



Annual Report of Boundary Pass Acoustic Monitoring Year 2 (October 2019 to December 2020)

ECHO Program Summary

The Vancouver Fraser Port Authority (VFPA) Enhancing Cetacean Habitat and Observation (ECHO) Program manages 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. In May 2020, two permanently cabled underwater hydrophone arrays were deployed, in place of Autonomous Multichannel Acoustic Recorders (AMARs), and have been operating continuously since June 2020. Acoustic data from December, 2018 to October, 2019 were analyzed, and the obtained results were presented in the first annual Boundary Pass report. This second annual report contains analysis of data acquired between October, 2019 and December, 2020.

What questions was the study trying to answer?

The analysis of acoustic data is an ongoing effort that has been occurring after each AMAR servicing trip, and continuously since the ULS was installed. The acoustic analysis seeks to answer the following key questions:

- What are the long and short term trends in ambient noise levels measured at Boundary Pass?
- Which classes and quantities of commercial vessels have been measured at the ULS 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?

Two versions of JASCO's underwater acoustic recorders were used during the Year 2 reporting period. AMARs were used from October 2019 to June 2020 when two shore-cabled compact hydrophone arrays (ULS) were deployed and commissioned. The AMARs recorded at 128,000 samples per second with a recording bandwidth of 10 Hz to 64 kHz. Each channel of the ULS recorded at 512,000 samples per second (10 Hz to 256 kHz recording bandwidth) with 24-bit resolution.

Analysis of ambient noise 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. Additional data, including water current speed from an acoustic Doppler current profiler, 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. All detections were manually verified by an experienced analyst.

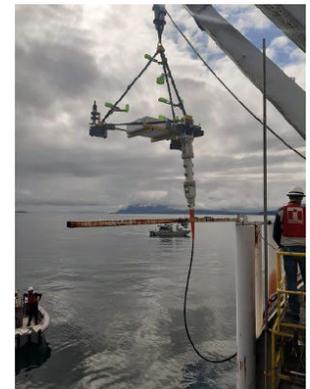


Figure 1: Underwater Listening Station (ULS) deployment in May 2020.

What were the key findings?

Ambient Noise

- Long-term trends in ambient sound levels were influenced by changes in mooring noise from the autonomous AMAR deployments to the cabled ULS, even after filtering out time periods when current speeds exceeded 0.5 m/s. Fast currents in Boundary Pass had the ability to cause elevated sound levels, in particular at lower frequencies.
- Across time periods with consistent equipment, sound levels appeared to increase during winter when wind speeds were higher.
- Ambient sound levels did not appear to be dependent on the day of the week, but were found to increase during daylight hours in the summer, potentially due to recreational vessel traffic.
- Vessel traffic presence, assessed using AIS records, led to substantial increases in ambient sound levels. Sound levels in all frequency bands increased by several decibels when AIS vessels were within 6 km of the hydrophones, with the exception of the highest frequency band recorded on the ULS (100–256 kHz).

Vessel Source Levels

- A total of 8069 vessel source level measurements were made using JASCO's ShipSound application during this study period. Of these, 5751 (approximately 71%) passed manual quality control checks. Considering all accepted vessel measurements, the maximum and minimum radiated noise levels (RNL) were 205.4 dB (container ship \geq 200 m) and 156.8 dB re 1 μ Pa m (naval vessel) respectively.
- Bulklers made up approximately 53% of all accepted measurements, while container ships accounted for approximately 24% of the measurements during the study period.

Marine Mammal Detections

- Over 27,800 marine fauna detections (fish sounds and cetacean vocalizations) were found in the acoustic data for the ~15 month study period.
- In total, killer whale vocalizations were detected on 83 days, and humpback whale vocalizations were detected on 148 days. No Pacific white-sided dolphins were detected and in total, fish sounds were detected on 29 days.

Conclusions and next steps

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

Ambient noise levels in Boundary Pass are affected by current-induced water flow and mooring noise. On a seasonal basis, sound levels increase in winter due to high wind speeds, while short term (hourly) differences in sound level occur during the summer, likely due to recreational traffic. Identifications of marine fauna at the Boundary Pass ULS have increased in Year 2, relative to Year 1 and now include the detection of fish sounds.

The Boundary Pass ULS operates on a continual basis, collecting ambient noise, vessel source levels, and marine mammal detection data. This is the second of several planned annual reports in support of the long-term Boundary Pass ULS monitoring program that is currently funded through March 2023.



Annual Report of Boundary Pass Acoustic Monitoring

Year 2, October 2019 to December 2020

Submitted to:

Krista Trounce
Vancouver Fraser Port Authority
Contract: 19-0280

Authors:

Dana A. Cusano
Graham A. Warner
Héloïse Frouin-Mouy
Zizheng Li

18 March 2021

P001507-001
Document 02323
Version 2.1

JASCO Applied Sciences (Canada) Ltd
Suite 2305, 4464 Markham St.
Victoria, BC V8Z 7X8 Canada
Tel: +1-250-483-3300
Fax: +1-250-483-3301
www.jasco.com



Suggested citation:

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

Disclaimer:

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

Contents

EXECUTIVE SUMMARY 1

1. INTRODUCTION 3

2. METHODS..... 5

 2.1. Data Acquisition 5

 2.1.1. Acoustic Measurements..... 5

 2.1.2. Water Current Measurements..... 9

 2.1.3. Vessel Traffic Logging 10

 2.1.4. Wind Speed Measurements..... 10

 2.2. Data Analysis 10

 2.2.1. Ambient Noise Analysis 10

 2.2.2. Marine Fauna Detections 11

 2.2.3. Vessel Source Levels 11

3. RESULTS..... 12

 3.1. Ambient Noise Results..... 12

 3.1.1. Comparison of Sound Levels Between Recorders 12

 3.1.2. Temporal Variability of Sound Levels 16

 3.1.3. Influence of Water Currents 20

 3.1.4. Influence of Wind Speed 27

 3.1.5. Influence of Vessel Traffic..... 30

 3.2. Marine Fauna Detection Results..... 32

 3.3. Vessel Source Level Measurement Summary 37

4. DISCUSSION AND CONCLUSION 43

5. ACKNOWLEDGEMENTS..... 45

GLOSSARY 46

LITERATURE CITED 50

APPENDIX A. EXAMPLE AMBIENT NOISE REPORT FOR ONE MONTH A-1

APPENDIX B. EXAMPLE MARINE MAMMAL DETECTION REPORT FOR ONE MONTH B-1

APPENDIX C. NEAR-SURFACE WATER CURRENTS C-1

APPENDIX D. ADDITIONAL AMBIENT NOISE RESULTS D-3

APPENDIX E. SUMMARY OF VESSEL SOURCE LEVEL METHODS E-6

APPENDIX F. SUMMARY OF VESSEL SOURCE LEVEL MEASUREMENTS F-1

Figures

Figure 1. Map showing the locations of the data acquisition equipment.	4
Figure 2. Boundary Pass mooring for Autonomous Multichannel Acoustic Recorder Generation 3 (AMAR G3)	6
Figure 3. Boundary Pass mooring for Autonomous Multichannel Acoustic Recorder Generation 4 (AMAR G4)	6
Figure 4. Underwater Listening Station (ULS) Frame B connected to cable termination and being deployed on 18 May 2020.....	7
Figure 5. Boundary Pass Underwater Listening Station (ULS) mooring	8
Figure 6. Acoustic Doppler Current Profiler (ADCP) mooring used for the Autonomous Multichannel Acoustic Recorder (AMAR) deployments	9
Figure 7. AMAR 629 waveform and spectrogram showing intermittent mooring noise.....	12
Figure 8. ULS A1 waveform and spectrogram for the same time period as AMAR 629 recordings contained mooring noise.....	13
Figure 9. ULS B2 waveform and spectrogram for the same time period as AMAR 629 recordings contained mooring noise.....	13
Figure 10. Decade band sound level cumulative density functions (CDF), during Automatic Identification System (AIS) vessel absence, measured by simultaneously recording instruments.....	15
Figure 11. Decade band sound level cumulative density functions (CDF) when Automatic Identification System (AIS)-broadcasting vessels were within 6 km of the hydrophones, measured by simultaneously recording instruments.....	16
Figure 12. Cumulative distribution functions (CDFs) comparison for increasing (left) broadband and (right) 4th “decade” bandwidths using Underwater Listening Station (ULS) data.	17
Figure 13. Monthly sound level statistics as functions of time in each indicated frequency band before filtering out periods with current speeds greater than 0.5 m/s.	18
Figure 14. Monthly sound level statistics as functions of time in each indicated frequency band after filtering out periods with current speeds greater than 0.5 m/s.....	19
Figure 15. Weekly rhythm plot showing the median sound pressure level (SPL) during July 2020 measured by the Underwater Listening Station (ULS).	20
Figure 16. Daily rhythm plot showing median sound pressure level (SPL) during July 2020 measured by the Underwater Listening Station (ULS).	20
Figure 17. Probability density of near-seafloor current speed magnitude from all available Acoustic Doppler Current Profiler (ADCP) measurements	21
Figure 18. Comparison of near-seafloor current speed magnitude during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs).....	22
Figure 19. Comparison of near-seafloor current speed broken down by directional component during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs).	22
Figure 20. AMAR G3 (2019 Oct 15 to 2020 Jan 31): Two-dimensional (2-D) normalized histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler- (ADCP)-measured seafloor current speed.....	24
Figure 21. AMAR G4 (2020 Jan 31 to 2020 Jun 09): Two-dimensional (2-D) normalized histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler- (ADCP)-measured seafloor current speed.....	25
Figure 22. Cabled ULS (2020 Jun 09 to 2020 Dec 31): Two-dimensional (2-D) normalized histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler- (ADCP)-measured seafloor current speed.....	26

