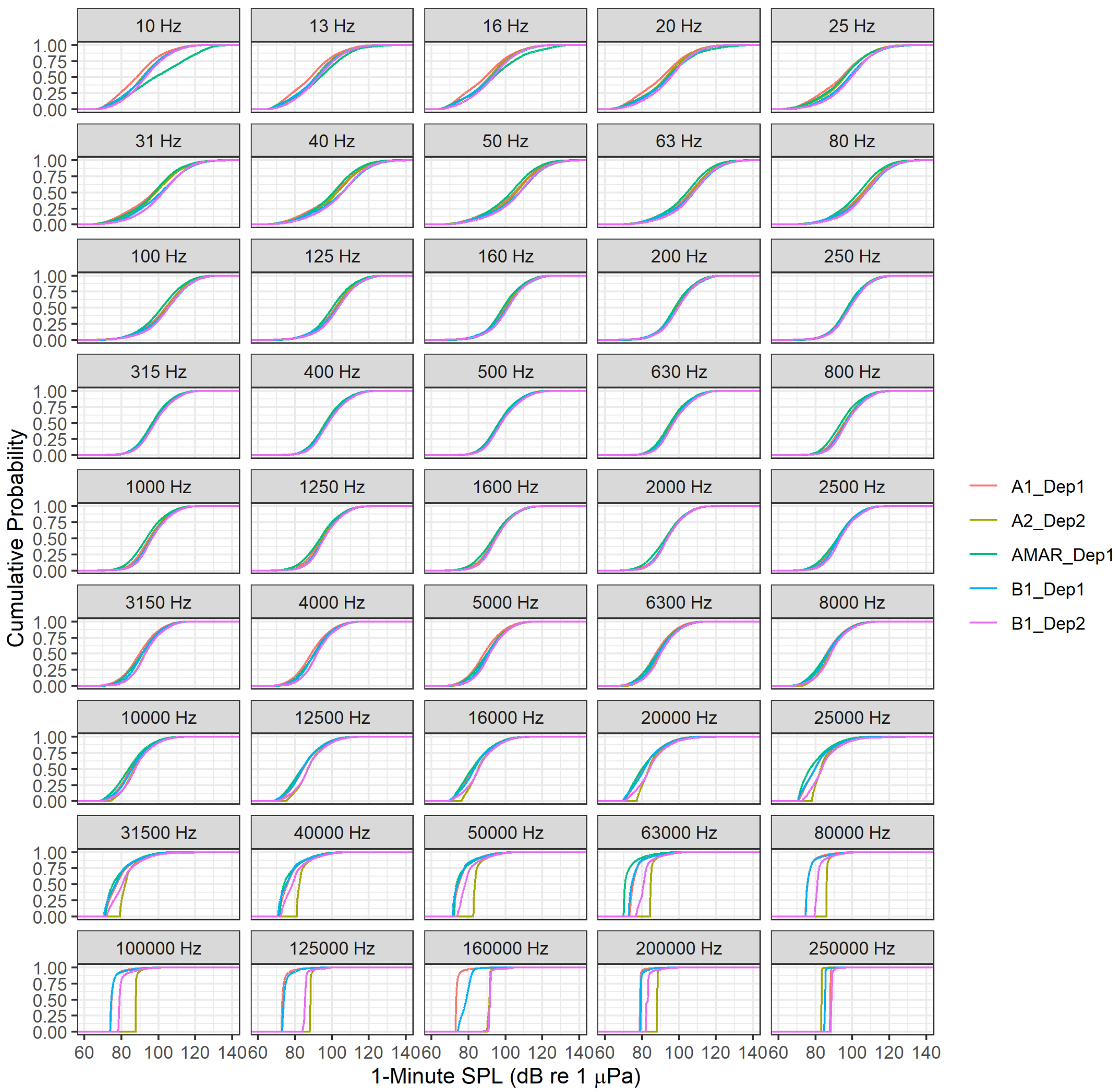

Figure 14. Loud periods on all (ULS and AMAR) recorders: Cumulative density functions of decidecade band sound levels, measured by all recorders in 2021. Each recorder operated for different time periods (see Table 1). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s (no filter applied for the presence of vessels). Panel headings indicate the centre frequency of the decidecade band.

Figure 15 shows sound levels from both ULS frames during the week of 10–17 Oct (i.e., after ULS servicing), where Frame A2 used HTI hydrophones and Frame B1 used GTI hydrophones. The high frequency noise floor was higher in level and smoother across frequencies for Frame A2 than for Frame B1. On Frame B1.1, there is system noise at frequencies above 20 kHz (especially above 50 kHz) that was not observed in the Frame B1.1 GTI data before the ULS servicing. Figure 16 shows an example spectrogram of Frame B1.1 data from 13 Oct, where the persistent high frequency system noise is evident. At the time of writing this report, this issue is still being investigated, including analysis of sound levels from the other three hydrophones on Frame B1.

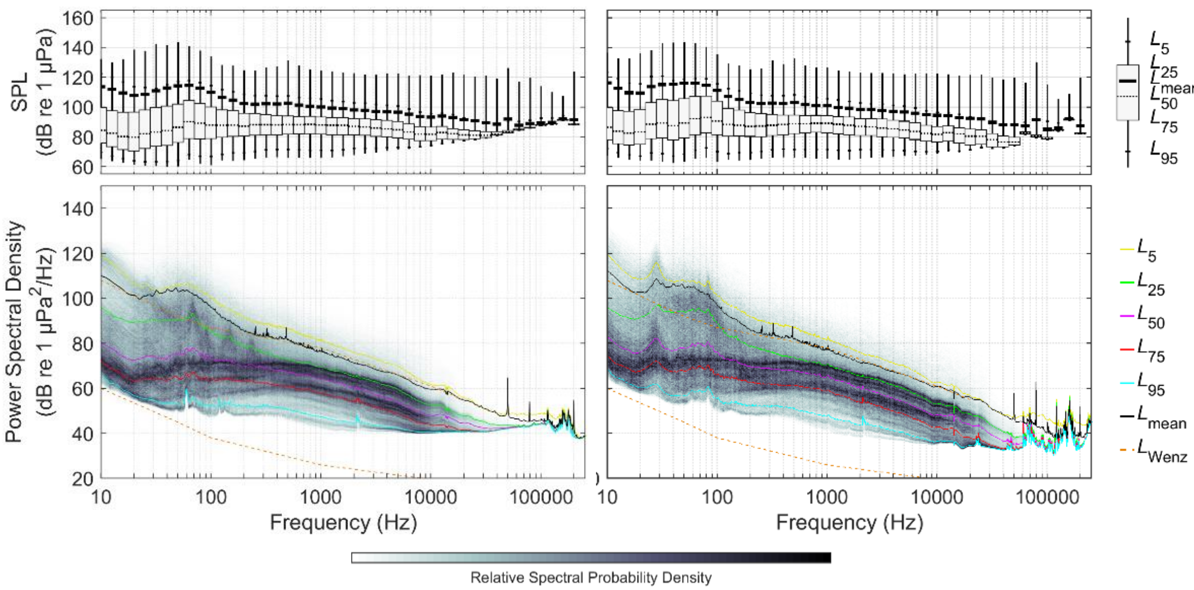

Figure 15. (Top) Boxplots of decidecade band sound pressure levels (SPL) and (bottom) power spectral density statistics during the week of 10–17 Oct 2021 from (left) the Frame A2.1 HTI hydrophone and (right) the Frame B1.1 GTI hydrophone.

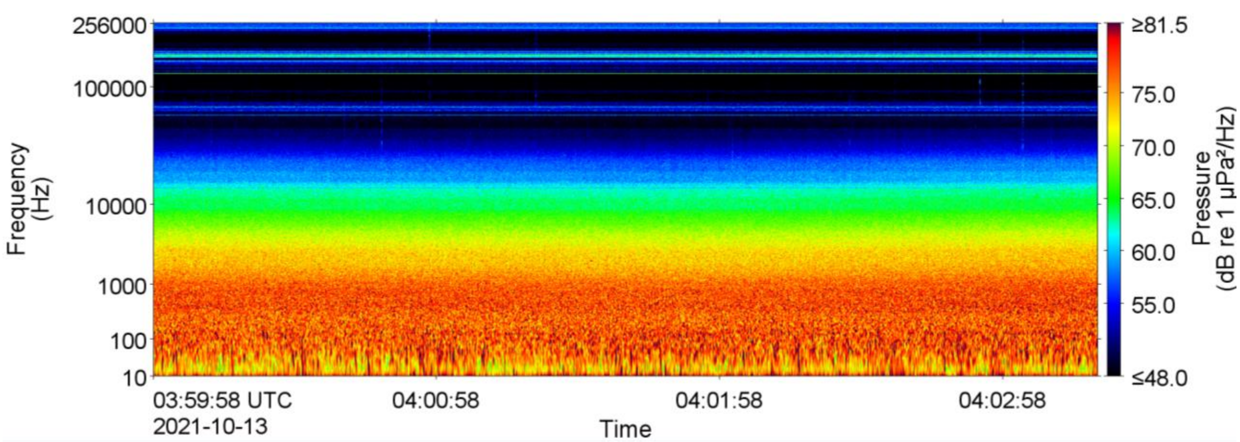

Figure 16. Spectrogram of sound recorded on Frame B1.1 on 13 Oct 2021 after servicing, showing persistent high-frequency system noise, which is under investigation.

3.1.2. Temporal Variability of Sound Levels

Long term trends in sound levels were analyzed by compiling broadband and decade-band sound level statistics by calendar month during 2021. Sound levels during the ULS servicing operation (6–9 Oct) were excluded from this analysis. Figure 17 shows the trends in sound level statistics computed over each month. Sound levels were generally consistent over time or within the monthly variability, but there were two notable exceptions. The first is that the higher percentile broadband levels (L05, L25) were lower in Jul–Sep. We suspect this is due to lower vessel noise from slower commercial vessels participating in the ECHO program's 2021 Haro Strait and Boundary Pass voluntary slowdown. The other exception is the increase in the 10–100 and 100–256 kHz band levels after the ULS servicing operation. We believe this is caused by the higher high-frequency noise floor from the Frame B1.1 hydrophone after servicing (also see Figure 14). There was also an increase in the lower percentiles in the 1–10 kHz band after the ULS servicing operation, but we do not expect this is because of the change in hydrophone. It is currently hypothesized that this increase observed in the lower percentiles is due to noise related to high winds and rain starting in late October and observed up to February. Further investigation to test this hypothesis is still required.

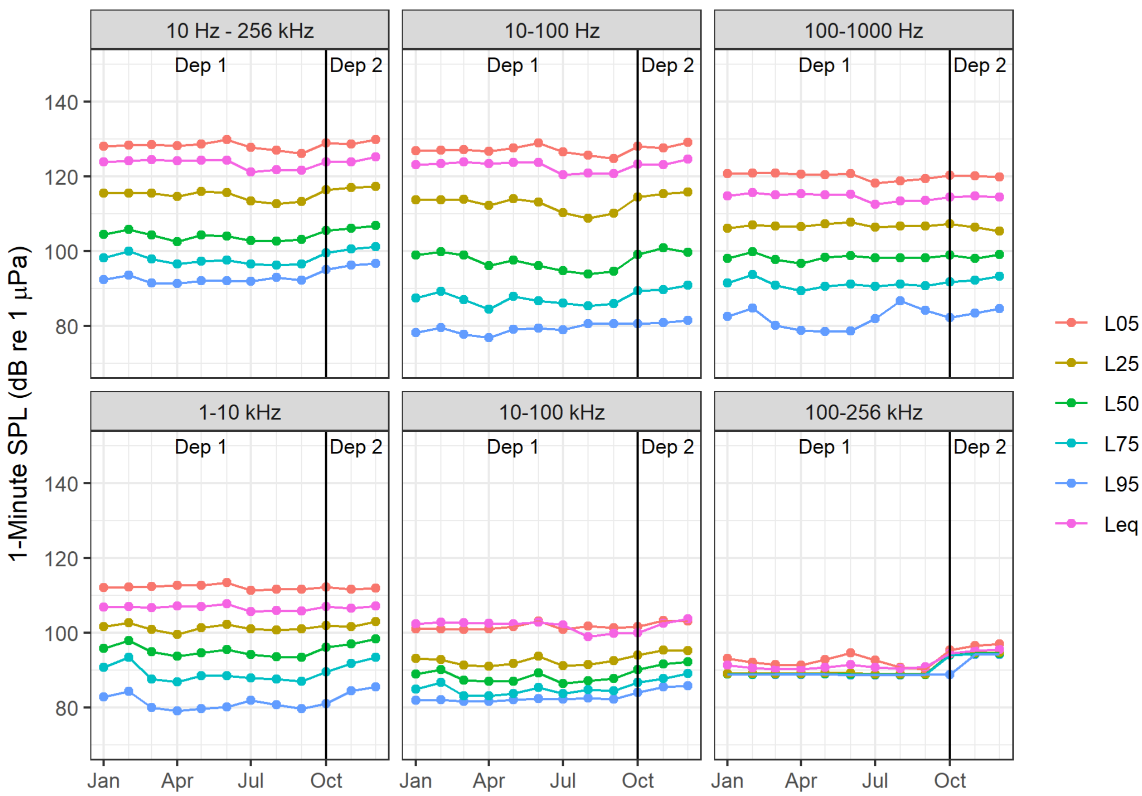

Figure 17. Monthly sound pressure level (SPL) statistics in each indicated frequency band before filtering out periods with current speeds greater than 0.5 m/s for Year 3 (2021). Data are from Frame A1.1 before the servicing operation (Dep 1) and from Frame B1.1 after servicing (Dep 2).

Monthly sound level statistics were also computed after filtering out periods when current speeds were greater than 0.5 m/s (Figure 18). The filtering resulted in lower levels, primarily in the low frequency bands, and also reduced month-to-month variability in the 100–256 kHz band. The reason for this variability at high frequency is still unknown, but based on underwater video at the ULS it is hypothesized that it could be related to noise generated by sediment turbulence during strong currents.

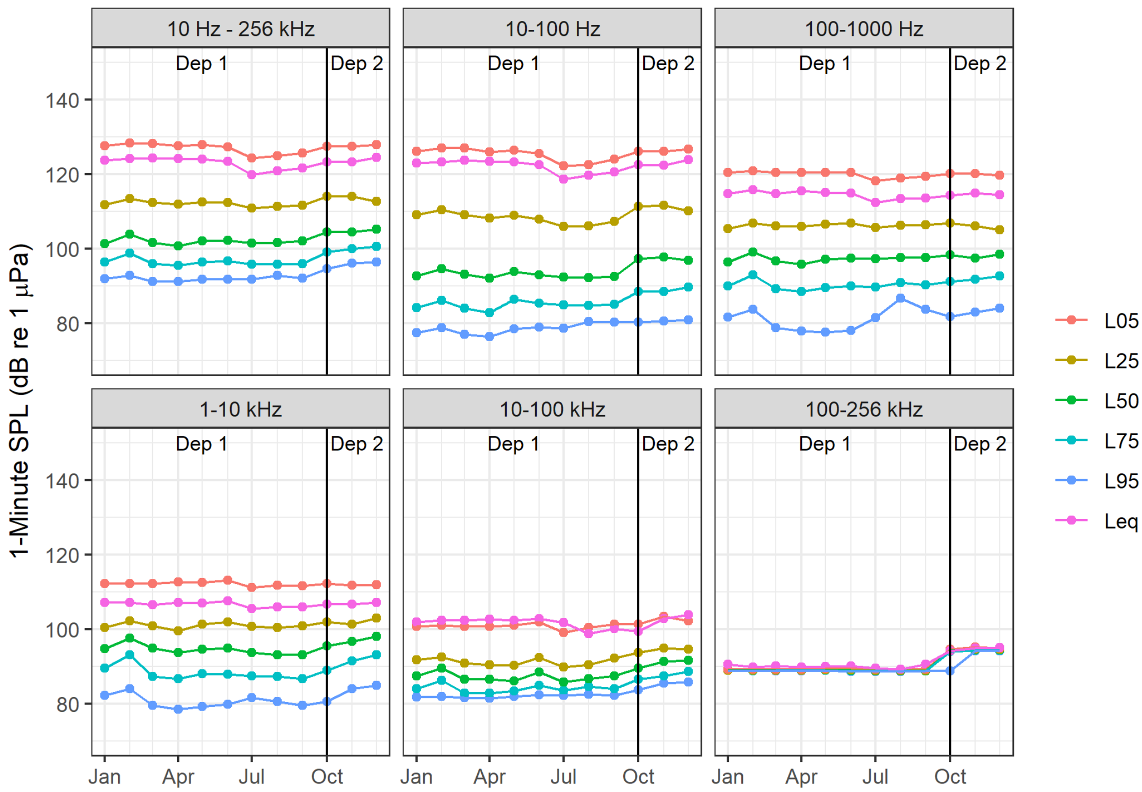

Figure 18. Monthly sound pressure level (SPL) statistics in each indicated frequency band after filtering out periods with current speeds greater than 0.5 m/s for Year 3 (2021). Data are from Frame A1.1 before the servicing operation (Dep 1) and from Frame B1.1 after servicing (Dep 2).

Analysis of sound levels on shorter timescales performed for the monthly reports showed that the trends in sound levels over the days of the week were largely determined by the tidal cycle, and they did not show a strong weekday/weekend difference. One short-term trend unrelated to the tidal cycle was that sound levels on Christmas Day (25 Dec 2021) and New Year's Day (1 Jan 2022, included here as a second example of sound levels during a holiday) were noticeably lower than those on the preceding or following days (Figure 19). This decrease in sound level was largely due to the decrease in AIS-enabled vessel traffic on those dates (Figure 20).

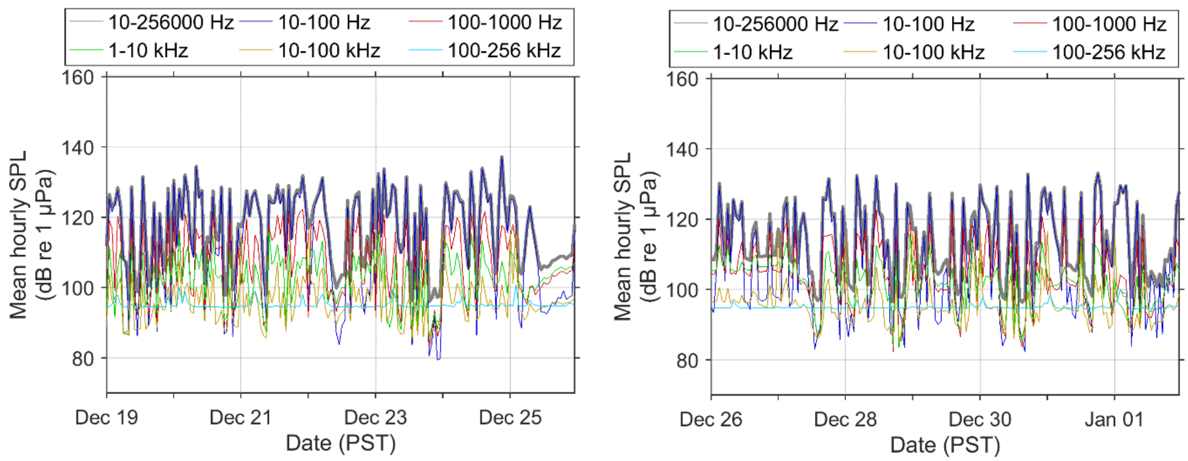

Figure 19. Sound pressure levels (SPL) around (left) Christmas Day 2021 and (right) New Year's Day 2022.

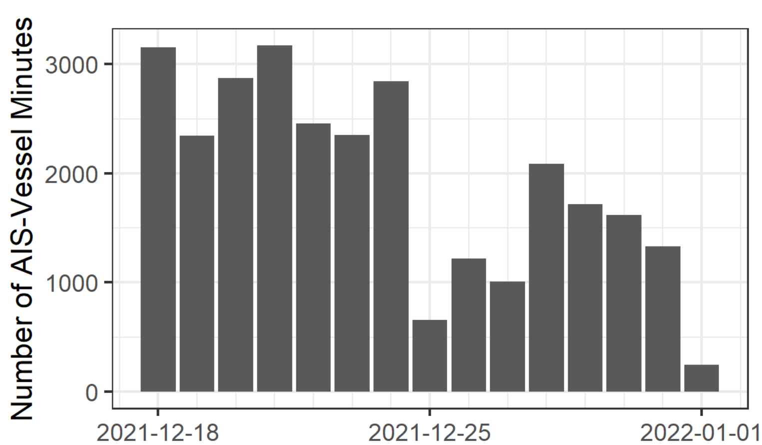

Figure 20. Number of minutes per day that AIS-enabled vessels were within approximately 6 km of the underwater listening station (ULS) around Christmas Day and New Year's Day.

3.2. Marine Fauna Detection Results

During Year 3 (1 Jan to 31 Dec 2021), the automated detectors reported 9180 killer whale vocalizations (5892 SRKW, 3256 Transient/Bigg's, and 32 UNKW), 4193 humpback whale vocalizations, and 10,982 fish sounds (groans, croaks, and knocking) in Boundary Pass. No Pacific white-sided dolphins were detected during the year. Figure 21 shows the proportion of detections by species/group for 2021, with killer whale vocalizations displayed at the ecotype level. Unknown killer whale classification was due to limited detections and either masking by vessel noise (Figure 26) or low signal-to-noise ratio (SNR) (Figure 27). The detections on 4 Oct were mainly whistles, which are more difficult to determine ecotype. On 7 Feb, no stereotypical calls were present that are used to classify ecotype.

The hourly and monthly detection counts of killer whale vocalizations, humpback whale vocalizations, and fish sounds are illustrated in Sections 3.2.1, 3.2.2, and 3.2.3, respectively. All graphs are in Pacific Time unless otherwise indicated.

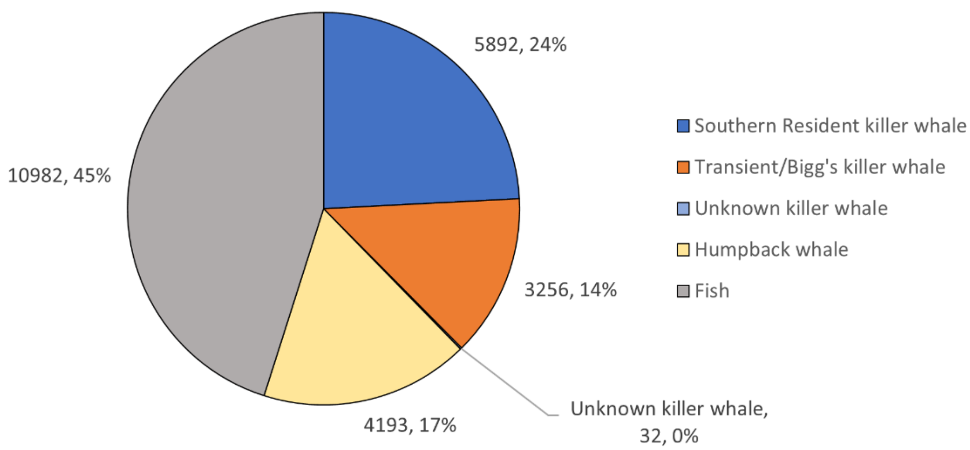

Figure 21. Proportion of detections by marine species/group for Year 3 (1 Jan to 31 Dec 2021).

3.2.1. Killer Whales

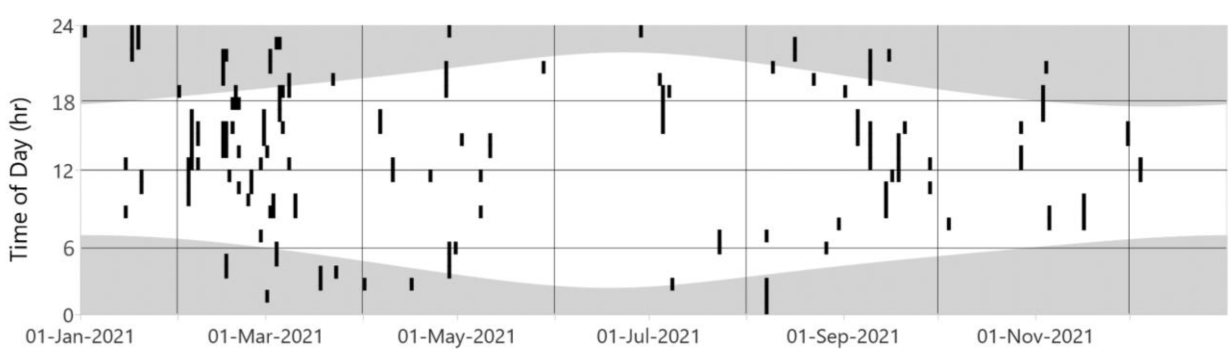

Figure 22. Year 3 (1 Jan to 31 Dec 2021): Daily and hourly occurrence of killer whale vocalizations at Frame A. Black blocks indicate validated detections, and grey areas indicate darkness periods. The plot also includes some misclassified instances of humpback whale, as described in Table 4.

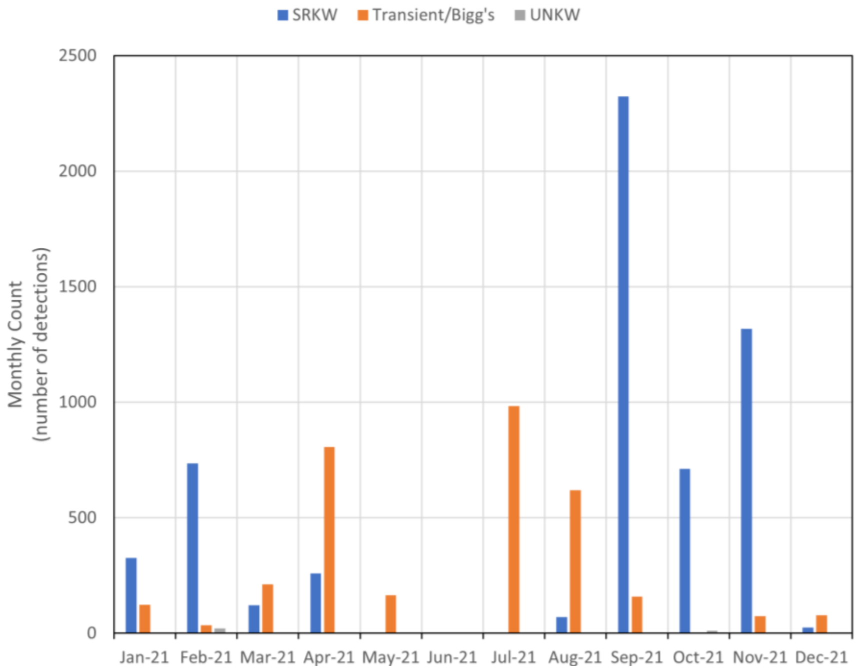

Figure 23. Year 3 (1 Jan to 31 Dec 2021): Monthly validated detection counts of killer whale vocalizations by ecotype—Southern Resident killer whale (SRKW), Transient/Bigg's, and unknown killer whale (UNKW)—at Frame A or B (the ULS frame used during each of three time periods is shown in Table 3).

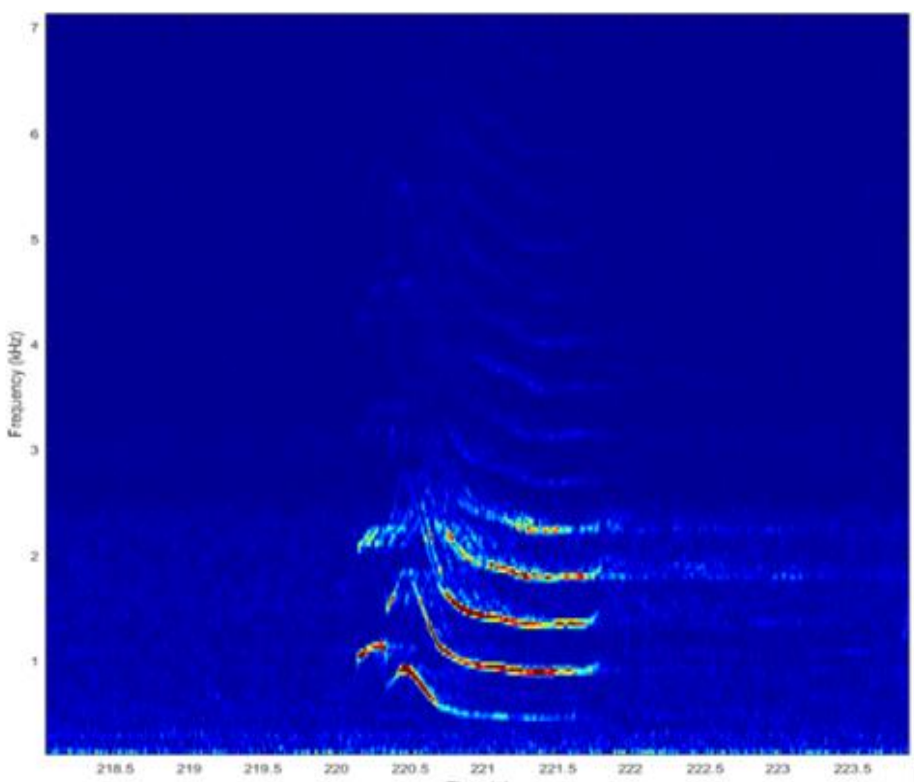

Figure 24. 5 Jul 2021 (23:37): Spectrogram of Transient/Bigg's killer whale vocalization at Frame A1.

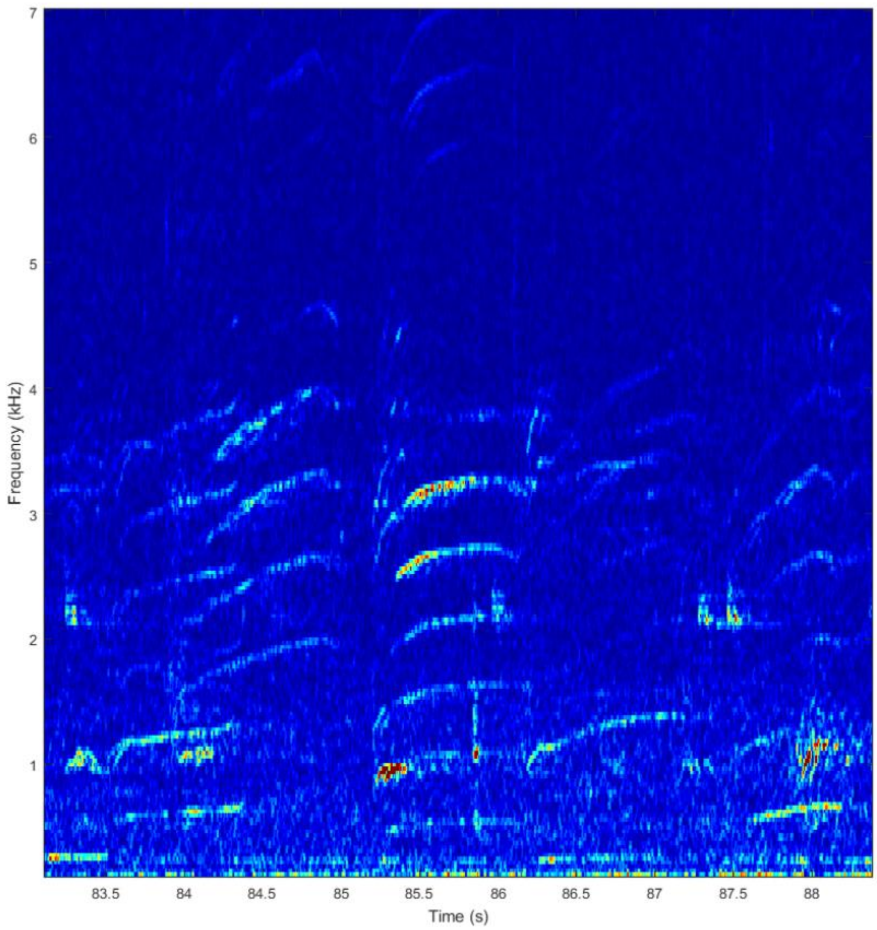

Figure 25. 10 Mar 2021 (17:22): Spectrogram of Southern resident killer whale vocalizations at Frame A1.

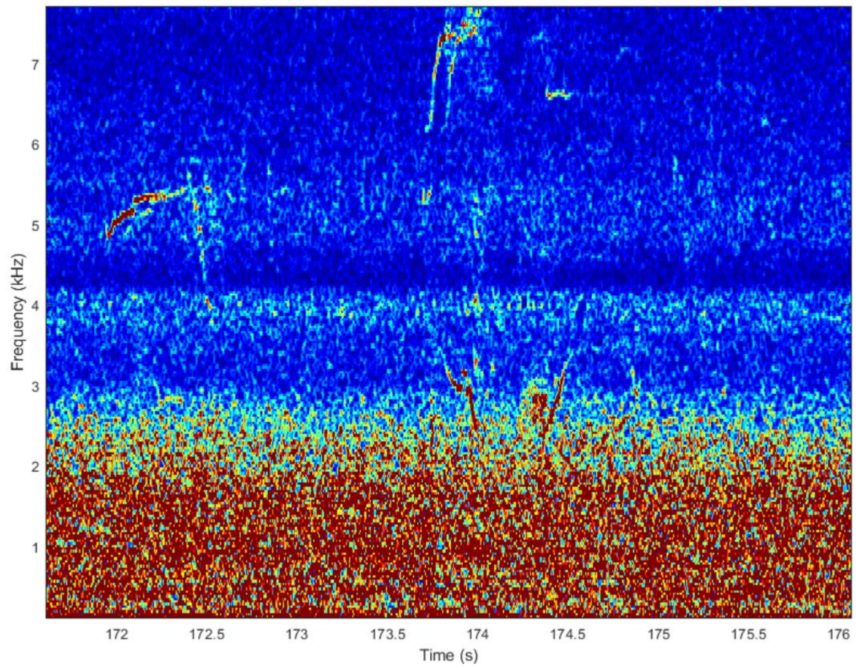

Figure 26. 4 Oct 2021 (15:59): Spectrogram of unknown killer whale vocalizations during loud vessel noise at Frame A1.

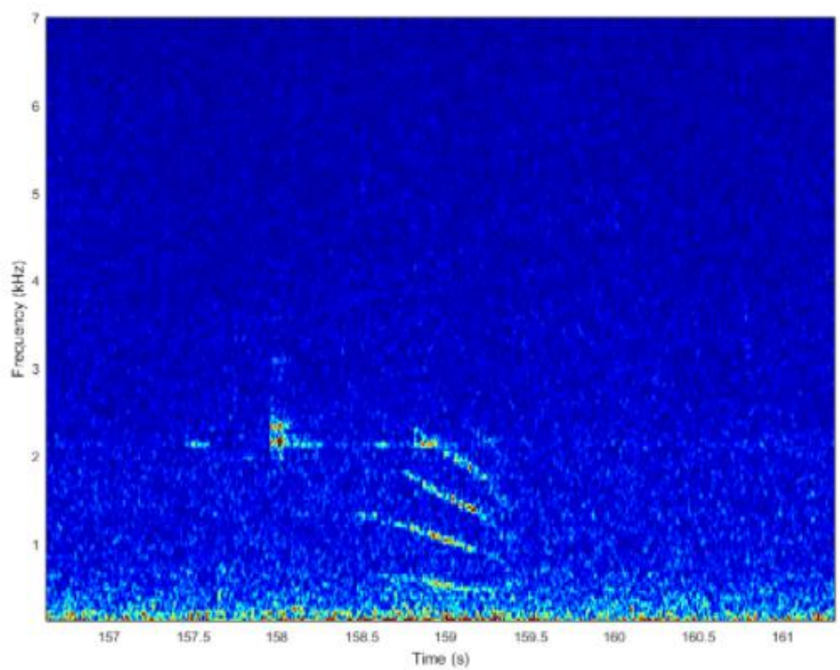

Figure 27. 7 Feb 2021 (20:27): Spectrogram of faint unknown killer whale vocalization at Frame A1.