Figure 23. Histogram of wind speed during the analysis period. 27

Figure 24. Box-and-whisker plot of wind speed as a function of month during the analysis period 27

Figure 25. AMARs G3 and G4: Two-dimensional (2-D) histograms of decade-band sound pressure level (SPL) versus wind speed 28

Figure 26. Underwater Listening Station (ULS): Two-dimensional (2-D) histograms of decade-band sound pressure level (SPL) versus wind speed..... 29

Figure 27. AMARs G3 and G4: Cumulative distribution functions (CDFs) for periods with and without Automatic Identification System (AIS) vessel traffic within 6 km of the hydrophone in broadband and decade bands 30

Figure 28. Underwater Listening Station (ULS): Cumulative distribution functions (CDFs) for periods with and without Automatic Identification System (AIS) vessel traffic within 6 km of the hydrophone in broadband and decade bands 31

Figure 29. Proportion of detections by marine mammal species for Year 2 32

Figure 30. (Top) Hourly and (bottom) daily detection counts (PST) of killer whale vocalizations for Year 2..... 33

Figure 31. (Top) Hourly and (bottom) daily detection counts (PST) of humpback whale vocalizations for Year 2 33

Figure 32. (Top) Hourly and (bottom) daily detection counts (PST) of fish sounds for Year 2..... 34

Figure 33. Spectrogram of vocalizations from (top) killer whales on 21 Feb 2020 (PST), (middle) humpback whales on 3 Dec 2020 (PST), and (bottom) fish sounds on 4 Aug 2020 (PDT). 35

Figure 34. Number of vessel source level measurements, by vessel category, that passed the manual quality control checks for each calendar month..... 37

Figure 35. Box-and-whisker plots of monopole source levels (MSL) for vessel categories with more than 50 accepted measurements during the study period..... 39

Figure 36. Cumulative distribution functions (CDFs) for distance at the closest point of approach (CPA) for vessels which were accepted (passed manual quality control) and rejected (did not pass quality control checks)..... 40

Figure 37. Acceptance and rejection rates of vessels by (horizontal) closest point of approach (CPA) distance..... 40

Figure 38. Histogram of closest point of approach (CPA) distances in the cross-track direction..... 41

Figure 39. Oscillating interference patterns in a spectrogram for a tug passing AMAR 629 in Boundary Pass..... 42

Figure 40. Diagram showing how quantiles are displayed on a box-and-whisker plot..... 46

Figure A-1. Broadband, decade band sound pressure level (SPL) versus time and spectrogram through the analysis period (1-hour resolution).A-3

Figure A-2. The top panel shows percentiles and mean 1/3-octave-band sound pressure level (SPL) (1 minute) over the analysis period. The bottom panel shows percentiles and mean power spectral density levels over the same time period.A-4

Figure A-3. The median 1-minute sound pressure level (SPL) versus time of day (10-minute resolution) over the analysis period.A-6

Figure A-4. The median 1-minute sound pressure level (SPL) versus day of week (30-minute resolution) over the analysis period.A-6

Figure A-5. The broadband and decade-band sound pressure level (1 minute) statistics over the analysis period.A-7

Figure B-1. The process for automatic detections of killer whales, humpback whales, Pacific white-side dolphins, and fish sounds.....B-2

Figure B-2. Key processing steps of the detector.B-3

Figure B-3. Relative vocalization detections from 1 Jul to 31 Jul 2020.B-4

Figure B-4. Hourly and daily detection counts (PDT) of killer whale vocalizations at ULS A1 from 1 Jul to 31 Jul 2020.....B-5

Figure B-5. Spectrogram of killer whale vocalizations at ULS A1 on 24 Jul 2020.....B-5

Figure B-6. Hourly and daily detection counts (PDT) of humpback whale vocalizations at ULS A1 from 1 Jul to 31 Jul 2020.....B-6

Figure B-7. Spectrogram of humpback whale vocalizations at ULS A1 on 28 Jul 2020B-6

Figure B-8. Hourly and daily detection counts (PDT) of fish sounds at ULS A1 from 1 Jul to 31 Jul 2020.B-7

Figure B-9. Spectrogram of fish sounds at ULS A1 on 21 Jul 2020B-7

Figure C-1. Probability density of near-surface (~20 m depth) current speed magnitude from all available Acoustic Doppler Current Profiler (ADCP) measurements..... C-1

Figure C-2. Comparison of near-surface (~20 m depth) current speed magnitude during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs)..... C-2

Figure C-3. Comparison of near-surface (~20 m depth) current speed broken down by directional component during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs). C-2

Figure D-1. AMAR G3 (2019 Oct 15 to 2020 Jan 31): Two-dimensional (2-D) histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler (ADCP)-measured seafloor current speed. D-3

Figure D-2. AMAR G4 (2020 Jan 31 to 2020 Jun 09): Two-dimensional (2-D) histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler (ADCP)-measured seafloor current speed. D-4

Figure D-3. ULS (2020 Jun 09 to 2020 Dec 31): Two-dimensional (2-D) histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler (ADCP)-measured seafloor current speed. D-5

Figure E-1. Spectrogram of a single vessel measurement from ShipSound.....E-6

Figure E-2. Background noise comparison and adjustment process as part of the first (automated) phase of quality control.E-7

Tables

Table 1. Autonomous Multichannel Acoustic Recorder (AMAR) and Underwater Listening Station (ULS) recorder locations and periods 5

Table 2. Acoustic Doppler Current Profiler (ADCP) recorder locations and recording periods. 10

Table 3. Increases in sound levels due to Automatic Identification System (AIS) vessel presence within 6 km of the hydrophone for different frequency bands..... 31

Table 4. Number of marine mammal detections and days with detections by calendar month and species for Year 2 36

Table 5. Summary of broadband radiated noise levels (RNL) by vessel category. 38

Table 6. Potential reasons for rejection of source level measurements and the frequency with which they occurred. 42

Table A-1. The analysis was conducted over calendar month periods from July to September 2020.A-1

Table A-2. ULS locations and periods used for analysis.A-1

Table A-3. Broadband and 1/3-octave-band sound levels (dB re 1 µPa) for the 95th, 75th, 50th, 25th, and 5th percentiles.....A-5

Table A-4. Sound pressure level (1 minute) statistics (dB re 1 µPa) used to generate the sound pressure level (SPL) box plot in Appendix A.4.6.A-7

Table B-1. The ULS deployment coordinates and recording start/end times used for analysisB-1
Table F-1. Number of accepted vessel source level measurements during Year 2F-1
Table F-2. Acceptance rate (percent) of vessel source level measurements during Year 2.....F-2

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 and provides the results of the analysis.

JASCO is also responsible for operating the ULS and acquiring the acoustic data under a separate agreement with Transport Canada. The data acquisition started 12 Dec 2018 and will continue to at least 31 Mar 2023. For the first 18 months of the program, acoustic data were acquired using autonomous multichannel acoustic recorders (AMAR). In May 2020, two permanently cabled underwater acoustic hydrophone arrays were deployed, and these have been operating continuously since June 2020. Additional metadata are being 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 public weather stations.

Acoustic data from 12 Dec 2018 to 15 Oct 2019 were analyzed, and the obtained results were presented in the first annual report (Warner and Frouin-Mouy 2019). This second annual report contains analysis of data acquired between 15 Oct 2019 and 31 Dec 2020. 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, and investigates the effect of water currents, wind speed, and vessel traffic on sound levels, as well as the temporal variability of sound level statistics and the acoustic performance of the moorings. This is the second of several planned annual reports in support of the long-term Boundary Pass ULS monitoring program that is currently funded through March 2023.

Water currents in Boundary Pass were often fast, reaching speeds up to ~2 m/s or ~4 knots. Comparison of current measurements from the autonomous ADCP and the ULS ADCP showed that near-seafloor (and near-surface) currents were a bit slower at the hydrophones than at the autonomous ADCP station that was approximately 1.5 km southwest of the ULS location. The currents were found to create flow and mooring noise in the acoustic recordings in all decade bands except for the 1–10 kHz band, even though all hydrophones were fitted with special, fabric, water-flow shields. The level and nature of the flow and mooring noise was highly dependent on the mooring design; the autonomous moorings were much more susceptible to flow and mooring noise than the rigid tetrahedral frames of the cabled arrays. The AMAR mooring used between January and June 2020 had highest levels of flow and mooring noise. The differences were analyzed by comparing long-term trends in ambient noise levels and sound levels during periods when multiple instruments recorded simultaneously.

During relatively quiet times (when vessels were absent), sound levels between recorders differed at frequencies at or below 160 Hz. During louder times (when vessels were present within 6 km of the hydrophone), sound levels between recorders agreed well at frequencies above 50 Hz. There was generally good agreement between data from each of the two ULS frames. Differences at higher frequencies were largely due to differences between the model-specific hydrophone noise floor characteristics for time periods when ambient noise was very low.

During quiet times, wind speed was found to increase sound levels at all frequencies below 100 kHz. This effect was clearest on the cabled system recordings, likely due to their lower susceptibility to flow noise than the autonomous recorders, and the trends closely matched those from the literature.

Long-term trends in ambient sound levels were influenced largely by changes in mooring noise, even after filtering out time periods when current speeds exceeded 0.5 m/s. Across time periods with consistent equipment, sound levels appeared to increase during winter when wind speeds were higher. A small increase in high-level percentiles was observed in November and December 2020, the start of which coincided with the end of the ECHO program's 2020 voluntary slowdown in Haro Strait and Boundary Pass. Sound levels did not appear to be dependent on the day of the week but were found to increase during daylight hours in summer.

Vessel traffic was found to substantially increase sound levels over a wide frequency range. Median broadband sound levels increased by 15–18 dB when AIS-tracked vessels were within 6 km of the hydrophone. The increases were largest in the 10–100 Hz, 100–1000 Hz, and 1–10 kHz bands. The higher frequency 10–64 and 10–100 kHz bands also increased substantially for the 95th percentile (L_5 exceedance percentile). At higher frequencies (100–265 kHz), sound attenuates quickly with range and there was a relatively small increase in sound levels due to vessel traffic than for lower frequency bands.

Over 27,800 manually validated marine fauna detections were found in the acoustic data during the 14.5 month data collection period for this report. Most (55%) of these detections were of humpback whale sounds, which were detected in most months. Killer whales were detected in all months, and for the first time in this study, fish sounds were detected (in the ULS recordings). No Pacific white-sided dolphin vocalizations were detected. There were substantially more marine-fauna detections for this reporting period than in the first annual reporting period, likely because better flow and mooring noise performance of the cabled ULS allowed for the detection of quieter marine fauna sounds.

Over 8000 vessel source level measurements were acquired during this study period, and these were analyzed with ShipSound, an application within JASCO's PortListen software. A large fraction of these measurements were of bulker (53%) and container ships (24%). Container ships had the highest average radiated noise levels (RNL), followed by vehicle carriers, bulkers, tankers, and large tugs. The quietest vessel type was naval vessels. The hydrophone location was suitable for processing source level measurements for vessels travelling in the inbound and outbound international shipping lanes. The fraction of measurements passing the manual quality control checks was higher for vessels that passed closer to the hydrophones, and an analysis of the vessel tracks suggested that the ULS location was optimal for measuring the largest number of vessels transiting through Boundary Pass.

1. Introduction

Underwater acoustic data have been collected continuously in Boundary Pass since December 2018 as part of a long-term measurement program for 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 a cabled real-time Underwater Listening Station (ULS) was deployed in May 2020. Water current speed, wind speed, and vessel traffic data have also been collected as part of this measurement program to assist with acoustic data interpretation. Figure 1 shows a map of the instrument locations.

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 after each AMAR servicing trip, and every three months since the ULS was installed. The ongoing analysis includes:

- Ambient noise statistics,
- Detection and manual validation of marine mammal vocalizations, and
- ANSI (12.64-2009 (R2014)) vessel source levels (including radiated noise levels per the standard and monopole source levels using a similar approach).

Acoustic data from December 2018 to December 2020, corresponding to the five autonomous recorder deployments and approximately six months of continuous ULS recordings, have been analyzed and reported for ambient noise statistics (Grooms and Warner 2019a, 2019b, Grooms and Warner 2020, Warner 2020a, 2020b, 2021, Warner and Dofher 2021) and marine mammal vocalizations (Frouin-Mouy 2019a, 2019b, 2020a, 2020b, 2020c, 2020d). 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 2019) presented analysis of measurements from December 2018 to October 2019. The current report contains a comprehensive analysis of the study results since the first report, covering the period October 2019 to December 2020, for this second annual report.

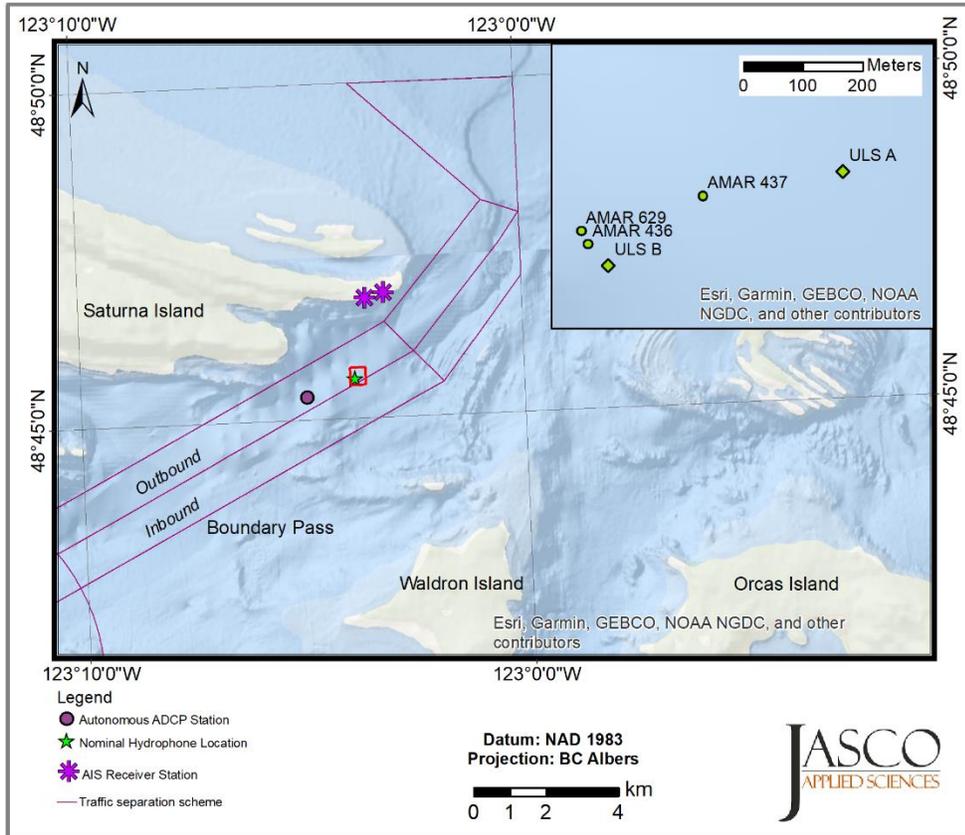


Figure 1. Map showing the locations of the data acquisition equipment. The Autonomous Multichannel Acoustic Recorder (AMAR) and underwater listening station (ULS) deployment locations of each recorder deployed during the analysis period are shown on the inset map and are labelled with the AMAR's serial number or ULS frame identifier. The cabled Acoustic Doppler Current Profiler (ADCP) is mounted on Frame A. The vessel lane separation paths are shown as purple lines.