3.2.2. Humpback Whales

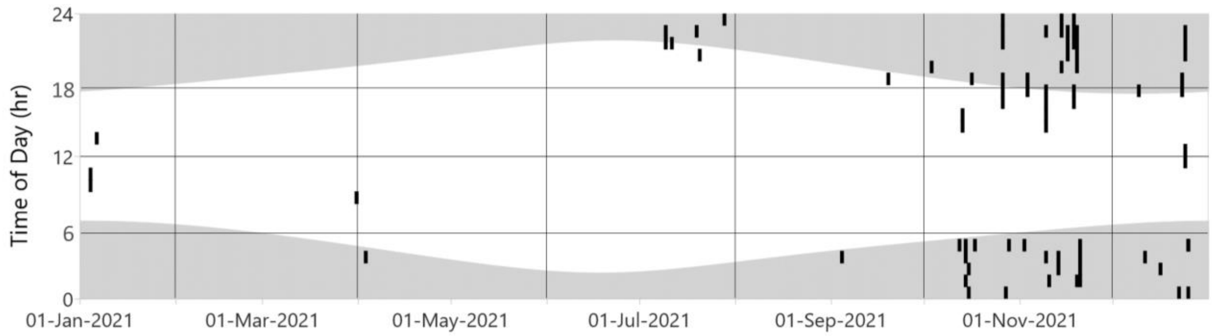

Figure 28. Year 3 (1 Jan to 31 Dec 2021): Daily and hourly occurrence of humpback whale vocalizations at Frame A (arrays as indicated in Figure 3). Black blocks indicate validated detections, and grey areas indicate darkness periods. See Table 4 for additional validated humpback whale vocalizations not included in this plot.

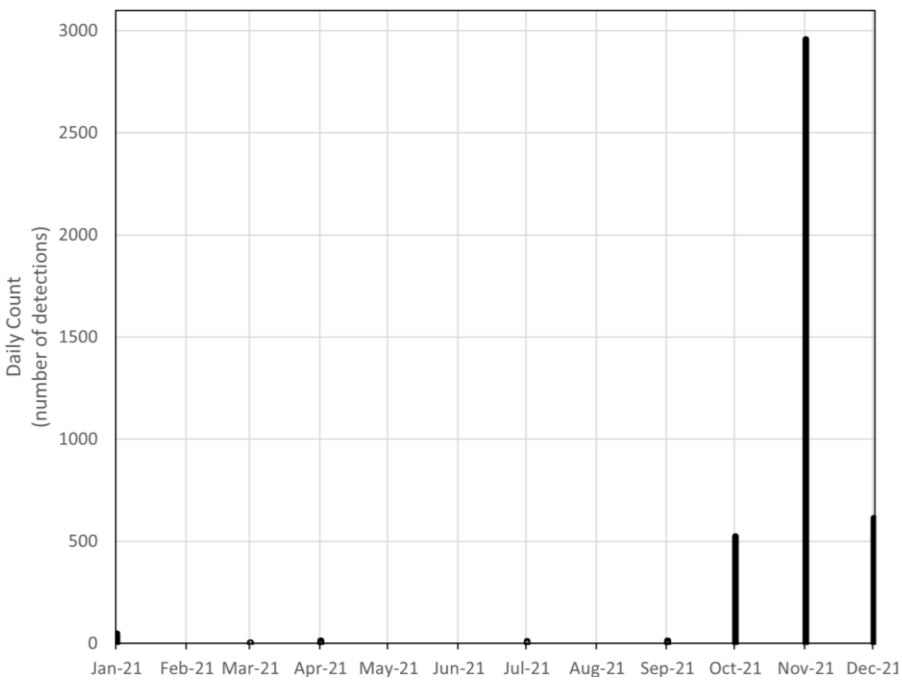

Figure 29. Year 3 (1 Jan to 31 Dec 2021): Monthly validated detection counts of humpback whale vocalizations at Frame A (arrays as indicated in Figure 3).

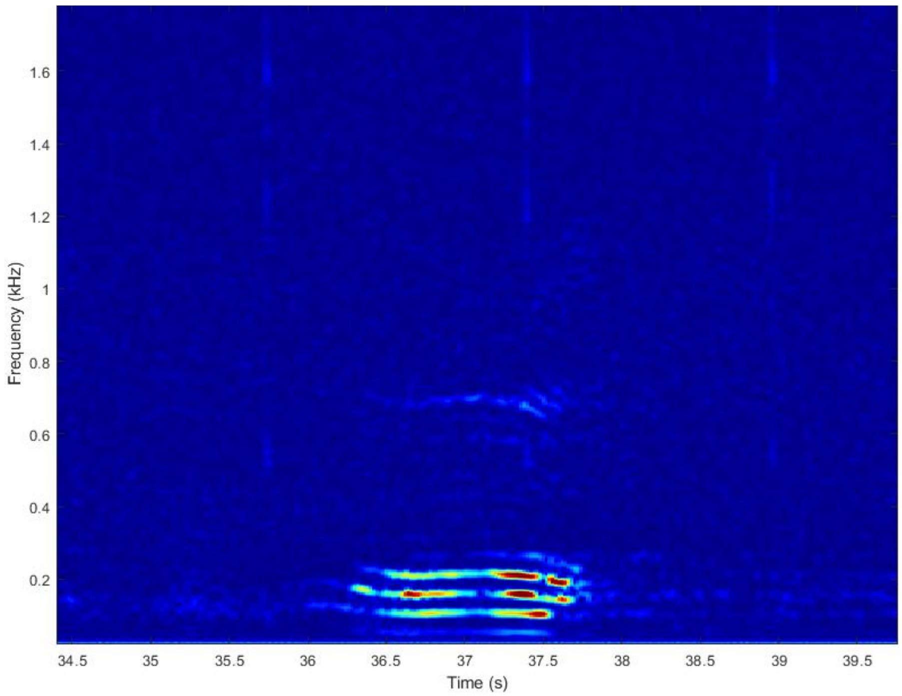

Figure 30. 13 Oct 2021 (11:53): Spectrogram of humpback whale vocalizations at Frame A2.

3.2.3. Fish

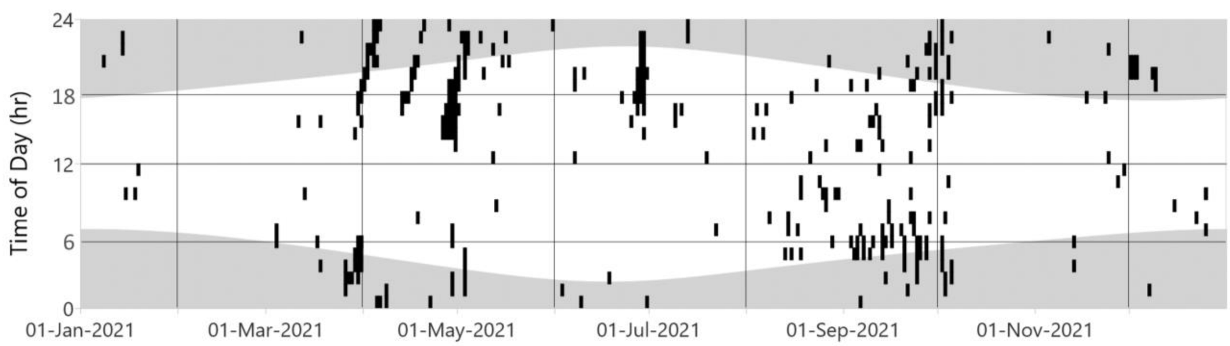

Figure 31. Year 3 (1 Jan to 31 Dec 2021): Daily and hourly occurrence of fish sounds at Frame A (arrays as indicated in Figure 3). Black blocks indicate validated detections, and grey areas indicate darkness periods.

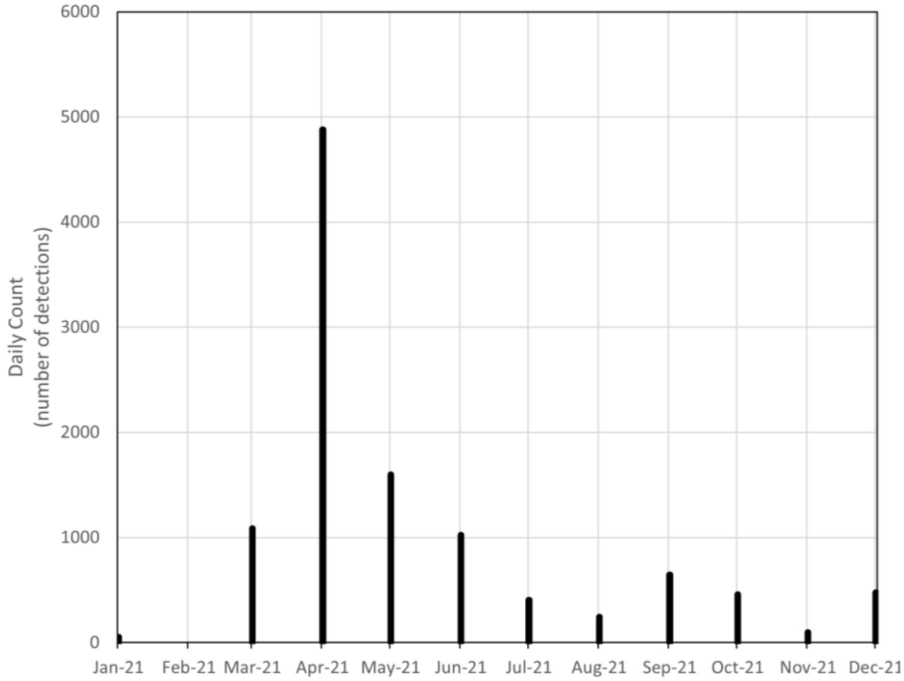

Figure 32. Year 3 (1 Jan to 31 Dec 2021): Monthly validated detection counts of fish sounds at Frame A (arrays as indicated in Figure 3).

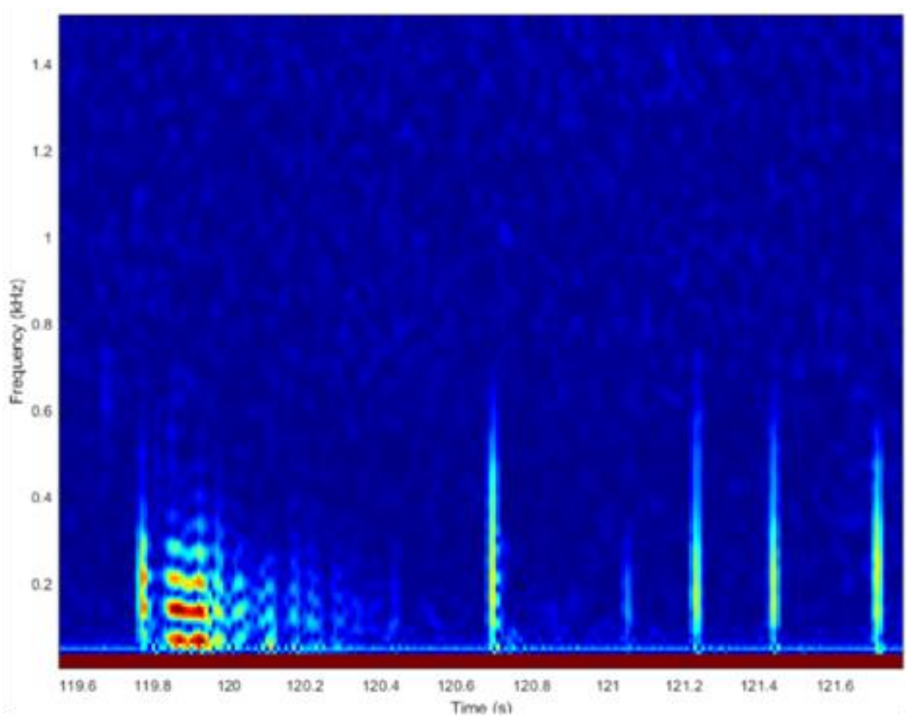

Figure 33. 9 Sep 2021 (13:05): Spectrogram of fish sounds at Frame A1.

3.2.4. Summary

Overall, killer whale vocalizations were detected on 57 days (16% of recording days, Table 5). The month with the most detection days was September (10 days). Humpback whale vocalizations were detected on 34 days (9% of recording days, Table 5) with November having the most detection days (9 days). No Pacific white-sided dolphins were detected on the Boundary Pass recorders during the reporting period. Fish sounds were detected on 134 days (37% of days analyzed for fish sounds, Table 5). April and September had the most days with fish sound detections (23 days each).

Table 5. Number of marine mammal detections and days with detections by calendar month for each species/group for Year 3 (1 Jan to 31 Dec 2021).

Month	Humpback whale		Killer whale		Fish	
	Detections	Days with detections	Detections	Days with detections	Detections	Days with detections
Jan	49	2 / 31	450	3 / 31	53	5 / 31
Feb	0	0 / 28	791	6 / 28	0	0 / 28
Mar	6	1 / 31	334	7 / 31	1087	12 / 31
Apr	14	1 / 30	1067	8 / 30	4882	23 / 30
May	0	0 / 31	164	5 / 31	1600	12 / 31
Jun	0	0 / 30	0	0 / 30	1026	13 / 30
Jul	11	5 / 31	983	4 / 31	406	7 / 31
Aug	0	0 / 31	691	6 / 31	246	17 / 31
Sep	14	3 / 30	2481	10 / 30	647	23 / 30
Oct	526	7 / 31	723	2 / 31	459	6 / 31
Nov	2959	9 / 30	1393	5 / 30	97	7 / 30
Dec	614	7 / 31	103	2 / 31	479	9 / 31
Total	**4193**	**34 / 365**	**9180**	**57 / 365**	**10982**	**134 / 356**

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. Source levels were computed from recordings from both ULS frames. Two sets of source levels were obtained for most vessel transits through Boundary Pass. Only one measurement per transit was obtained between 17 Jun and 8 Oct while only one ULS was operational (see Table 1). A total of 10 709 vessel source level measurements were made in 2021 and of these, 7884 (74%) passed the manual quality control checks. Figure 34 shows the number of vessel transits that yielded zero, one, or two accepted measurements during each month. For the accepted measurements, 1866 correspond to unique passes measured at only one ULS, while 3009 correspond to duplicate passes measured at two ULS. When two ULS frames were operational, it was much more common for both measurements to be accepted than for just one measurement to be accepted. The two ULS frames were ~300 m apart and oriented along the shipping lanes, so the time window that was processed around the closest point of approach to each frame was a bit different. Sometimes only one measurement was accepted because other vessels were too close during one measurement time window but not the other, or the background sound levels changed over time.

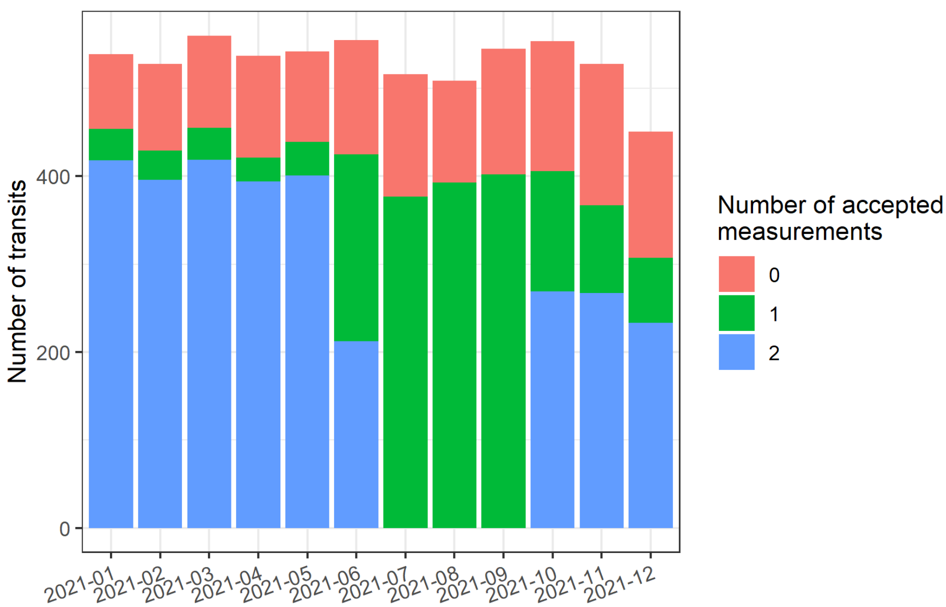

Figure 34. Monthly number of vessel transits through Boundary Pass with zero, one, or two accepted ShipSound measurements in 2021. A maximum of one accepted measurement was possible in Jul–Sep because only one ULS frame was operating.

The overall measurement acceptance rate was 77% for ULS Deployment 1 measurements (January to October) and 64% for ULS Deployment 2 measurements (October to December). To investigate this decrease in acceptance rate, the reasons for rejection were analyzed. A measurement can be rejected for one or more reasons. Table 6 lists the frequency with which each rejection reason was identified for all measurements, separated by ULS deployment. "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 50–1000 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. The frequency with which these two reasons occurred increased for Deployment 2, and the increase was larger for background noise contamination than for other vessels nearby.

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. Between 1% and 2% of measurements were rejected for this reason.

Table 6. Potential reasons for rejection of source level measurements and the frequency with which they occurred. Note that the rejection reasons are not mutually exclusive.

Rejection reason	Occurrence (%)	
	Deployment 1	Deployment 2
Other vessels nearby	16	21
Many frequency bands contaminated by background noise	5	12
Vessel sound levels saturated the recording system	1	2
Other	<1	3

Measurements with larger CPA distances were found to be less likely to pass the manual quality control checks. Figure 35 shows the cumulative density functions for accepted and rejected measurements as a function of CPA distance. Figure 36 shows the acceptance and rejection rates as a function of CPA distance. These findings are similar to those found in the previous annual report for Year 2 (Cusano et al. 2021).