2. Methods

2.1. Data Acquisition

2.1.1. Acoustic Measurements

Two versions of JASCO's underwater acoustic recorders were used during the Year 2 reporting period. Autonomous Multichannel Acoustic Recorders Generation 3 (AMAR G3s) were used from October 2019 to January 2020, and AMAR G4s were used from then to June 2020, when two shore-cabled compact tetrahedral hydrophone arrays were deployed and commissioned. All recorders were deployed on the seabed between the inbound and outbound international shipping lanes in Boundary Pass. Table 1 lists the deployment locations and recording periods of each recorder. The deployment locations are also shown in Figure 1. AMAR 436 data were used during time periods when AMAR 437 also recorded, because AMAR 436 data appeared less susceptible to flow and mooring noise. ULS A1 data were used during time periods when AMAR 629 also recorded, because the ULS data appeared less susceptible to flow and mooring noise. ULS A1 data were used during times when either ULS B1 or ULS B2 also recorded data because the hydrophone model was consistent over a longer period and acoustic doppler current profiler sounds could be easily filtered out of the data.

Table 1. Autonomous Multichannel Acoustic Recorder (AMAR) and Underwater Listening Station (ULS) recorder locations and periods. The recorder locations are also shown in Figure 1.

Serial number	Hydrophone	Latitude	Longitude	Water depth (m)	Start	End
AMAR 436 (G3)	GTI M36-V35-100	48° 45.57965' N	123° 3.89494' W	189	2019 Oct 15 18:49	2019 Dec 11 13:10
AMAR 437 (G3)	GTI M36-V35-100	48° 45.62342' N	123° 3.79050' W	192	2019 Dec 06 00:00	2020 Jan 31 18:12
AMAR 629 (G4)	GTI M36-V35-100	48° 45.59152' N	123° 3.90083' W	193	2020 Jan 31 19:20	2020 Jun 14 04:57
ULS A1	GTI M36-V35-100	48° 45.64598' N	123° 3.66336' W	193	2020 Jun 09 17:07	2020 Dec 31 23:59
ULS B2	HTI 99-HF	48° 45.56056' N	123° 3.87671' W	195	2020 Jun 08 16:21	2020 Sep 14 08:43
ULS B1	GTI M36-V35-100	48° 45.56056' N	123° 3.87671' W	195	2020 Sep 14 11:57	2020 Dec 31 23:59

The AMAR moorings 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. Because the pressure housings of AMARs G3 and G4 had different diameters, they could not use the same flotation and mooring design. Figure 2 shows the G3 mooring design. Figure 3 shows the G4 mooring design.

Each AMAR was equipped with an M36-V35 omnidirectional hydrophone (GeoSpectrum Technologies Inc., -165 ± 3 dB re 1 V/ μ Pa nominal sensitivity). The AMARs recorded at 128,000 samples per second (10 Hz to 64 kHz recording bandwidth) with 24-bit resolution and 6 dB gain. The hydrophones were protected by a hydrophone cage, which was covered with a shroud to minimize noise artifacts from water flow.

Immediately upon deploying each AMAR mooring, a GPS measurement was taken to record the tentative AMAR deployment position. Water currents, however, caused the moorings to drift horizontally as they descended 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.

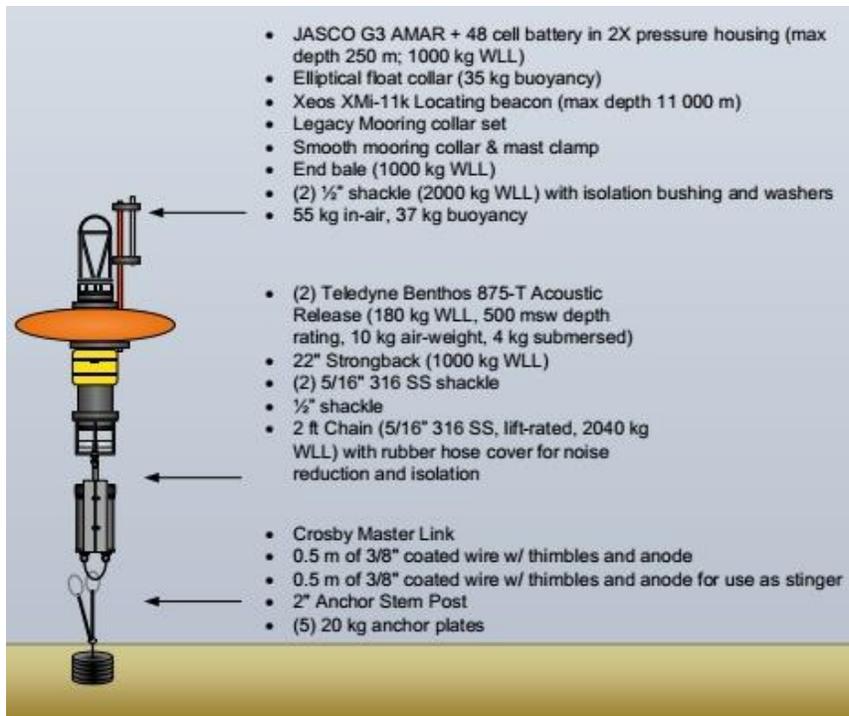


Figure 2. Boundary Pass mooring for Autonomous Multichannel Acoustic Recorder Generation 3 (AMAR G3) (JASCO design 202). The hydrophone was located a few metres above the seabed, inside the protective cage at the top of the AMAR.

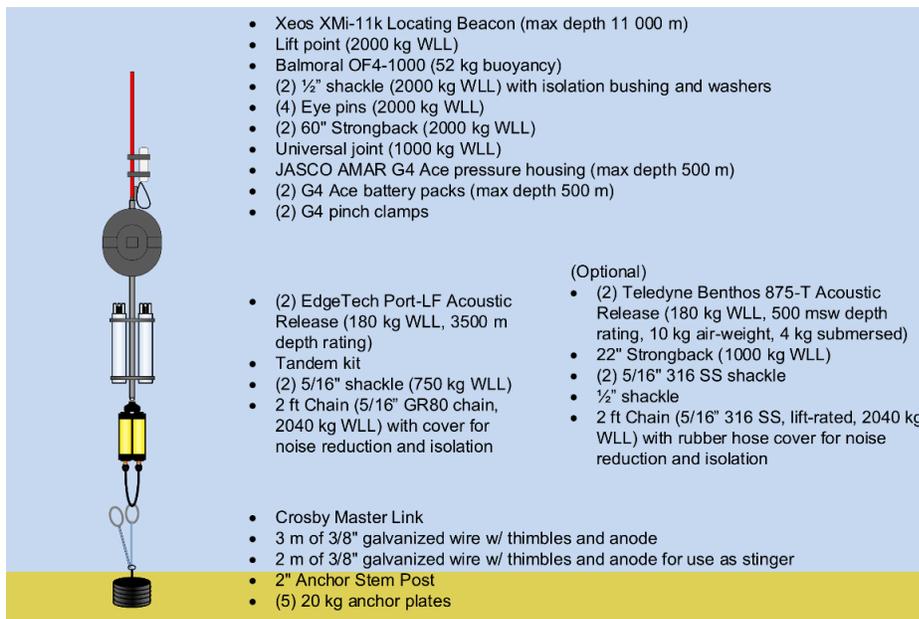


Figure 3. Boundary Pass mooring for Autonomous Multichannel Acoustic Recorder Generation 4 (AMAR G4) (JASCO design 234). The hydrophone was located a few metres above the seabed at the top of the AMAR.

In May 2020, two cabled ULS were installed from a barge using a remotely operated vehicle (ROV) at the same nominal location as the AMARs in Boundary Pass (Figure 4). Several days of testing were conducted for the ULS equipment, and the ULS was officially commissioned on 10 Jun 2020. Figure 5 shows the mooring design for the ULS frames.

Each ULS frame (denoted A and B) supports four GTI M35-V35-100 hydrophones and four HTI 99-HF hydrophones. Only one set of hydrophones from each frame recorded at any given time. The hydrophones were mounted on the tetrahedral frame of each ULS, 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. Each channel of the ULSs recorded at 512,000 samples per second (10 Hz to 256 kHz recording bandwidth) with 24-bit resolution. Unless otherwise noted, ULS sound levels in this report are from channel 1 of the GTI Frame A hydrophone (denoted A1).