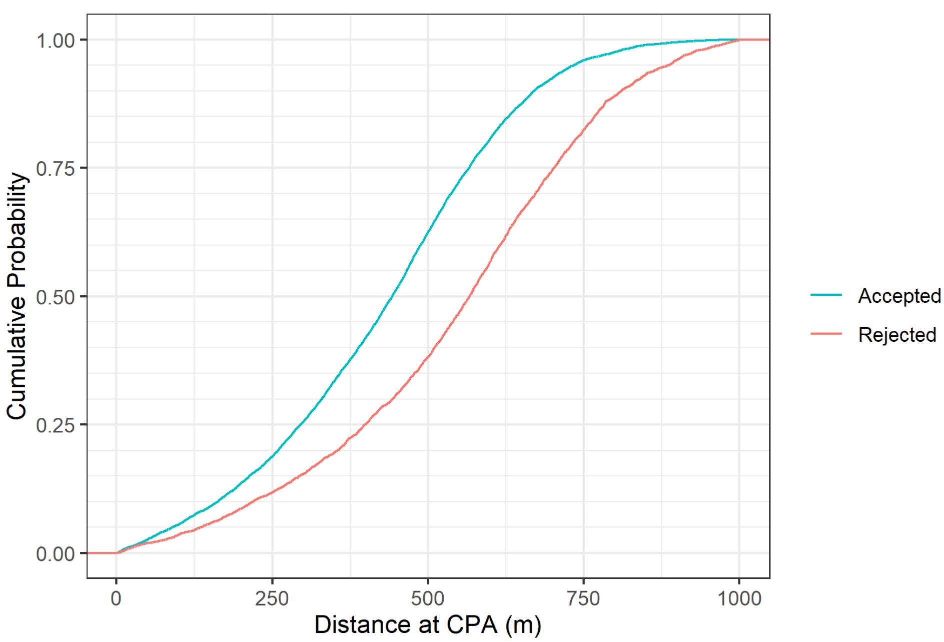

Figure 35. Cumulative distribution functions for distance at the closest point of approach (CPA) for vessel measurements that were accepted (passed manual quality control) and rejected (did not pass quality control checks).

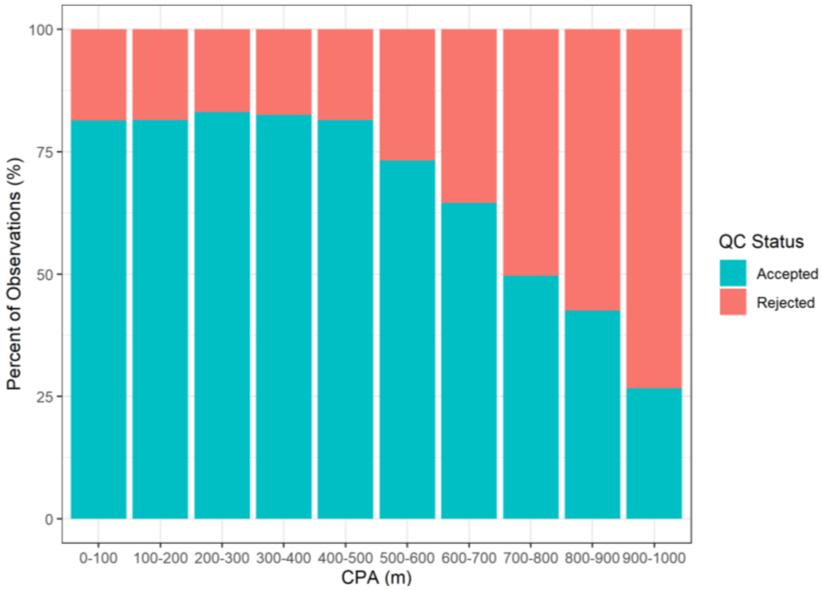

Figure 36. Acceptance and rejection rates of vessels by (horizontal) closest point of approach (CPA) distance.

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 37 shows histograms of the CPA distances for accepted and rejected measurements along a line in the cross-track direction. A total of 5452 outbound measurements (3939 accepted) and 5257 inbound measurements (3945 accepted) are included. The figure is limited to CPA distances of 1 km because that is the maximum measurement distance criterion used in ShipSound. The histograms of Figure 37 show that the vessels have a more constrained outbound route than when they are inbound (i.e., the outbound histogram is more peaked and narrow around -500 m CPA than the inbound histogram). Based on these results, the ULS location is approximately optimal for minimizing the CPA distances for both shipping lanes and therefore maximizing the number of vessel measurements passing the manual quality control checks.

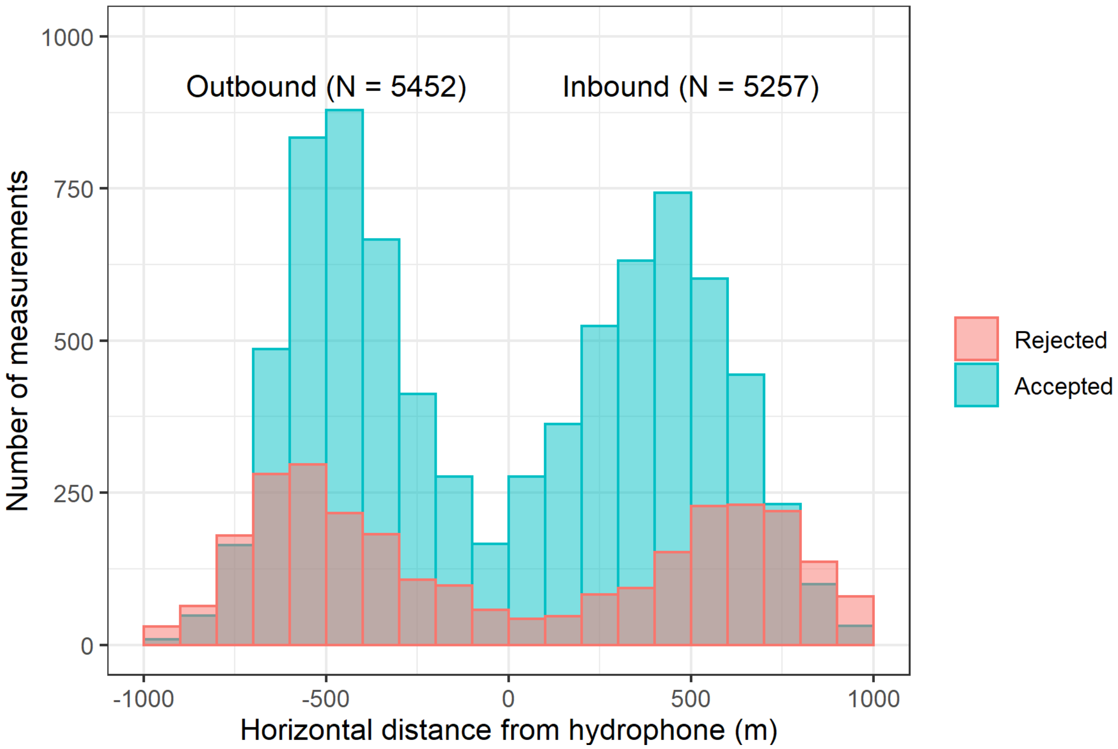

Figure 37. Histogram of closest point of approach (CPA) distances in the cross-track direction. A total of 5452 outbound measurements (3939 accepted) and 5257 inbound measurements (3945 accepted) are included in the histogram.

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 (see Figure 34). 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). Vessels may have operated differently during these different periods and noise levels during their corresponding background periods may have varied.

Figure 38 shows CDFs for the differences between broadband radiated noise level (RNL) for the same vessel transit (Frame A RNL minus Frame B RNL, frame arrays as indicated in Table 3). For Deployment 1, the mean was −0.3 dB with a standard deviation of 1.3 dB (2240 measurements). For Deployment 2, the mean was −1.0 dB with a standard deviation of 1.1 dB (769 measurements). The negative difference in means indicates that Frame B source levels were generally slightly higher than Frame A source levels. Regarding the difference in the mean RNL for the two systems we note the following:

- 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).

Although this difference could be due to system calibration, it could also be related to having less data in the Deployment 2 average. This theory will be tested as we acquire more data.

Figure 39 shows boxplots for the differences in decidecade RNL between ULS frames. The spread of the differences was much larger than for the broadband source levels. The higher scatter in Deployment 1 could be due to the larger number of measurements included in the plot. In addition, the larger outliers in Deployment 1 were caused by the ShipSound ADCP detector failing to remove 1-second sound levels containing multipath ADCP signals from the calculations. The distributions were shifted farther from zero at higher frequencies (above 10 kHz), particularly for Deployment 2, where different hydrophone models were used. This indicates larger source level uncertainty at higher frequencies.

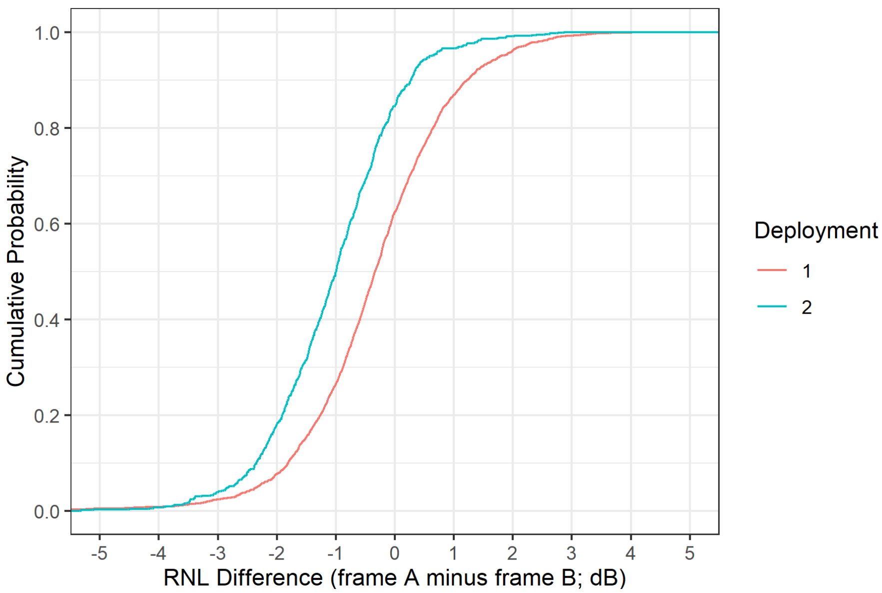

Figure 38. Differences between broadband radiated noise levels (RNL) for the same vessel transit through Boundary Pass as measured by Frames A and B in 2021, before (Deployment 1) and after (Deployment 2) the servicing operation in October. A positive difference means source levels were higher on Frame A; a negative difference means source levels were higher on Frame B. Frame arrays used for data collection changed over time as indicated in Table 3.

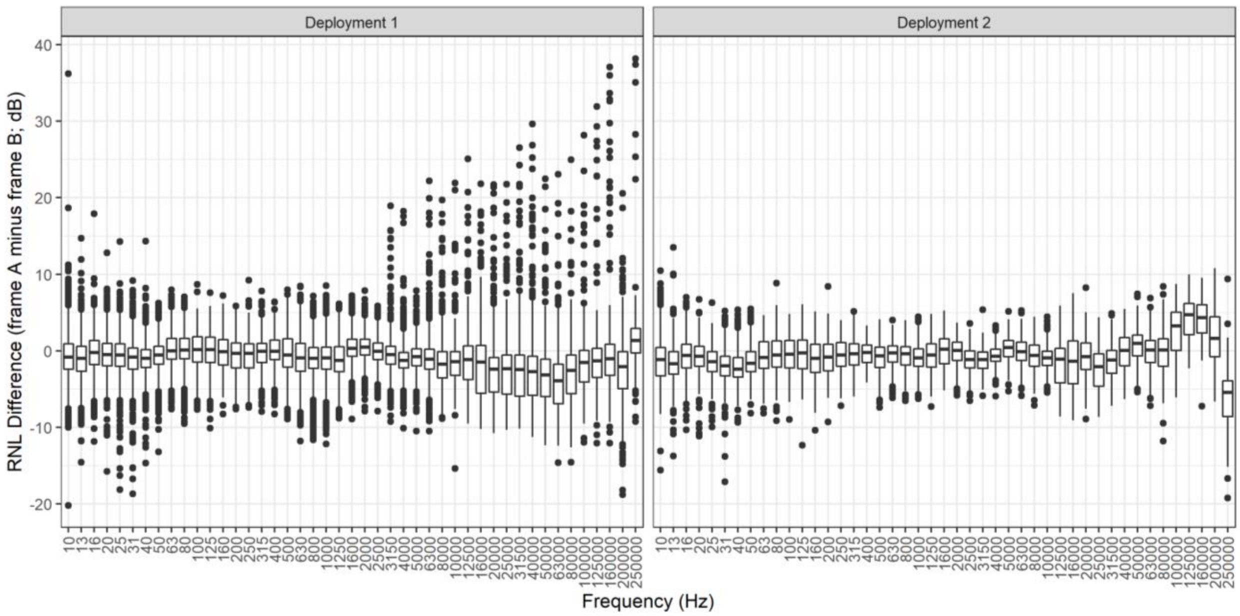

Figure 39. Differences between decidecade radiated noise level (RNL) for the same vessel transit through Boundary Pass as measured by Frames A and B in 2021, before (Deployment 1, left, 2240 measurements) and after (Deployment 2, right, 769 measurements) the servicing operation in October. A positive difference means source levels were higher on Frame A; a negative difference means source levels were higher on Frame B. Frame arrays used for data collection changed over time as indicated in Table 3.

3.3.3. Average Source Levels by Vessel Category

Figure 40 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 7 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 percentages listed in Table 7. 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 41.

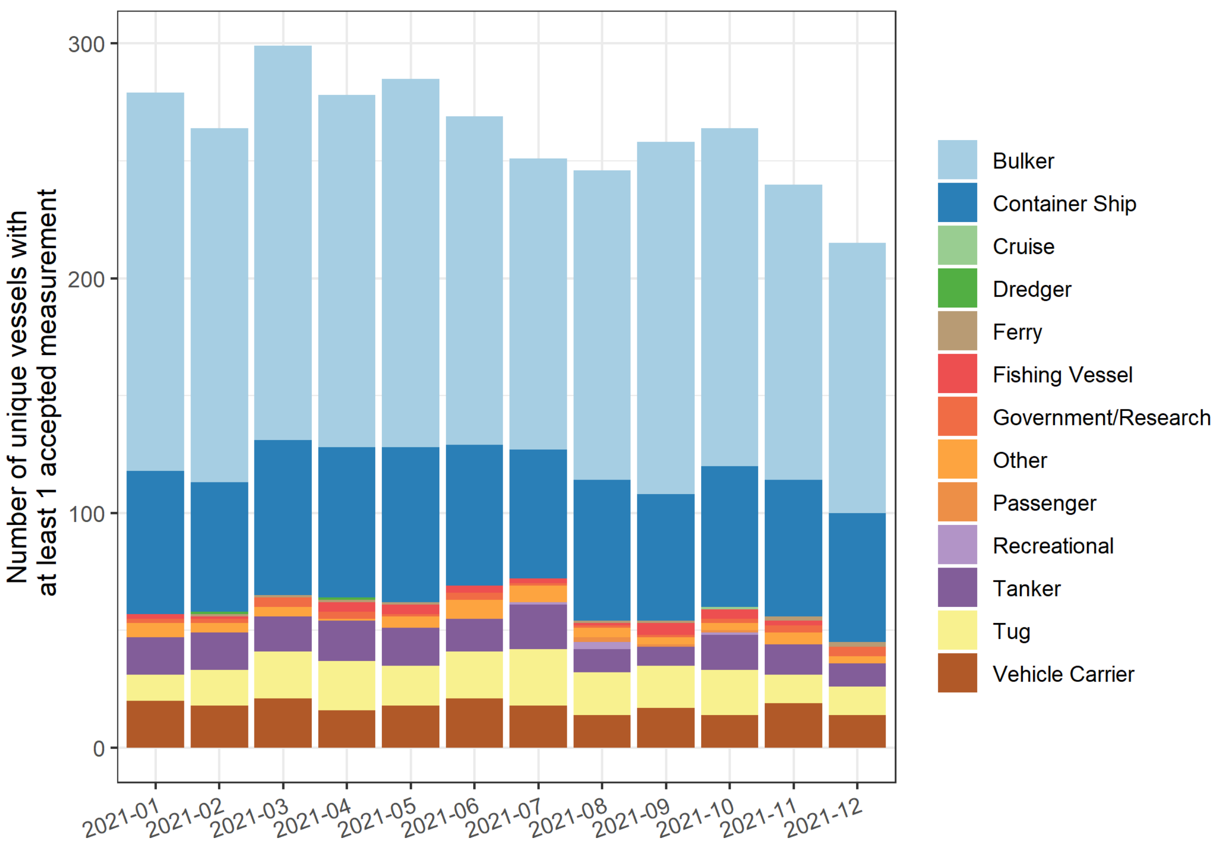

Figure 40. Number of unique vessels with at least 1 accepted source level measurement, by vessel category, that passed the manual quality control checks for each calendar month.