Figure 4. Underwater Listening Station (ULS) Frame B connected to cable termination and being deployed on 18 May 2020.

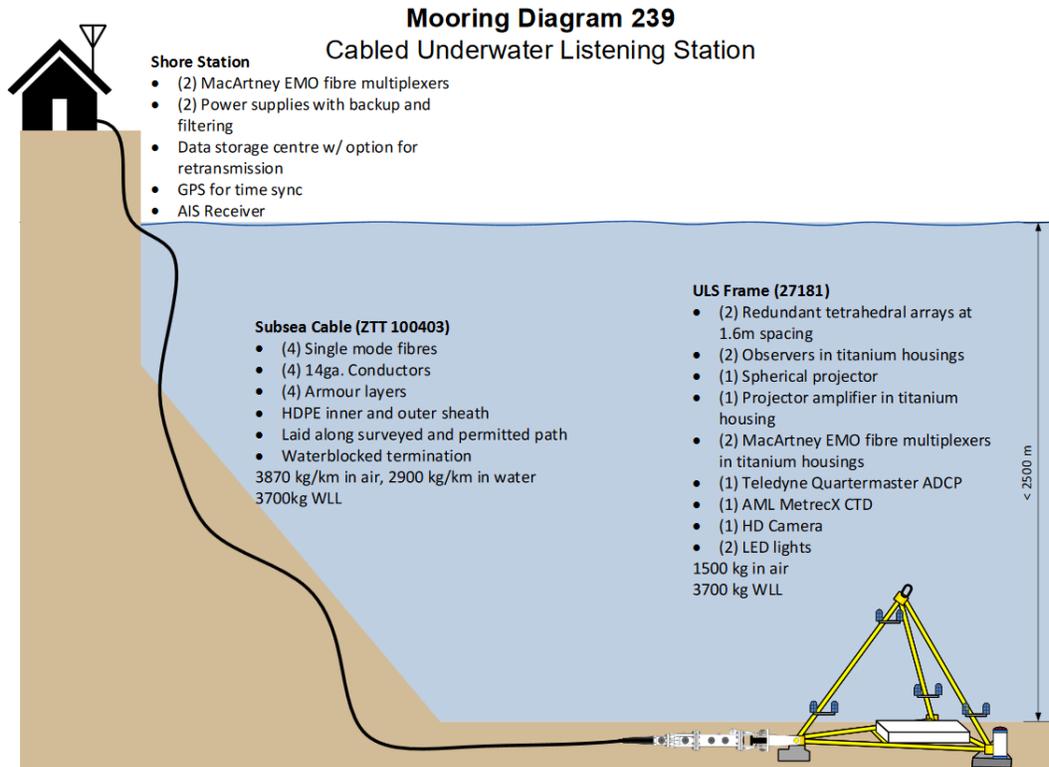


Figure 5. Boundary Pass Underwater Listening Station (ULS) mooring (JASCO design 239). The Acoustic Doppler Current Profiler (ADCP), which was only present on ULS A, was mounted at the lower corner of the tetrahedral frame (depicted here as the white cylinder at the bottom right).

The laboratory calibrations of the AMAR and ULS hydrophones at a single frequency were verified to within 0.5 dB before deployment, and the AMAR hydrophones after retrieval 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 pressure. 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 Acoustic Doppler Current Profilers (ADCP). For the AMAR deployments, water current speed and direction, as functions of depth, were recorded with an autonomous Workhorse Sentinel 300 kHz ADCP (Teledyne), deployed on sub-sea moorings between 5 and 10 m above the seafloor and approximately 1.5 km southwest of the AMARs (Figure 6). This location was chosen because it was far enough from the AMARs that the acoustic energy from the ADCP would not contaminate the AMAR recordings, and because the water depth was shallow enough (approximately 100 m) that the upward-facing 300 kHz ADCP could measure near-surface currents. The ADCP moorings incorporated back-up retrieval measures, including tandem acoustic releases and satellite beacons, to reduce the likelihood of equipment loss (Figure 6).

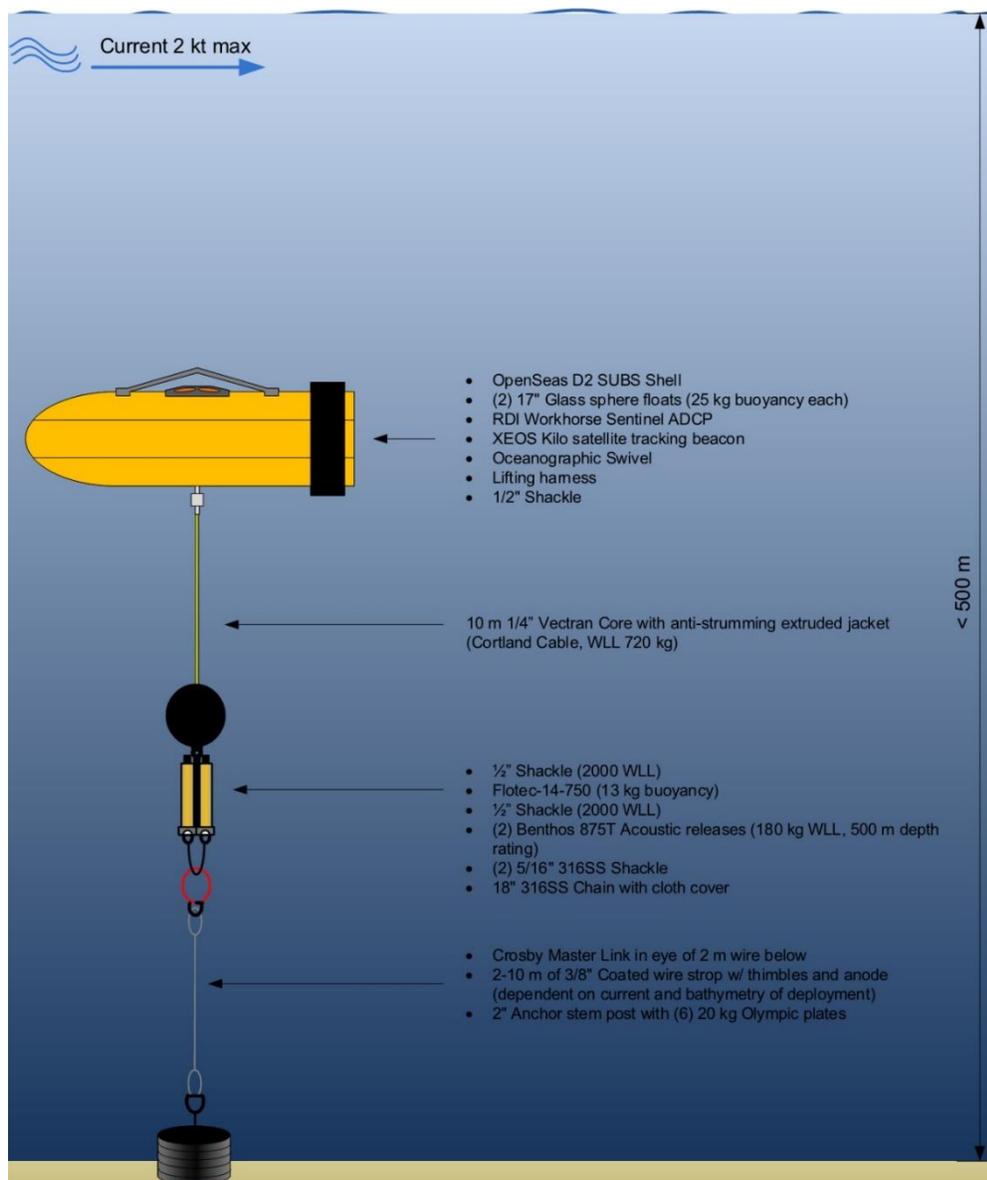


Figure 6. Acoustic Doppler Current Profiler (ADCP) mooring used for the Autonomous Multichannel Acoustic Recorder (AMAR) deployments (JASCO design 139). The ADCP was deployed between 5 and 10 m above the seafloor.

For the ULS deployment, a Quartermaster ADCP (Teledyne) was mounted on Frame A and integrated into the power supply and data cable of the ULS (Figure 5). The ADCP was oriented vertically to measure water current profiles. The Quartermaster operates at a lower frequency (150 kHz) than the Sentinel and is therefore able to measure water currents over a longer depth range. The ADCP was deployed approximately 1 m above the seafloor and can measure currents near the seabed (~190 m depth) to near the surface.