Table 7. 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	202.7	187.8	173.5	498	1861	23.6
Bulker ≥200 m	204.8	188.5	172.3	641	2319	29.4
Container Ship <200 m	196.1	185.7	177.1	11	45	0.6
Container Ship ≥200 m	205.4	191.6	177.1	244	1782	22.6
Dredger	185.2	183.0	181.0	2	4	0.1
Ferry ≥50 m	194.7	175.8	161.3	9	48	0.6
Fishing Vessel	187.9	180.2	164.0	13	63	0.8
Government/Research	185.5	175.3	164.0	12	63	0.8
Other	200.5	186.0	166.4	24	123	1.6
Passenger <100 m	177.7	171.5	163.9	3	9	0.1
Passenger ≥100 m	181.9	179.6	177.2	1	2	<0.1
Recreational	193.6	179.3	172.7	5	6	0.1
Tanker	200.1	187.2	175.2	106	376	4.8
Tug <50 m	191.0	180.5	168.2	60	471	6.0
Tug ≥50 m	192.6	186.2	173.9	15	146	1.9
Vehicle Carrier	199.2	189.3	178.9	133	566	7.2
All vessels	**205.4**	**188.2**	**161.3**	**1777**	**7884**	**100**

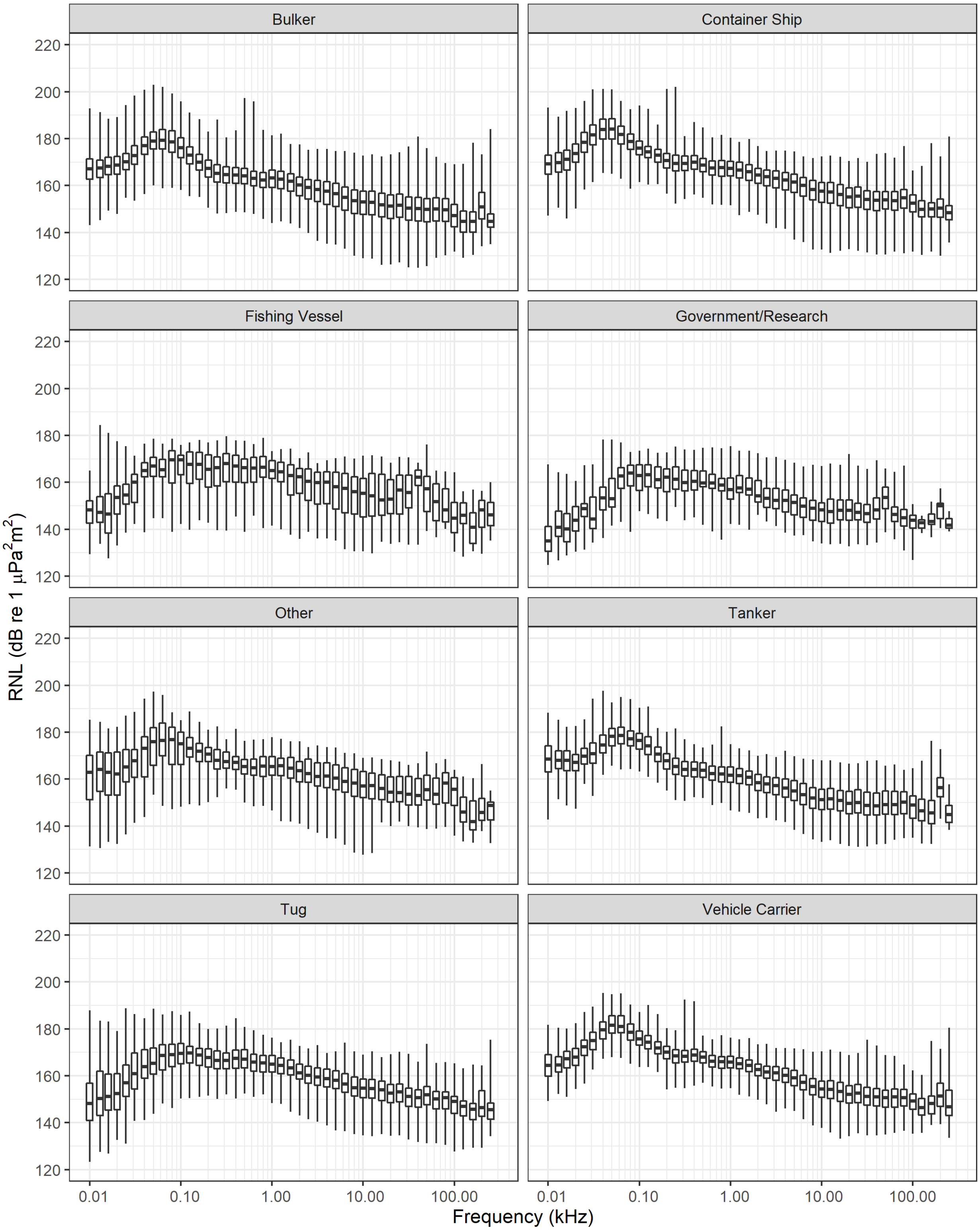

Figure 41. Box-and-whisker plots of radiated noise levels (RNL) for each vessel category with more than 50 accepted measurements during the study period (2021).

4. Discussion and Conclusion

Acoustic measurements were made using at least one ULS recorder every day in 2021 and using two recorders (either two ULS or one ULS and one AMAR) during 339 of 365 days in 2021. Ambient noise level statistics calculated from different recorder hydrophones at simultaneous times showed good agreement at mid 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. Differences at low frequencies seem to be caused by flow noise, while differences at high frequencies were generally due to differences in each hydrophone's noise floor or ADCP pings contaminating the measurements. There appears to be some high-frequency system noise on the GTI hydrophones on Frame B since the October 2021 servicing operation during which the frames were replaced. This issue affects sound levels above ~20 kHz and affected trends in the long-term (monthly) noise level statistics. This issue is currently being investigated to see if the system noise on the other three hydrophones is lower.

The ECHO Program's 2021 voluntary slowdown was likely responsible for the decrease in the sound level during Jul–Sep. The program ended in November, however, so sound levels were expected to be reduced until then. The lack of a reduction observed in October and November may be due to the aforementioned system noise observed after ULS servicing, and it will be investigated and described fully in JASCO's upcoming report to VFPA on the slowdown program.

Over 24 355 marine fauna detections were found in the acoustic data for the 12-month study period of 2021. Fish sounds were detected most frequently (45%), with detections occurring during all months of the year except February. Fish vocalizations appeared to increase in late spring, peaking in April, and early fall, which may be associated with the 'spring' spawning of Pacific herring (*Clupea harengus pallasi)* (Haegele and Schweigert 1985) and higher local abundance of other finfish. Calls also showed a slight diurnal pattern, with an increase in detections at dawn and dusk. The remaining marine fauna detections were from humpback and killer whales.

Killer whale vocalizations were detected in all months except June. SRKW vocalizations were absent from May until the end of August and peaked in September, while Transient/Bigg's vocalizations were present every month except June. These SRKW observations do not align with historical records, which suggest increased presence in the Salish Sea between June and September (DFO 2021). SRKW vocalizations were detected in much higher number than Transient/Bigg's vocalizations; however, this can be misleading in terms of presence because SRKW are generally more vocal.

Humpback whale vocalizations peaked in fall and winter (October to January) and were not present in February, May, June, or August. A clear diurnal pattern was observed for humpback whale vocalizations. These results validate previous studies demonstrating nightly singing patterns observed during the onset of the winter breeding season (Kowarski et al. 2019, Kowarski et al. 2021).

Over 10 000 vessel source level measurements of 1777 unique vessels were analyzed with JASCO's ShipSound application for Year 3 (2021). For a total of 7884 accepted measurements, 3009 correspond to vessels transiting through Boundary Pass that were measured twice (since two recorders were operating most of the time), while 1866 measurements correspond to measurements at a single recorder. The overall measurement acceptance rate decreased from 77% before the ULS servicing in October to 64% after ULS servicing. The decreased acceptance rate was primarily due to more frequent occurrence of other vessels nearby and background noise contaminating the measurements. As observed last year, the measurement acceptance rate was strongly related to the CPA distance, with closer measurements being more likely to be accepted. The ULS location was found to be approximately optimal in terms of minimizing the distance to vessels in the inbound and outbound shipping lanes, and therefore maximizing the probability of measurements passing the manual quality control checks.

Broadband RNL calculated from the same vessel transit through Boundary Pass were slightly different depending on which ULS frame was used. RNL differed by 0.3 and 1.1 dB (on average) before and after the ULS servicing, respectively. RNL for Frame B measurements were generally slightly higher than those from Frame A measurements. Differences in decidecade band levels were more variable than those of broadband RNL, sometimes because of ADCP sounds contaminating the measurements during the first deployment (before the servicing in October). These differences did not have a noticeable effect on the overall vessel-class broadband RNL statistics, which are dominated by energy in frequency bands below 1 kHz. Most vessels measured were either Bulker or Container ships.

Acknowledgements

We thank Greg Bellavance and the crew of the Moving Experience for their assistance with deploying and retrieving the temporary AMAR in July and October 2021. We thank David Osborne for allowing us to install our backup AIS logger at his home on Saturna Island. Mike Shaw and the crew at Island Tug and Barge provided expert marine services for retrieving and deploying ULS frames during the servicing work in October 2021. 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.

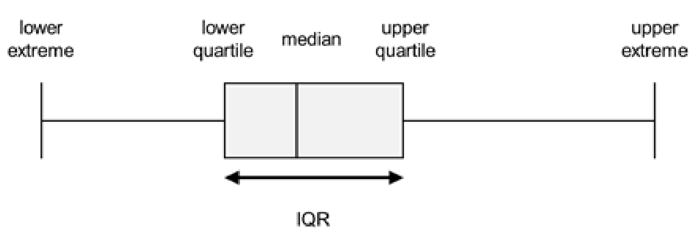

Figure 42. Diagram showing how quantiles are displayed on a box-and-whisker plot. IQR = interquartile range (i.e., the range between the 25th and 75th percentile).

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: $\mu Pa^2/Hz$.

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.

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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 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.

This report contains analysis of data collected from October to December 2021[3]. Between 6 and 9 Oct, both ULS frames (A and B) were replaced as part of a servicing operation. The servicing operation was conducted to restore functionality in Frame B that had been lost in June 2021 when an ethernet chip failed. An AMAR was also recording in early October, but these data are not presented for this report because it was sampling at a lower rate and had more flow noise than ULS Frame A.

For this report, we analyzed ULS data from Frame A before the servicing and from Frame B after the servicing. The reason for switching the frames was to keep the hydrophone model and noise floor characteristics as consistent as possible; before servicing Frame A used GTI hydrophones and after servicing Frame A used HTI hydrophones and Frame B used GTI hydrophones. The acoustic data were processed to compute ambient noise statistics.

A.2. Report Schedule

Table A-1. Periods analyzed for this report.

Month start	Month end	Weeks reported
1 Oct 2021 00:00 PDT	1 Nov 2021 00:00 PDT	Sun 3 Oct to Sat 9 Oct Sun 10 Oct to Sat 16 Oct Sun 17 Oct to Sat 23 Oct Sun 24 Oct to Sat 30 Oct
1 Nov 2021 00:00 PDT	1 Dec 2021 00:00 PST	Sun 31 Oct to Sat 6 Nov Sun 7 Nov to Sat 13 Nov Sun 14 Nov to Sat 20 Nov Sun 21 Nov to Sat 27 Nov Sun 28 Nov to Sat 4 Dec
1 Dec 2021 00:00 PST	1 Jan 2022 00:00 PST	Sun 5 Dec to Sat 11 Dec Sun 12 Dec to Sat 18 Dec Sun 19 Dec to Sat 25 Dec Sun 26 Dec to Sat 1 Jan

[3] This report has been truncated for this appendix to only show one month of results.

A.3. Ambient Noise Data Processing Methods

Location Name: **Boundary Pass**

Analysis Period: **1 Oct to 31 Dec 2021**

Table A-2. Underwater Listening Station (ULS) locations and periods used for analysis.

ULS	Hydrophone	Start date/time	End date/time	Latitude	Longitude	Water depth (m)
A1	GTI M36-V35-100	2021 Oct 1 00:00	2021 Oct 7 13:10	48° 45.55800' N	123° 3.87600' W	193
B1	GTI M36-V35-100	2021 Oct 7 18:53	2021 Dec 31 23:59	48° 45.65731' N	123° 3.65912' W	194

Before servicing, ULS A1 had a 150 kHz ADCP that emitted pings once every minute. These pings saturated the A1 hydrophones for less than one second each minute. When computing 1-minute sound levels, the second that contained saturated ADCP pings was excluded from the averages. The second following the ADCP ping was also excluded from the average in order to ignore surface reflections of the ADCP sound. The resulting 58 seconds used for the 1-minute averages better represent the ambient sound conditions in Boundary Pass as the ADCP signals are essentially system noise and attenuate quickly with range due to their high frequency. After servicing the ULS frames, the ADCP failed to operate so the sound levels represent full 1-minute averages.

This report summarizes ambient underwater noise measurements made in Boundary Pass during the analysis period. The results 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: 10–256000 Hz (broadband), 10–100 Hz, 100–1000 Hz, 1000–10000 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 one-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" was 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 were obtained from Acoustic Doppler Current Profiler (ADCP) measurements when it was operating and were supplemented with data from the WebTide Tidal Prediction Model (v 0.7.1) when the ADCP was offline.

A.4. Results: October 2021

A.4.1. Ambient Sound Pressure Level versus Time

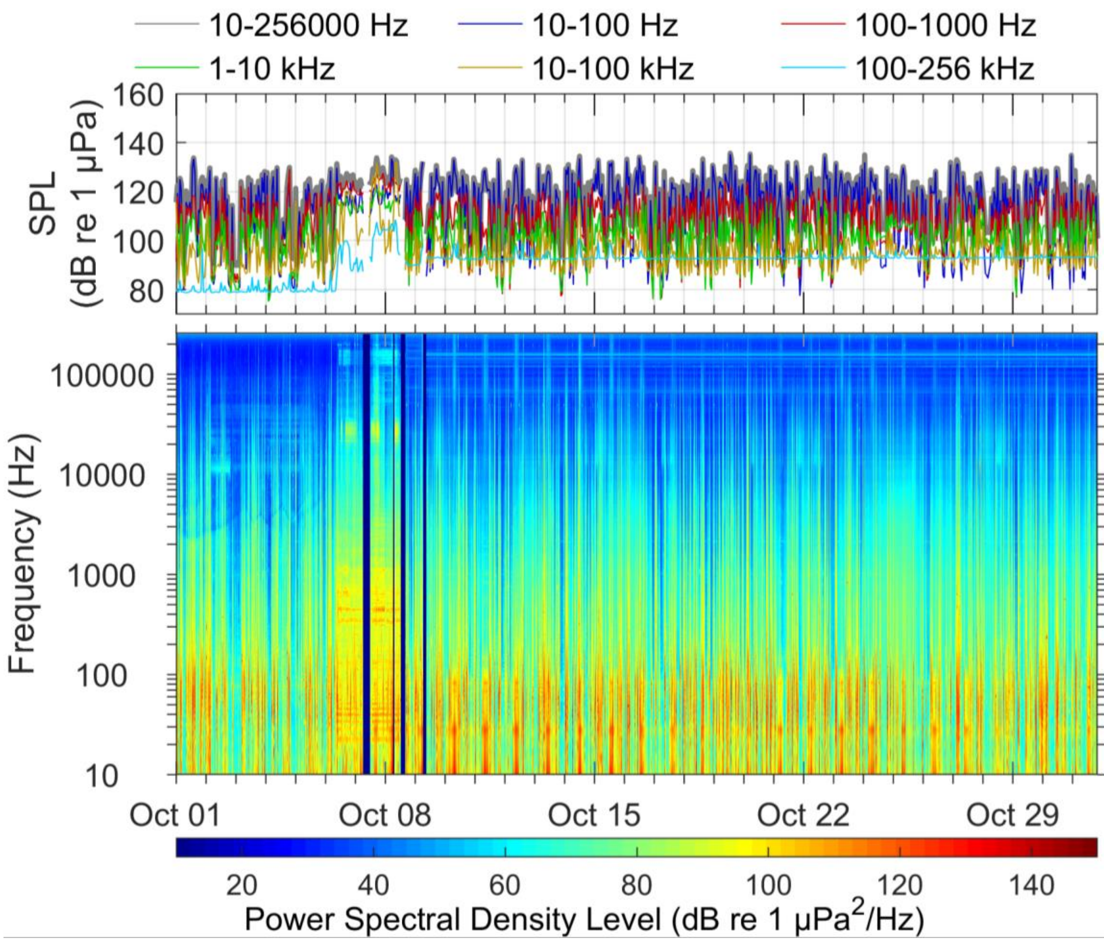


Figure A-1. October 2021: Broadband, decade band sound pressure level (SPL) versus time, and spectrogram through the analysis period.. The elevated noise levels and data gaps around 6–9 Oct were due to the ULS servicing vessels and the servicing operation.

A.4.2. Spectral Levels and decidecade Band Levels

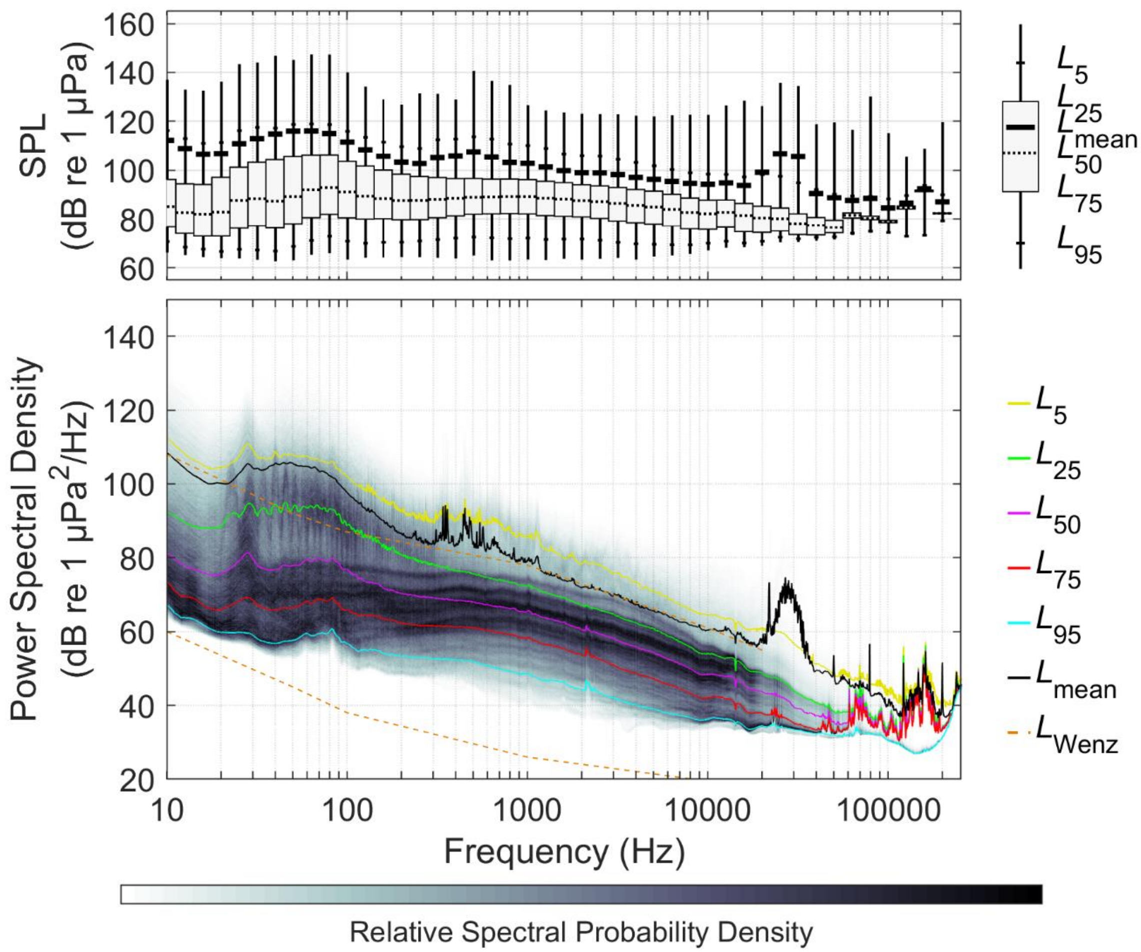


Figure A-2. October 2021: (Top) Percentiles and mean decidecade band sound pressure level (SPL; 1 minute) over the analysis period. (Bottom) Percentiles and mean power spectral density levels over the same time period.