Table 2. Acoustic Doppler Current Profiler (ADCP) recorder locations and recording periods. Note that ADCP 24647 was mounted to ULS Frame A (Table 1), whereas the other ADCPs were deployed ~1.5 km away from the hydrophones at the Autonomous ADCP Station (Figure 1).

ADCP serial number	Centre frequency (kHz)	Latitude	Longitude	Water depth (m)	Start	End
11402	300	48° 45.36200' N	123° 4.89200' W	100	2019 Oct 15 18:22	2020 Jan 31 16:42
24715	300	48° 45.39430' N	123° 4.79087' W	108	2020 Jan 30 19:26	2020 Jun 16 15:06
24647	150	48° 45.64598' N	123° 3.66336' W	193	2020 Jun 09 19:43	2020 Dec 31 23:53

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 is 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 from Environment Canada were downloaded to investigate effects of wind speed on underwater sound levels. High winds can also lead to frictional drag on vessels, and they affect ocean surface conditions, both potentially influencing vessel noise emissions. 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 location. Wind speed measurements from the Kelp Reefs weather station, located in Haro Strait approximately 27 km from the AMARs, were used for times when the Saturna Island CS weather station data were unavailable. Weather data from the Eastsound Orcas Island Airport were used when weather data from the Saturna Island CS and Kelp Reefs stations were unavailable.

2.2. Data Analysis

2.2.1. Ambient Noise Analysis

Analysis of ambient noise was conducted using JASCO's PAMlab acoustic analysis software suite. The initial ambient noise reports presented spectrograms, decade-band and decidecade- (or 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 2020, Warner 2020a, 2020b, 2021, Warner and Dofher 2021). This initial analysis was conducted for all recorded acoustic data and presented in monthly summaries. Before 2020, analysis was performed over synodic lunar month periods (29 days, 12 hours, 44 minutes). Starting January 2020, the analysis schedule was changed to be performed over calendar months. Appendix A is 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 also investigates the effects of other influential factors including currents, vessel presence, wind speed, and mooring noise.

2.2.2. Marine Fauna Detections

Automated detectors for killer whale, humpback whale, Pacific white-sided dolphin, and fish sounds were used on all collected acoustic data. The detectors, which are customized for each species and call type, are part of JASCO's PAMlab software suite. The killer whale detector did not differentiate between different ecotype populations of killer whales (e.g., Southern Resident, Northern Resident, or Biggs killer whales). 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 synodic or calendar month (Frouin-Mouy 2020a, 2020b, 2020c, 2020d). Appendix B is an example marine mammal detection report, which describes the detection algorithms. The present report summarizes the verified marine fauna detection results for Year 2.

2.2.3. Vessel Source Levels

Vessel source levels were calculated using ShipSound, a component of JASCO's PortListen® online noise measurement system. The methods are fully described in Appendix E. The analysis for this report consists of a summary of the number of measurements that passed the quality control checks described in Appendix E. The quality control acceptance criterion includes 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

3.1.1. Comparison of Sound Levels Between Recorders

The AMARs and ULS frames were deployed in the same nominal location in Boundary Pass, within ~300 m of each other. The relatively minor environmental differences between deployment locations are not expected to influence sound levels. Analyzing data acquired at the same time by different recorders can therefore be helpful when interpreting non-acoustic noise (e.g., system, current-induced, or mooring noise).

AMARs 436 and 437 overlapped for a few days in December 2019, and overlapping data from that period were in relatively good agreement, with levels from AMAR 436 having slightly less flow and mooring noise (Grooms and Warner 2020, Warner 2020a, 2020b, 2021, Warner and Dofher 2021). The differences were similar to previous deployment differences between AMAR G3s (Warner and Frouin-Mouy 2019). AMAR 629 overlapped with the cabled ULS recordings from 8–14 Jun 2020 and there were several important differences in the ambient noise levels between these systems that are attributed to different mooring noise.

An example of this noise is shown in the spectrogram of AMAR 629 in Figure 7. The noise is highest at low frequencies (below 100 Hz) but extends to higher frequencies as well. There is a rhythmic nature to the noise, but it is also somewhat variable over relatively short time periods within which we do not expect average water currents to change substantially. The noise mechanism is thought to be from moving mooring component(s), but it is unclear exactly how this noise was generated. For comparison, Figures 8 and 9 show recordings from the same time period and over the same frequency range on ULS frames A and B, respectively. The ULS recordings do not have this mooring noise.

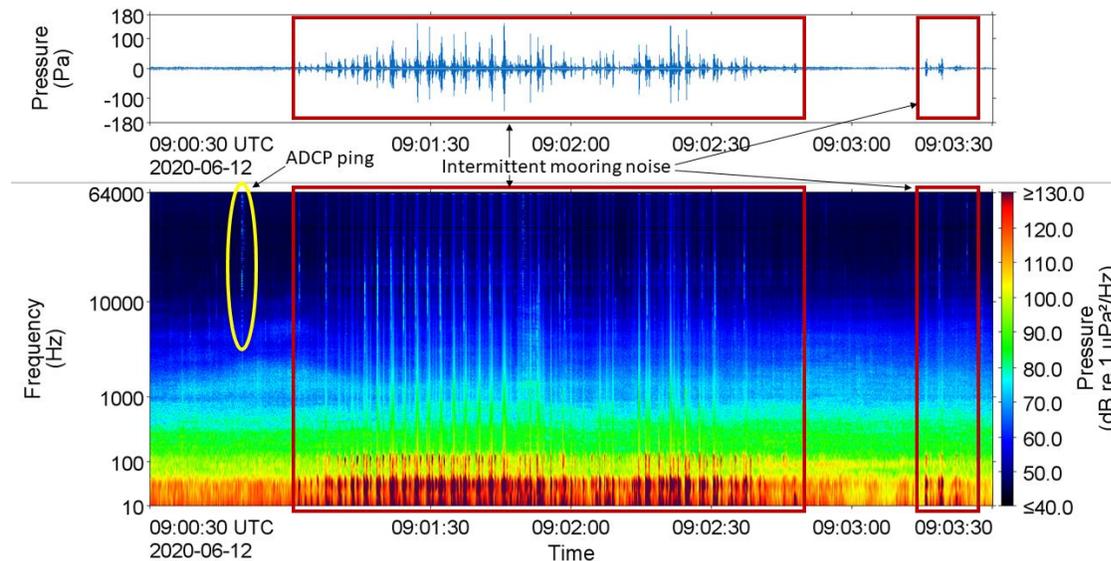


Figure 7. AMAR 629 waveform and spectrogram showing intermittent mooring noise. The most substantial mooring noise within the time window is outlined in red. Spectral leakage from one of the Underwater Listening Station (ULS) Acoustic Doppler Current Profiler (ADCP) pings is also highlighted. The ADCP pings occurred every minute, but other pings within the displayed time window are difficult to see because mooring noise masked the ADCP sounds.

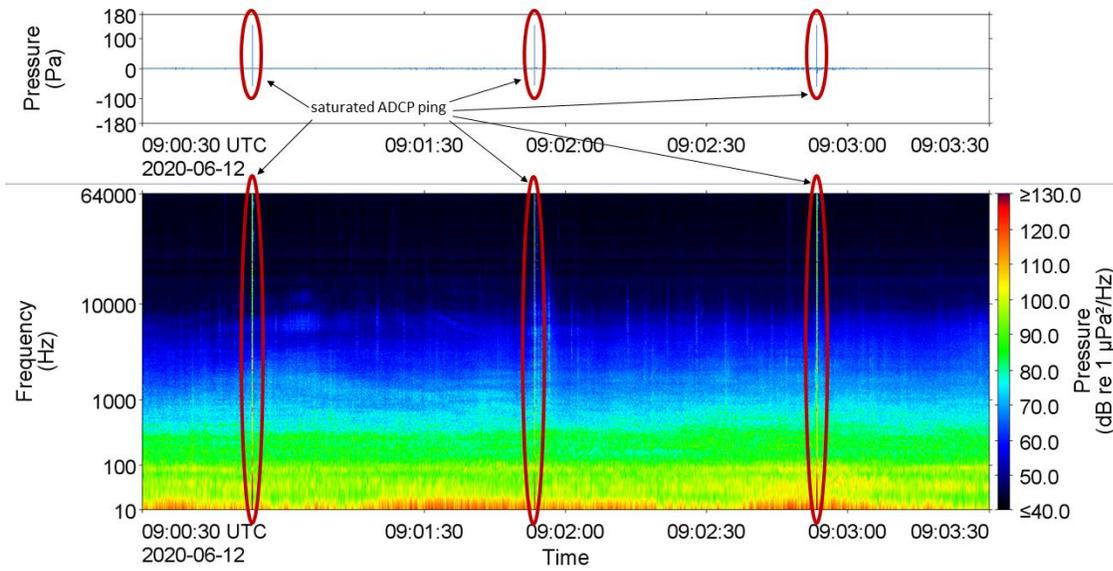


Figure 8. ULS A1 waveform and spectrogram for the same time period as AMAR 629 recordings contained mooring noise (see Figure 7). The frequency range is truncated to the frequency range of the AMAR data for easier comparison. The three spikes in pressure at 1-minute intervals are ADCP pings. Those pings were excluded from the 1-minute ambient noise analysis.