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

Table A-3. October 2021: 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	95.1	99.9	106.5	118.7	129.5
10	70.8	76.9	85.0	96.2	116.2
12.6	68.5	74.2	82.6	94.4	112.9
15.8	67.7	73.1	82.0	94.1	110.9
20	66.7	73.1	82.8	97.1	111.3
25.1	67.6	76.3	87.6	101.2	116.2
31.6	67.3	77.2	88.3	103.3	117.5
39.8	66.9	76.5	87.3	104.4	117.2
50.1	68.8	78.0	89.2	105.6	118.7
63.1	71.2	80.5	92.0	106.1	118.9
79.4	73.0	81.9	92.9	106.2	118.6
100	71.0	80.5	91.1	103.6	115.9
125.9	70.1	80.0	89.3	101.7	113.4
158.5	70.4	80.1	88.3	100.0	111.5
199.5	70.5	79.7	87.6	98.4	109.6
251.2	71.1	79.7	87.6	97.4	108.8
316.2	71.6	80.5	88.0	97.0	112.4
398.1	72.2	81.3	88.5	96.6	112.7
501.2	72.6	81.9	88.9	96.6	113.6
631	72.3	82.1	89.0	96.3	112.7
794.3	72.0	82.2	89.2	96.4	110.7
1000	72.2	82.1	89.2	96.1	110.1
1258.9	71.6	81.4	88.5	95.4	108.8
1584.9	71.9	81.1	88.1	94.9	106.6
1995.3	71.9	80.8	87.5	94.1	105.9
2511.9	71.3	80.2	87.1	93.6	105.7
3162.3	70.4	79.1	86.4	92.9	104.5
3981.1	69.9	78.4	85.6	92.1	103.2
5011.9	69.7	77.9	84.9	91.4	101.8
6309.6	69.5	77.1	83.9	90.1	100.3
7943.3	69.4	76.0	82.7	88.6	98.9
10000	70.1	75.9	82.1	87.7	98.4
12589.3	71.0	76.8	82.7	87.7	98.3
15848.9	70.2	74.9	81.4	86.4	97.2
19952.6	71.0	74.6	80.4	85.2	98.2
25118.9	72.6	75.2	80.1	84.5	97.5
31622.8	72.0	73.7	78.1	82.1	94.8
39810.7	72.5	73.6	77.2	80.6	92.1
50118.7	72.7	74.5	76.7	79.4	90.1
63095.7	74.2	80.4	81.5	82.5	89.4
79432.8	75.0	79.7	80.2	81.2	89.3
100000	74.5	78.5	78.8	79.4	88.2
125892.5	73.0	84.1	84.8	85.3	89.6
158489.3	73.3	91.2	91.6	91.8	93.8
199526.2	79.2	82.1	82.3	82.4	89.9

A.4.4. Daily Rhythm Plot

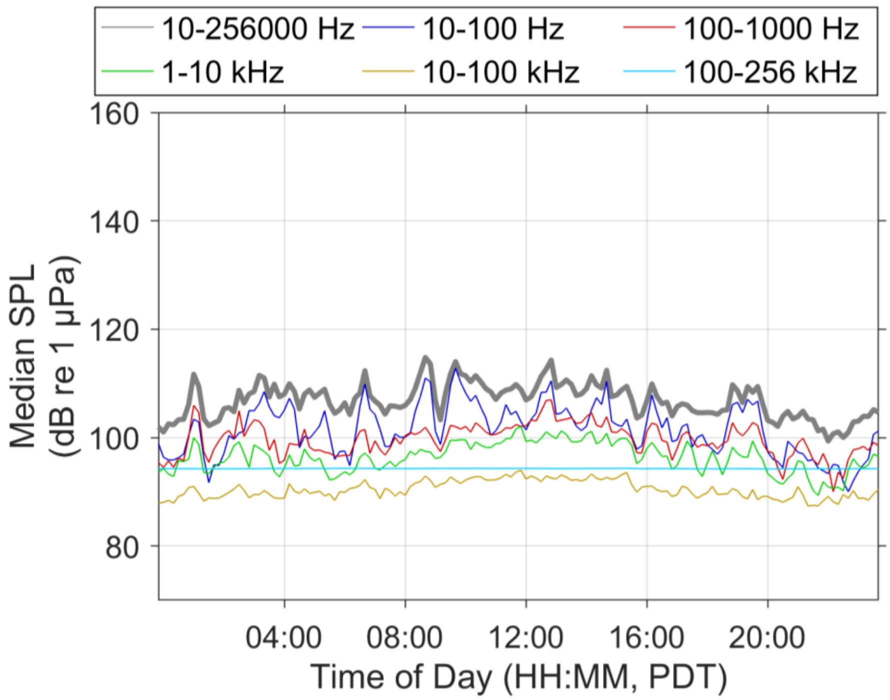


Figure A-3. October 2021: Median 1-minute sound pressure level (SPL) versus time of day (10 min resolution) over the analysis period.

A.4.5. Weekly Rhythm Plot

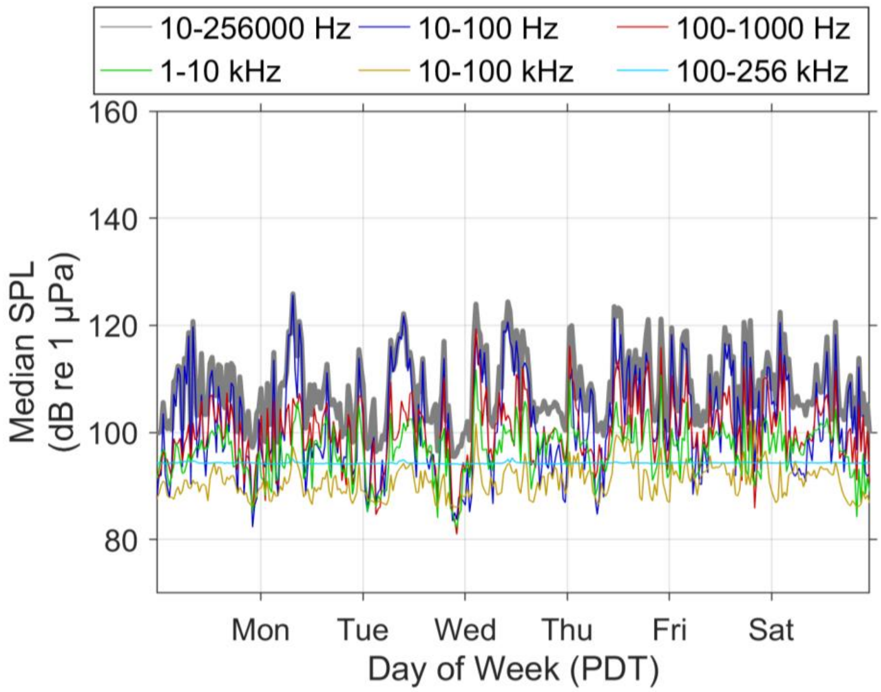


Figure A-4. October 2021: Median 1-minute sound pressure level (SPL) versus day of week (30 min resolution) over the analysis period.

A.4.6. SPL Box Plot

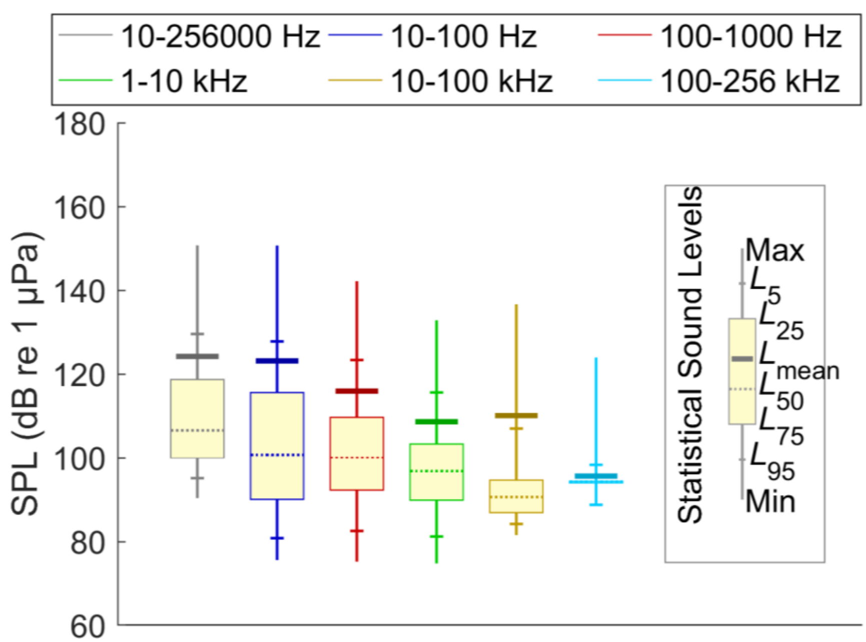


Figure A-5. October 2021: Broadband and decade-band sound pressure level (SPL; 1 min) statistics over the analysis period.

A.4.7. Table of Values

Table A-4. October 2021: 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	90.4	75.6	75.2	74.8	81.5	88.7
L_{95}	95.1	80.8	82.5	81.2	84.2	88.8
L_{75}	99.9	90.1	92.3	89.9	86.9	94.0
L_{50}	106.5	100.7	99.9	96.8	90.6	94.3
L_{25}	118.7	115.6	109.6	103.3	94.7	94.4
L_{5}	129.5	127.8	123.3	115.6	107	98.3
Max	150.7	150.7	142.2	132.8	136.6	123.9
Mean	124.2	123.1	115.9	108.6	110.1	95.6

A.4.8. Weekly Band Levels

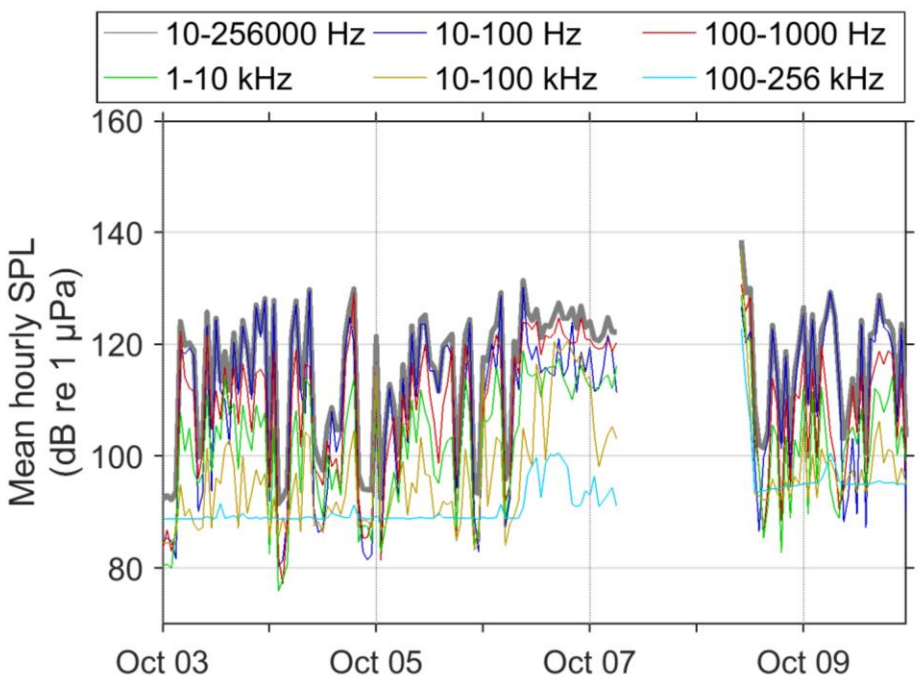


Figure A-6. 3–9 Oct 2021: Weekly broadband and decade band sound pressure level (SPL) versus time.

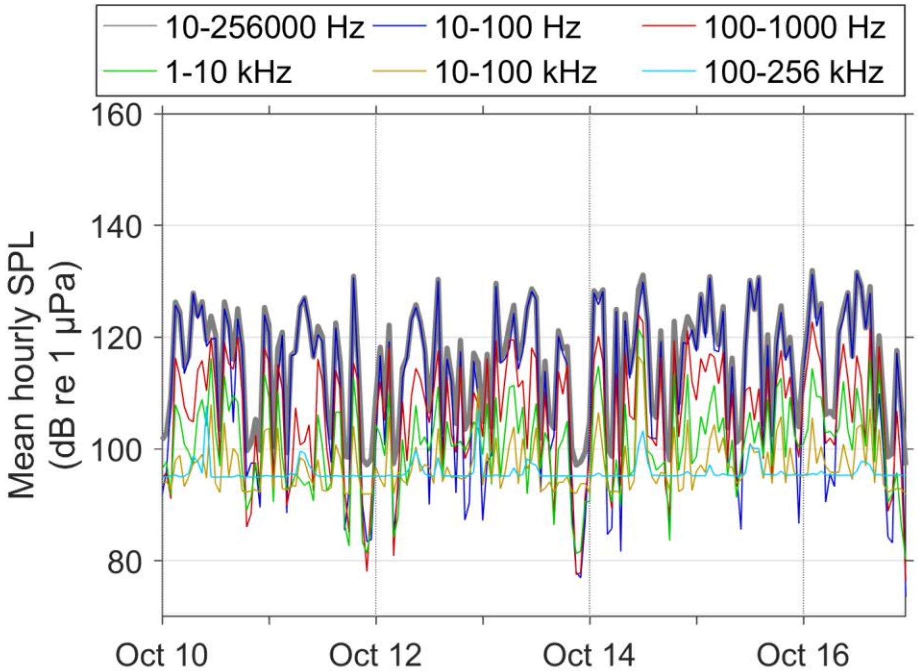


Figure A-7. 10–16 Oct 2021: Weekly broadband and decade band sound pressure level (SPL) versus time.

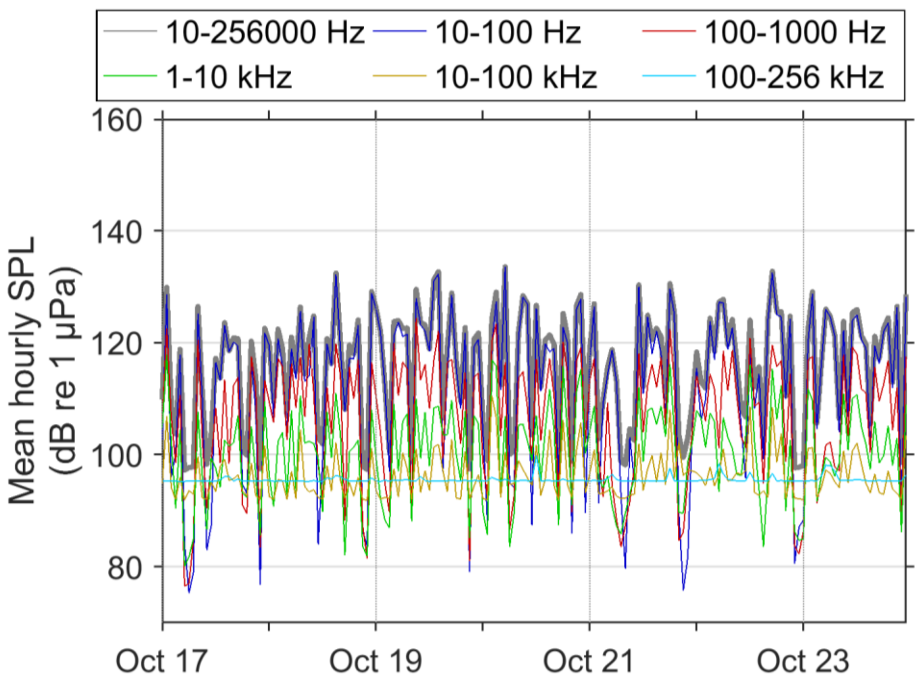


Figure A-8. 17–23 Oct 2021: Weekly broadband and decade band sound pressure level (SPL) versus time.

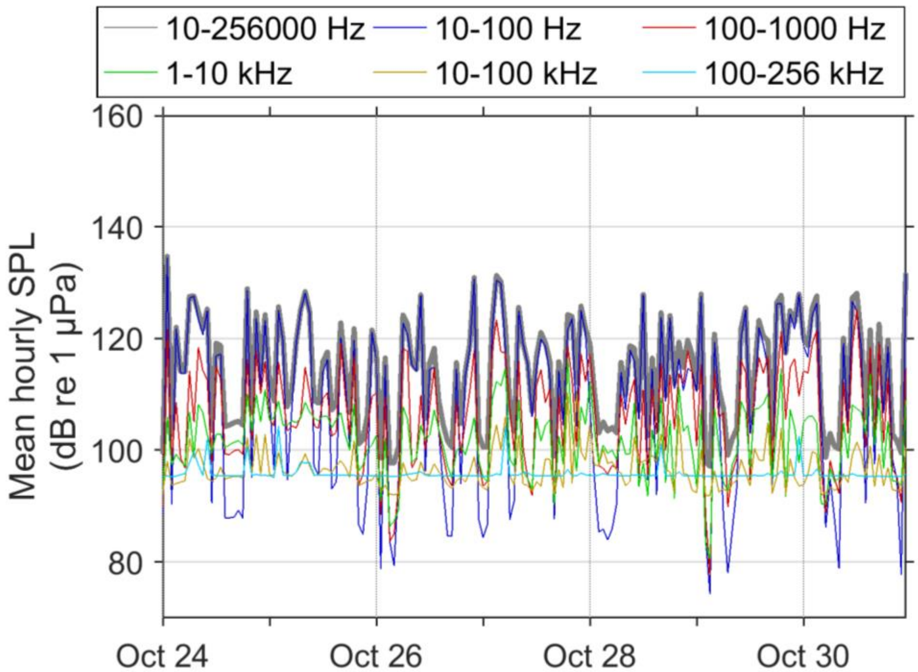


Figure A-9. 24–30 Oct 2021: Weekly broadband and decade band sound pressure level (SPL) versus time.