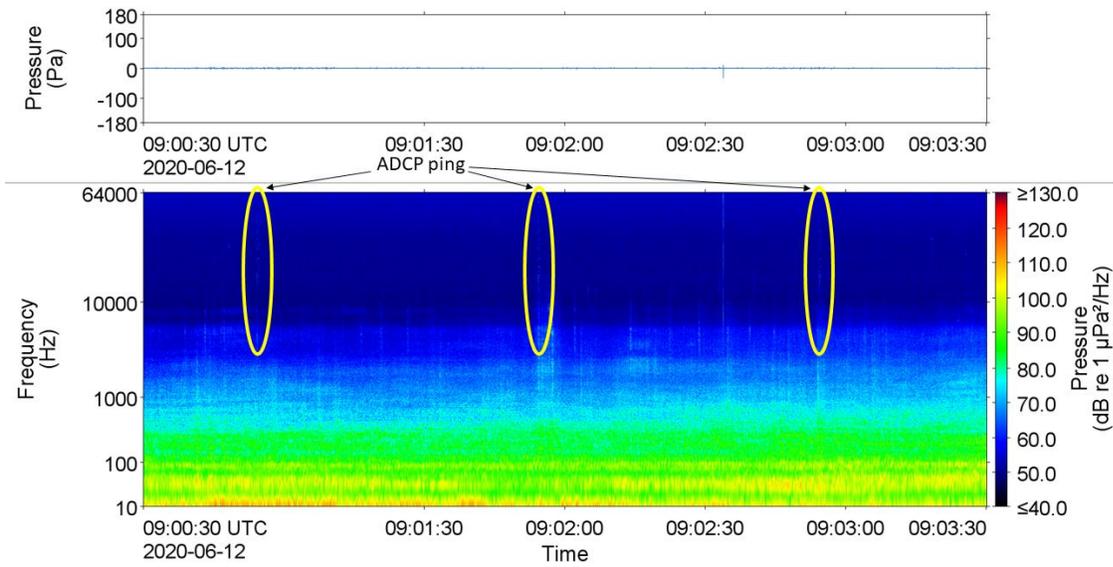


Figure 9. ULS B2 waveform and spectrogram for the same time period as AMAR 629 recordings contained mooring noise (see Figure 7). The frequency range is truncated to the frequency range of the AMAR data for easier comparison. Spectral leakage from the Underwater Listening Station (ULS) Acoustic Doppler Current Profiler (ADCP) pings can be seen in the spectrogram, but it is at relatively low levels.

Figure 10 shows the decidecade band level CDFs from the AMAR G4 (629), ULS A frame, and ULS B frame during the 6-day overlapping period. The top hydrophones were used for ULS data, where frame A used GTI hydrophones and frame B used HTI 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 ULS data were greatest in the first two decades (10–1000 Hz), and were generally smaller at higher frequencies. At the lower frequencies, the frame A and B levels from the ULS were in good agreement; however, the AMAR levels were substantially higher than ULS levels due to the AMAR's mooring noise discussed previously. At higher frequencies (above ~10 kHz), the differences were largely due to different noise floor characteristics of the hydrophones. The HTI hydrophones operating on frame B had a higher noise floor than the GTI hydrophones operating on frame A and on AMAR 629. The GTI hydrophone levels were in relatively good agreement with each other as the AMAR data matched more closely with the ULS frame A data.

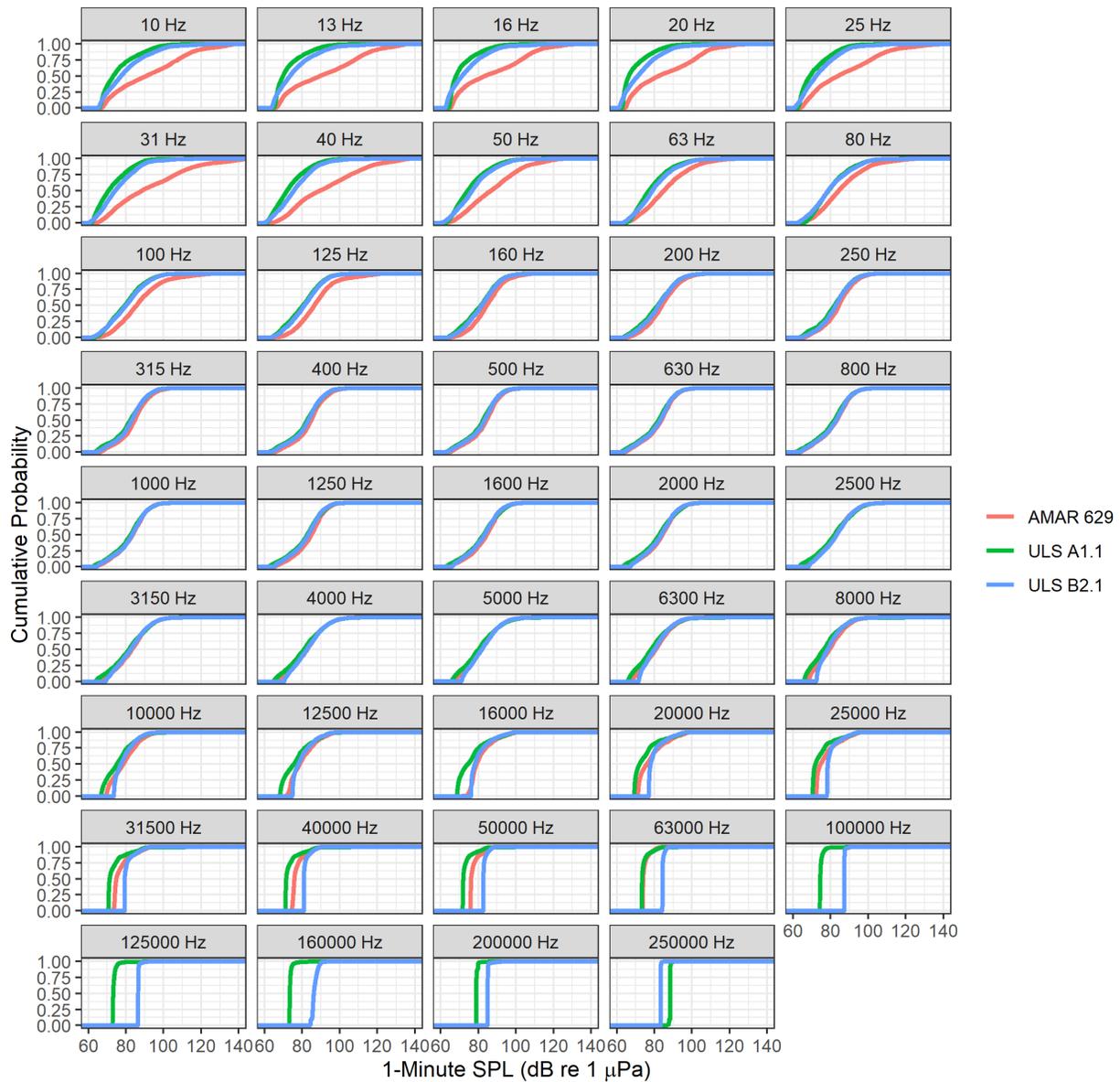


Figure 10. Decidecade band sound level cumulative density functions (CDF), during Automatic Identification System (AIS) vessel absence, measured by simultaneously recording instruments (4349 minutes). Data were pre-filtered to exclude minutes when AIS vessels were within 6 km of the hydrophones and/or 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 63000 Hz. Underwater Listening Station (ULS) measurements spanned the displayed frequency range (10–250000 Hz).