A.4.9. Hourly Wind Speed

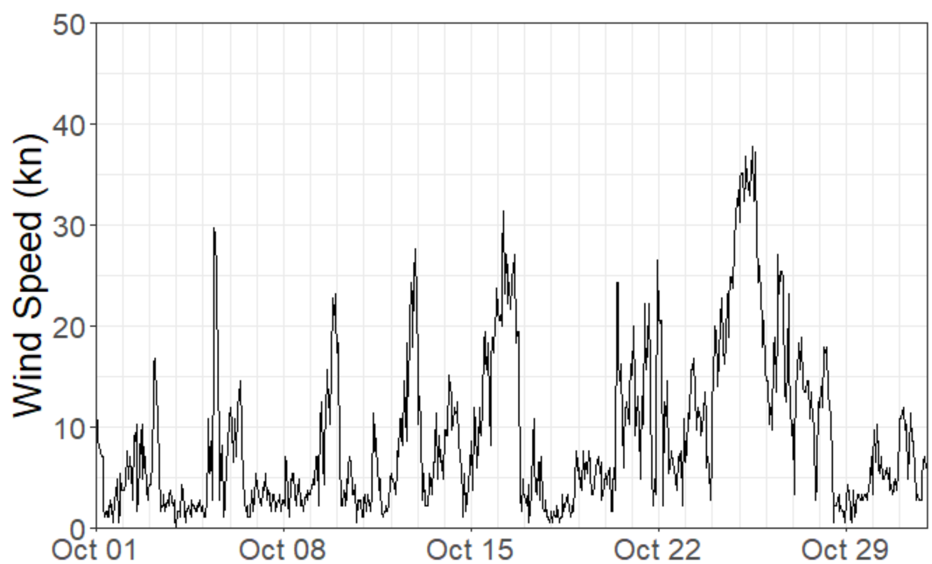


Figure A-10. October 2021: Hourly wind speed.

A.4.10. Near-seafloor Current Speed

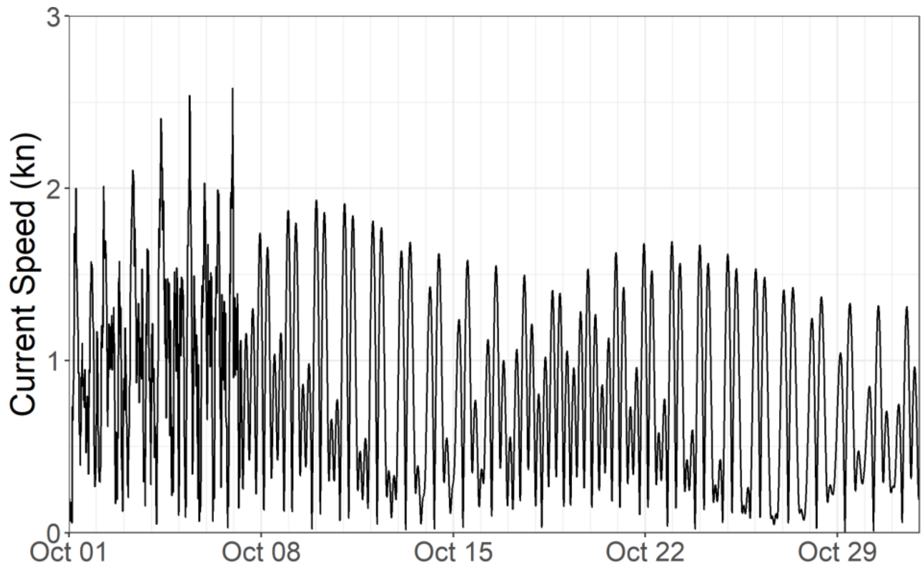


Figure A-11. October 2021: Near-seafloor current speed. Between October 01 to October 07 13:07 UTC the ADCP was still active. WebTide data was used after this time.

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 Oct 2021, 1 to 30 Nov 2021, and 1 to 31 Dec 2021[4]. 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 Pacific Time unless otherwise indicated.
- Graphs showing the number of validated detection counts per day for each species. All graphs are in Pacific Time unless otherwise indicated.
- Spectrograms showing how animal-vocalization frequencies varied in time.

This report includes a breakdown of killer whale detections into ecotype classifications:

- Southern Resident killer whale (SRKW)
- Transient/Bigg's killer whale
- Unknown killer whale (UNKW)—not able to distinguish between ecotypes

Killer whale ecotype classification was done manually by an experienced analyst by listening to and viewing spectrograms of the automatically detected killer whale calls. It is important to note that the number of detections between SRKW and Transient/Bigg's can be misleading in terms of presence since SRKW are much more vocal.

[4] This report has been truncated for this appendix to only show one month of results.

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 marine mammal detections exclusively from ULS Frame A. Frame B detections were reviewed manually to ensure there were no substantial differences with Frame A results.

Table B-1. Underwater listening station (ULS) locations and periods used for analysis.

ULS	Latitude	Longitude	Water depth (m)	Start date/time	End date/time
A1	48° 45.55800’ N	123° 3.87600’ W	193	2021 Oct 1 00:00	2021 Oct 7 13:10
A2	48° 45.56672’ N	123° 3.85010’ W	193	2021 Oct 8 17:54	2021 Dec 31 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-side 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.

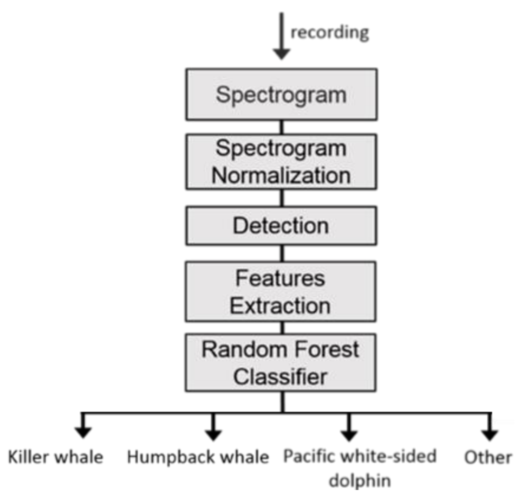


Figure B-1. The process for automatic detections of killer whale, humpback whale, Pacific white-side dolphin, and fish sounds.

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-side dolphin”, “fish”, and “other”. Figure B-2 illustrates the key processing steps of the detector on a recording that contained killer whale vocalizations.

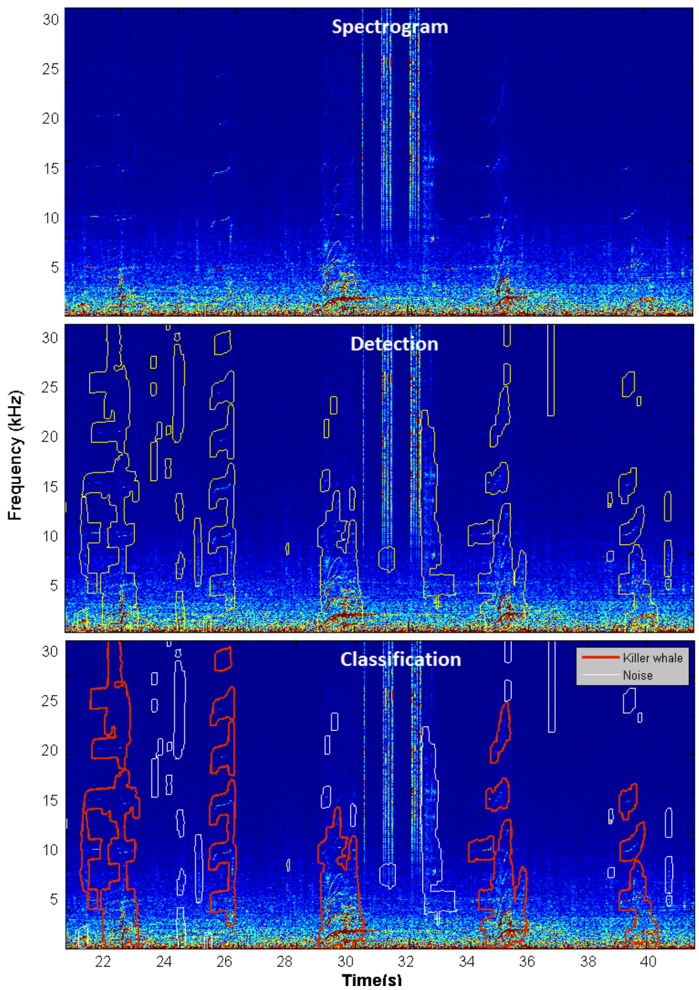


Figure B-2. Key processing steps of the detector. Top panel: Spectrogram with killer whale vocalizations. Middle panel: Acoustic events detected in the spectrogram. Bottom panel: Killer whale vocalizations classified using a random forest classifier.

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: Validation Process

Throughout the manual validation process, experienced acoustic analysts verified that some humpback whale vocalizations were misclassified by the killer whale detector (Table B-2). These detections were rejected under the killer whale detector but were manually added to the humpback whale results. Results displaying humpback whale vocalizations were updated in all sections of this report, except for graphs showing the daily and hourly occurrence.

Table B-2. Humpback whale vocalizations misclassified as killer whale vocalizations.

Start date and time	End date and time	Number of misclassified humpback whale calls
2021 Oct 12 12:42	2021 Oct 12 13:10	30
2021 Oct 15 08:23	2021 Oct 15 10:55	77
2021 Nov 9 23:13	2021 Nov 9 23:17	17
2021 Nov 10 00:08	2021 Nov 10 10:22	203
2021 Nov 13 10:53	2021 Nov 13 11:47	342
2021 Nov 17 04:59	2021 Nov 17 05:21	62
2021 Nov 19 06:13	2021 Nov 19 07:07	88
2021 Nov 20 03:47	2021 Nov 20 12:22	968
2021 Dec 24 02:04	2021 Dec 24 02:58	59
2021 Dec 25 04:41	2021 Dec 25 05:51	29
2021 Dec 29 22:16	2021 Dec 29 22:19	17

B.4. Results: 1 to 31 Oct 2021

B.4.1. Relative Vocalization Detections by Species

A total of 723 killer whale vocalizations (712= SRKW, 11= UNKW), 526 humpback whale vocalizations, and 459 fish sounds were validated from the automated detectors from 1 to 31 Oct 2021. There were no validated detections for Pacific white-sided dolphin vocalizations during this analysis period. Figure B-3 shows the proportion of detections by species for this period.

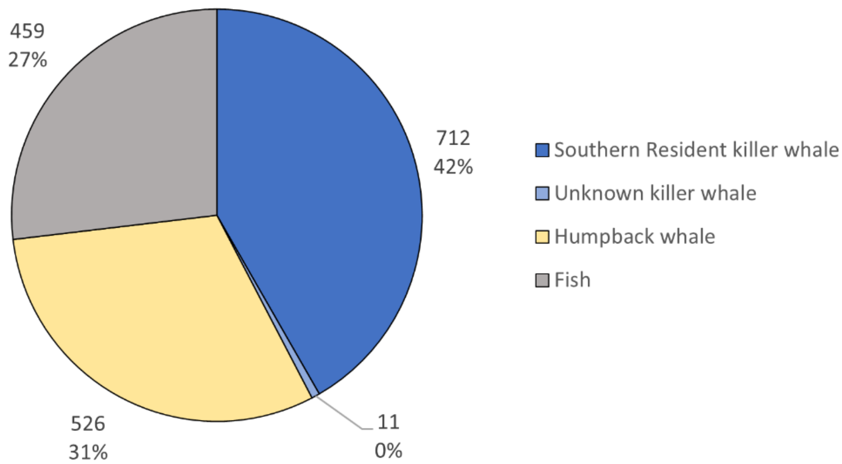


Figure B-3. 1 to 31 Oct 2021. Counts and proportion of vocalization detections per species.

B.4.2. Killer Whales

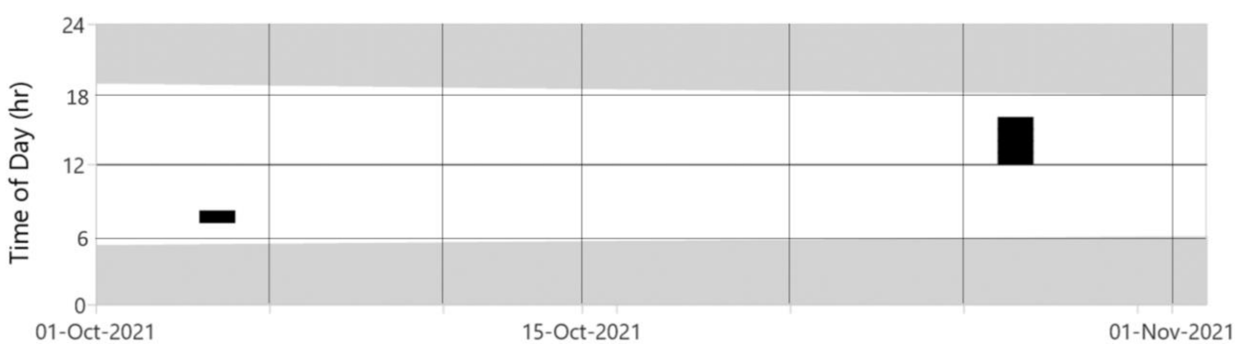


Figure B-4. 1 to 31 Oct 2021. Daily and hourly occurrence of killer whale vocalizations at ULS Frame A. Black blocks indicate validated detections, and grey areas indicate darkness period.

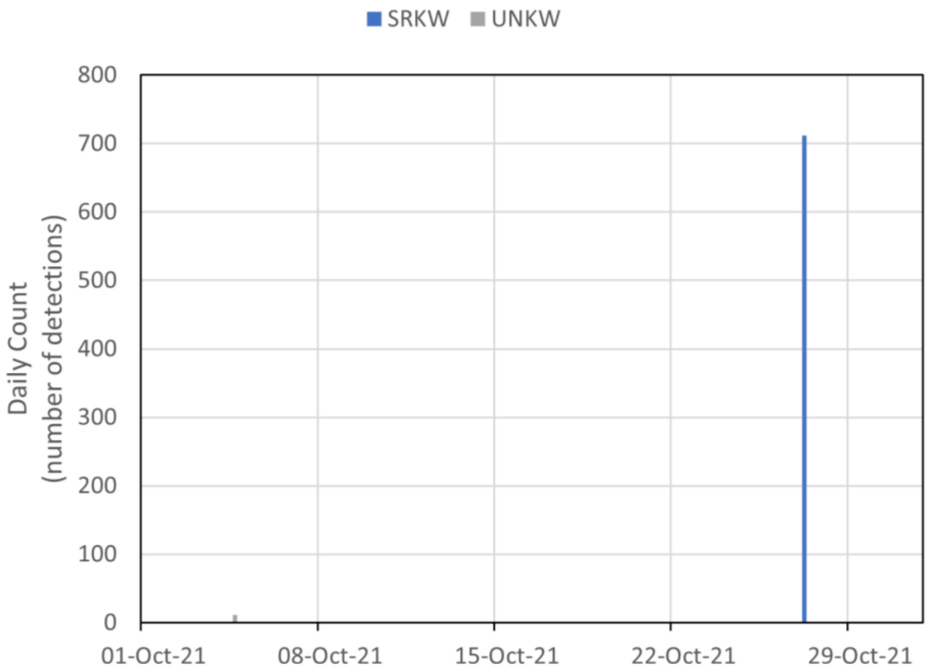


Figure B-5. 1 to 31 Oct 2021. Daily validated detection counts of Southern Resident killer whales (SRKW), Transient/Bigg's, and Unknown Killer Whales (UNKW) vocalizations at ULS Frame A.

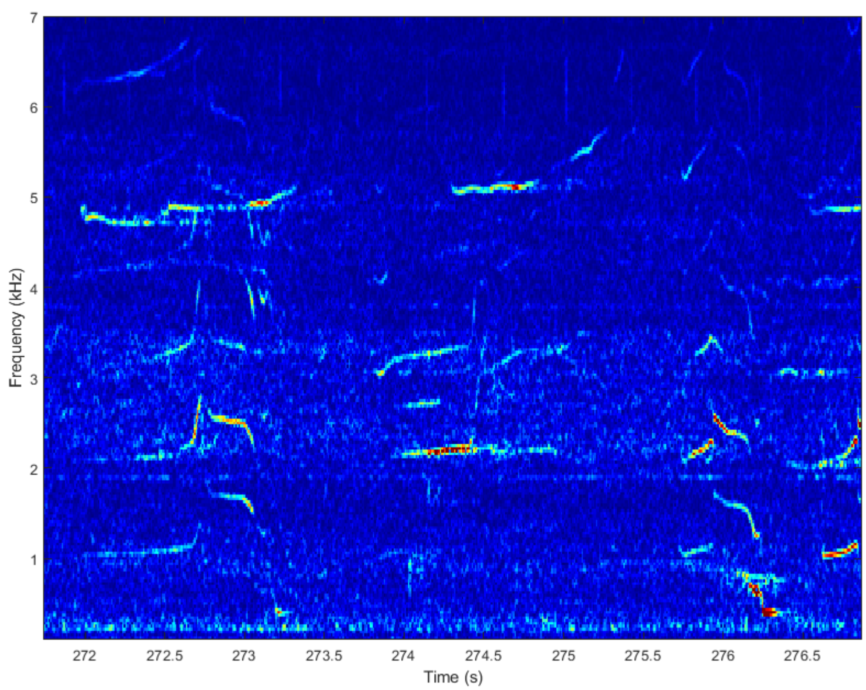


Figure B-6. 27 Oct 2021 (21:40 UTC): Spectrogram of SRKW killer whale vocalizations at ULS Frame A.

B.4.3. Humpback Whales

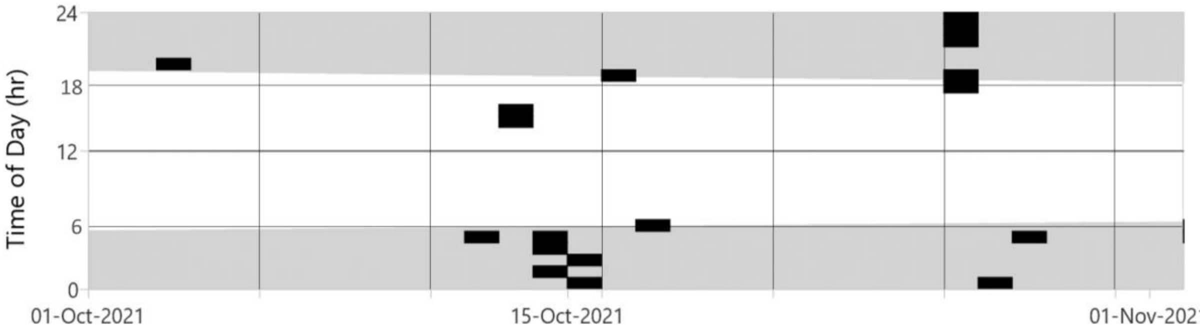


Figure B-7. 1 to 31 Oct 2021. Daily and hourly occurrence of humpback whale vocalizations at ULS Frame A. Black blocks indicate validated detections and grey areas indicate darkness period. See Table B-2 for additional validated humpback whale vocalizations not included in this plot.

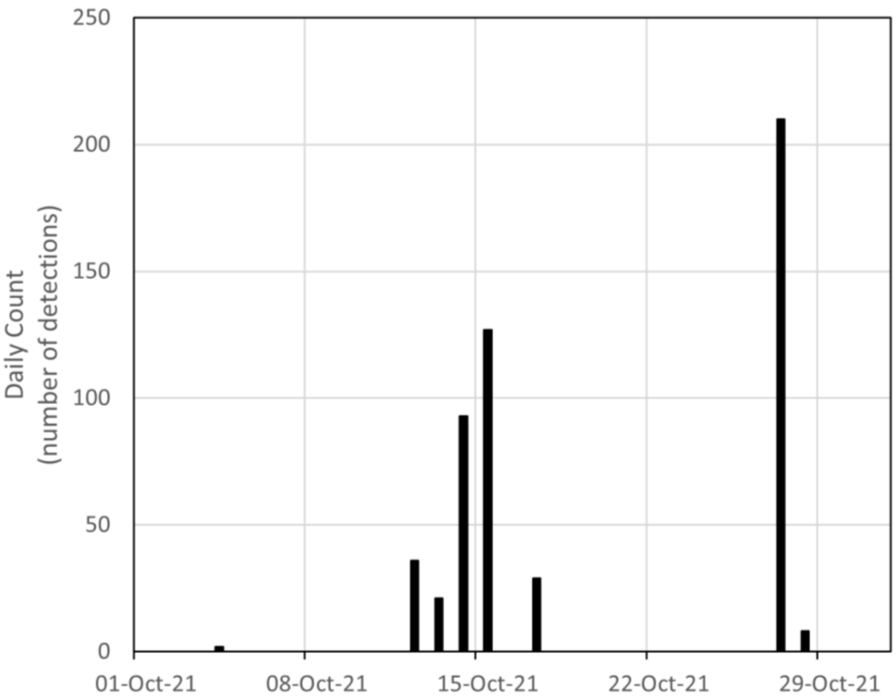


Figure B-8. 1 to 31 Oct 2021. Daily validated detection counts of humpback whale vocalizations at ULS Frame A.

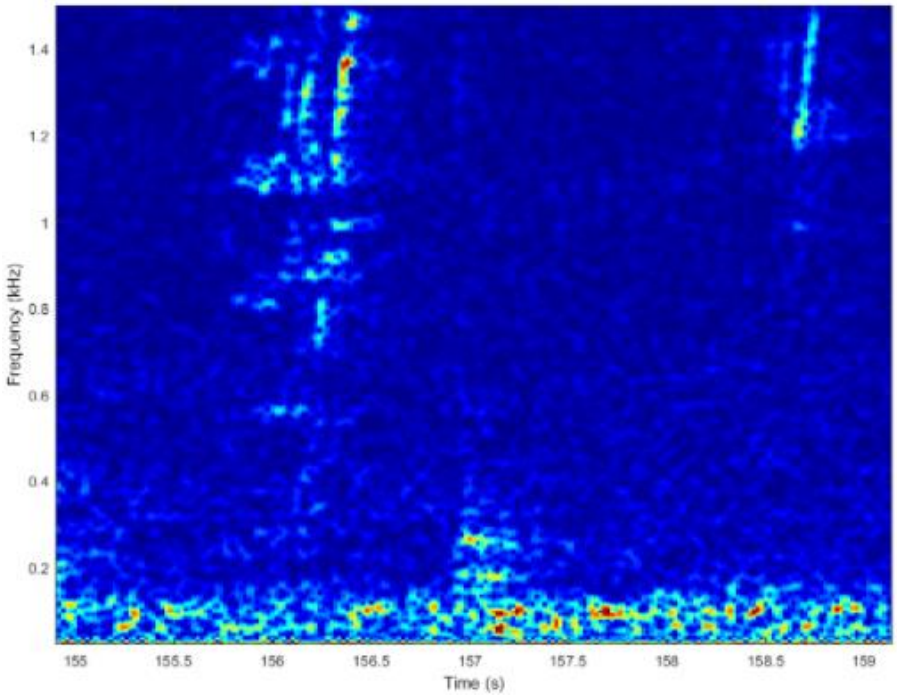


Figure B-9. 15 Oct 2021 (08:48): Spectrogram of humpback whale vocalization at ULS Frame A.

B.4.4. Pacific White-sided Dolphins

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

B.4.5. Fish

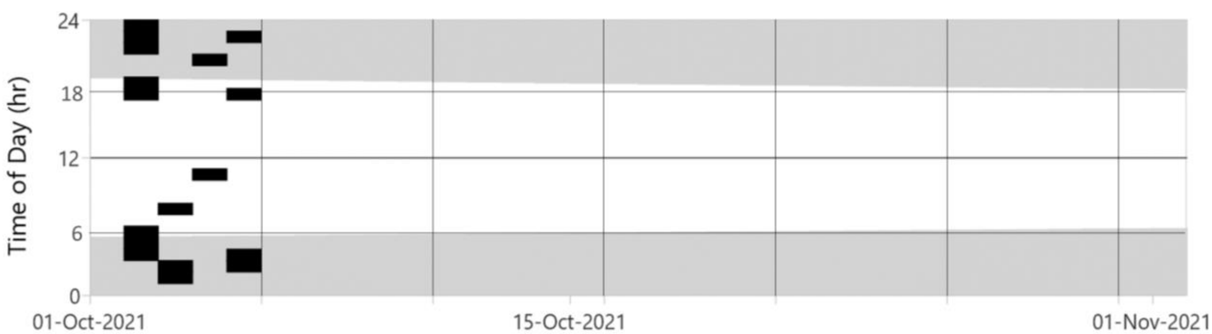


Figure B-10. 1 to 31 Oct 2021. Daily and hourly occurrence of fish sounds at ULS Frame A. Black blocks indicate validated detections and grey areas indicate darkness period.

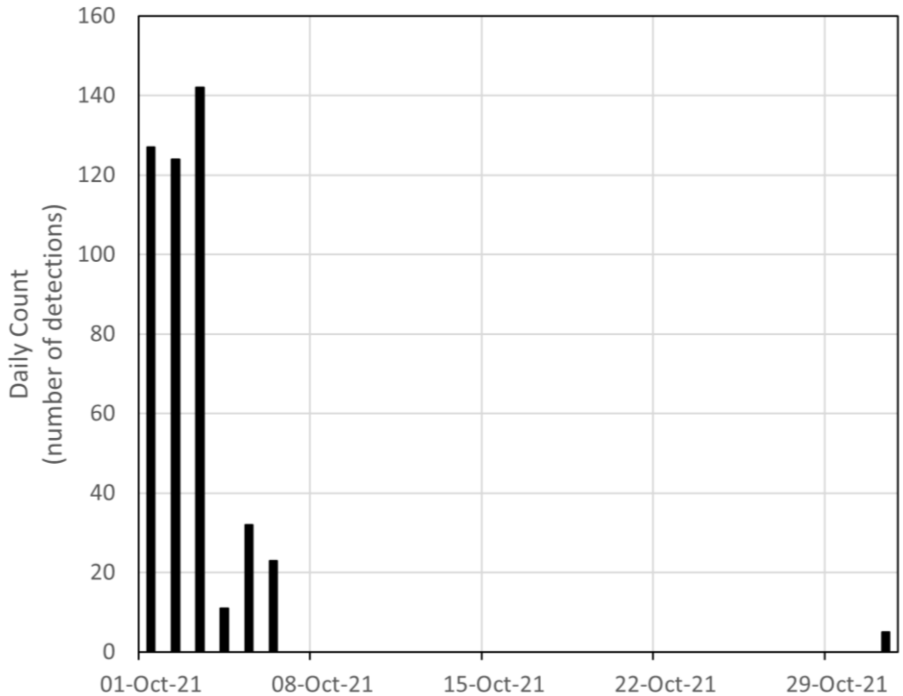


Figure B-11. 1 to 31 Oct 2021. Daily validated detection counts of fish sounds at ULS Frame A.

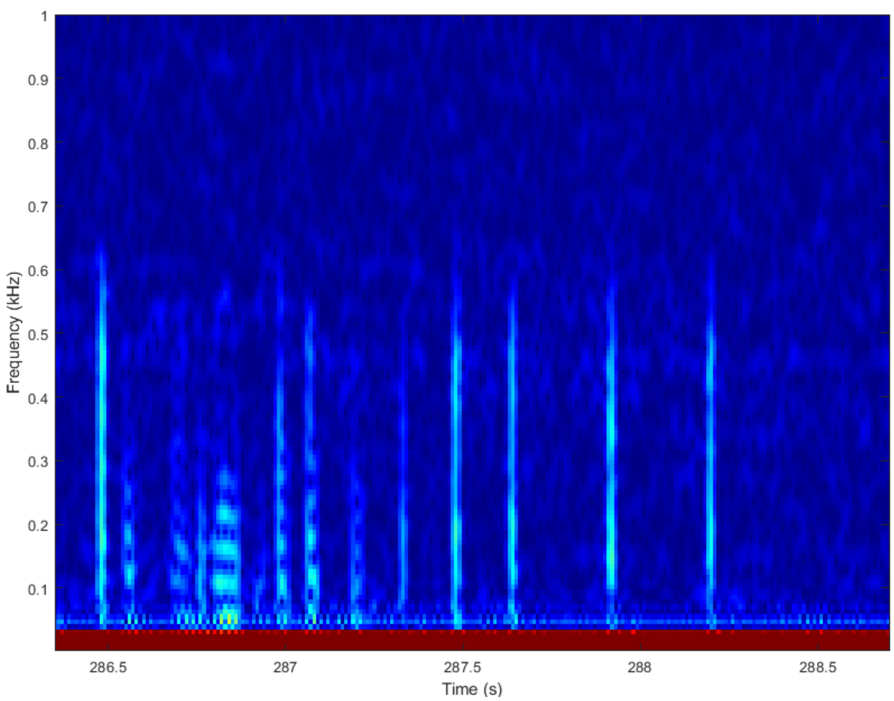


Figure B-12. 03 Oct 2021 (01:17): Spectrogram of fish sounds at ULS Frame A.

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 s fast Fourier transforms, shaded using a Hanning window.

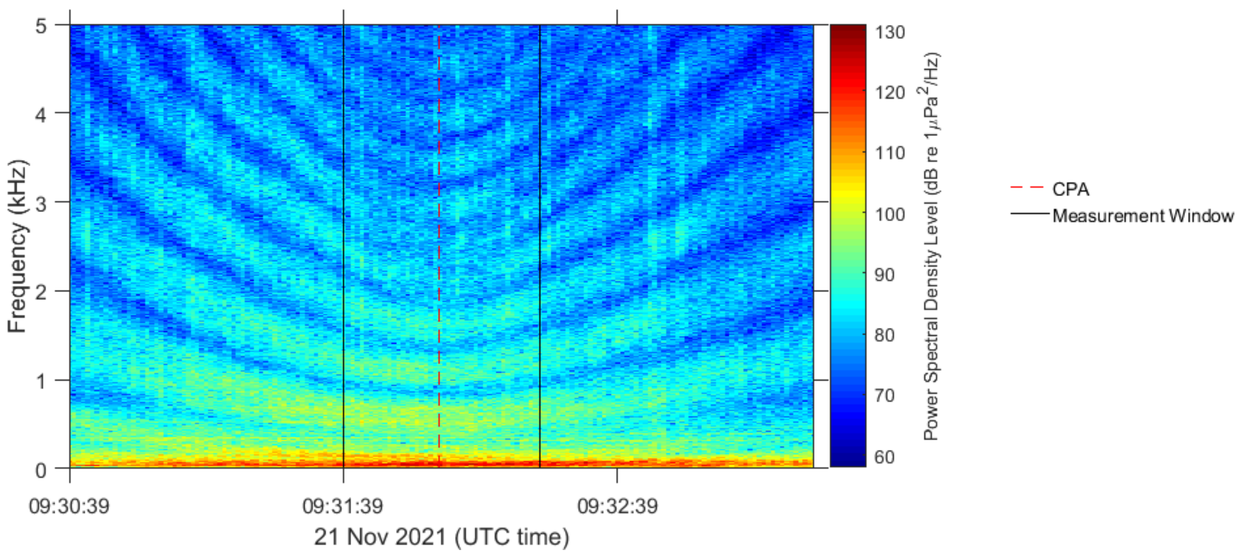


Figure C-1. Spectrogram of a single vessel measurement from ShipSound, showing the closest point of approach (CPA) time (dashed red line) and the measurement window (black box) used for calculating vessel source levels. The spectrogram shows the spectrum of the underwater sound pressure recorded on the ULS versus time and frequency. Although acoustic data were characterized up to 256 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 $20 \times \text{Log}_{10}(R)$ is applied to the spectra of each step separately. MSL is equal to the measured sound pressure level scaled according to a numerical acoustic propagation loss (PL) 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,

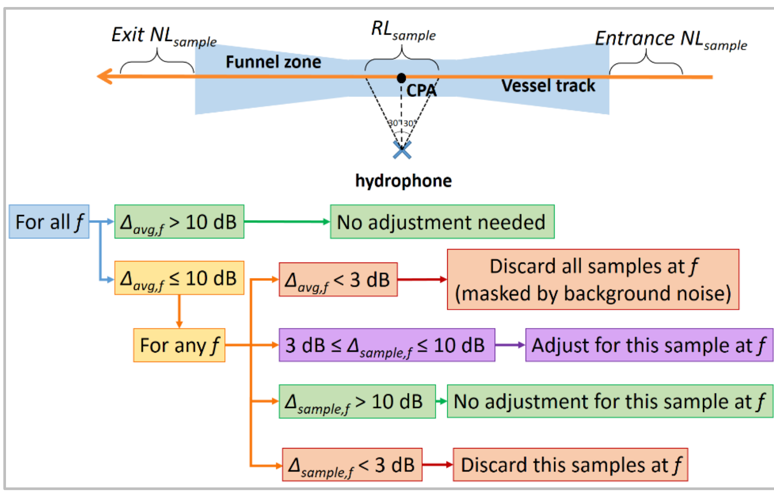
$$p = 0.3d/0.85,$$

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 Section 2.1.4). 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.



Definition:	
f	1/3-octave band frequency
$RL_{sample,f}$	1-s received level (along the track ±30° centered by CPA)
$NL_{sample,f}$	1-s noise level (1 min before enter and 1 min after exit the funnel zone)
$Rl_{avg,f}$	linear average over $RL_{sample,f}$
NL	background noise level (linear average over $NL_{sample,f}$)
$\Delta_{avg,f}$	$\Delta_{avg,f} = RL_{avg,f} - NL_f$
$\Delta_{sample,f}$	$\Delta_{sample,f} = RL_{sample,f} - NL_{sample,f}$

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 s 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 percentage.

Table D-1. Number of accepted vessel source level measurements during Year 3 (January to December 2021).

Vessel category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Bulker	500	479	484	422	442	307	180	193	223	349	312	289	**4180**
Container Ship	194	171	200	195	208	149	84	98	79	173	147	129	**1827**
Cruise	0	0	0	0	0	0	0	0	0	2	0	0	**2**
Dredger	0	2	0	2	0	0	0	0	0	0	0	0	**4**
Ferry	0	1	2	2	2	0	0	9	8	0	21	3	**48**
Fishing Vessel	5	2	0	8	15	11	3	2	9	5	3	0	**63**
Government/Research	3	4	8	14	1	9	1	2	1	6	4	10	**63**
Other	19	13	11	2	13	16	12	5	6	4	14	8	**123**
Passenger	0	0	0	0	0	0	0	5	1	3	0	0	**9**
Recreational	0	0	0	0	0	0	1	3	0	2	0	0	**6**
Tanker	38	35	41	44	43	31	26	13	12	35	31	27	**376**
Tug	40	59	70	70	65	58	41	41	34	59	45	35	**617**
Vehicle Carrier	73	59	58	56	51	56	29	22	29	37	57	39	**566**

Table D-2. Acceptance rate (percent) of vessel source level measurements during Year 3 (January to December 2021). 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	85	86	82	82	82	78	78	82	79	75	61	67	**78**
Container Ship	91	88	87	86	89	80	82	88	79	78	68	69	**82**
Cruise	NA	NA	NA	NA	NA	NA	NA	NA	NA	100	NA	NA	**100**
Dredger	NA	67	0	100	NA	NA	NA	NA	NA	NA	NA	NA	**57**
Ferry	NA	50	100	50	100	NA	NA	75	80	0	81	75	**76**
Fishing Vessel	63	100	NA	80	60	65	75	50	69	45	30	0	**58**
Government/Research	50	33	67	78	17	47	25	50	50	33	40	38	**46**
Other	63	57	85	33	93	100	100	63	100	31	34	67	**63**
Passenger	NA	NA	NA	NA	0	0	NA	63	25	60	NA	NA	**41**
Recreational	NA	NA	NA	NA	0	0	20	60	NA	100	NA	NA	**35**
Tanker	56	52	59	58	67	62	54	48	44	54	50	45	**55**
Tug	51	52	61	46	56	56	55	63	51	48	45	34	**51**
Vehicle Carrier	91	84	70	93	75	90	81	76	91	86	77	57	**80**