Figure 11 shows the CDFs when 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 levels were in much better agreement because the louder sounds from the vessels masked the mooring noise. As above, data from the two ULS frames agreed except at high frequencies, largely due to the different model of hydrophones. At low frequencies, the AMAR levels were higher than the ULS from mooring noise, but the differences were limited to frequencies below 160 Hz.

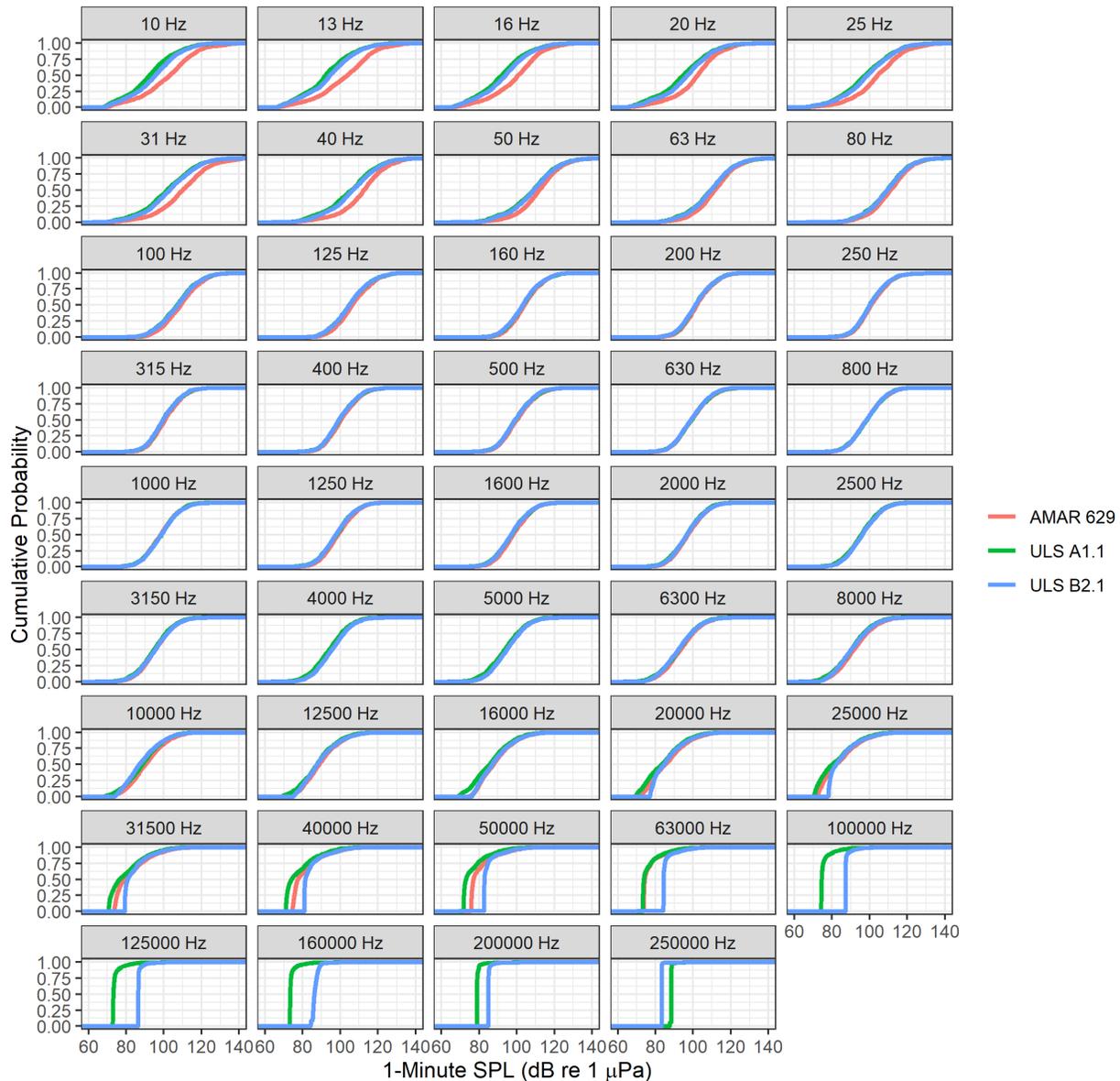


Figure 11. Decade band sound level cumulative density functions (CDF) when Automatic Identification System (AIS)-broadcasting vessels were within 6 km of the hydrophones, measured by simultaneously recording instruments (1492 minutes). Data were pre-filtered to exclude minutes when current speeds were greater than 0.5 m/s. Panel headings indicate the centre frequency of the decade band. AMAR measurements were limited to frequencies at or below 63000 Hz. Underwater Listening Station (ULS) measurements spanned the displayed frequency range (10–250000 Hz).

3.1.2. Temporal Variability of Sound Levels

The recording bandwidth must be considered when interpreting long-term trends across periods with different equipment. The bandwidth increased in June 2020 with the installation of the cabled ULS, where the broadband bandwidth increased from 10–64000 Hz to 10–256000 Hz. The 10–64 kHz band (4th “decade”) collected on the AMARs was replaced with the 10–100 kHz band collected on the ULS, and the 100–256 kHz band was added. The consequence of increasing the bandwidth was investigated by analyzing ULS data over the different frequency ranges (Figure 12). The results show that increasing the bandwidth caused the broadband level to increase by a few decibels during quieter times, and the 10–

64/100 kHz level increased by 1–2 dB for levels below the 80th percentile (0.8 cumulative probability). These increases are associated with the high-frequency noise floor of the hydrophone.

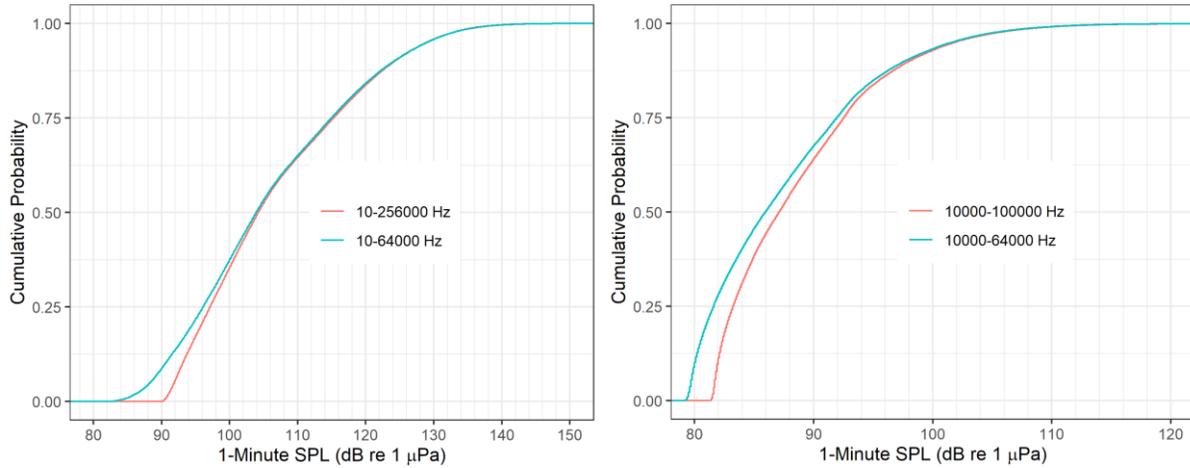


Figure 12. Cumulative distribution functions (CDFs) comparison for increasing (left) broadband and (right) 4th “decade” bandwidths using Underwater Listening Station (ULS) data.

With these expected sound level increases in mind, long term trends in sound levels were analyzed by compiling broadband and decade band monthly sound level statistics over the reporting period (October 2019 to December 2020). To maintain consistency with the quarterly ambient noise reports, the first three months of this period were analyzed over synodic months, and the last 12 months were analyzed over calendar months. Figure 13 shows the trends in sound level statistics computed over each month. The increase in low-frequency sound levels in February, and the subsequent drop in June, is largely attributed to the mooring for AMAR 629, which was used during most of the February to June time period. These results illustrate the issue of non-acoustic noise from mooring vibrations in high-current environments. All three mooring types: G3, G4, and cabled ULS produced noise that influenced the percentile levels for sound frequency bands below 1000 Hz. The rigid frame of the cabled ULS generated less noise than the autonomous recorder moorings, which included flotation and mechanical joints between components.

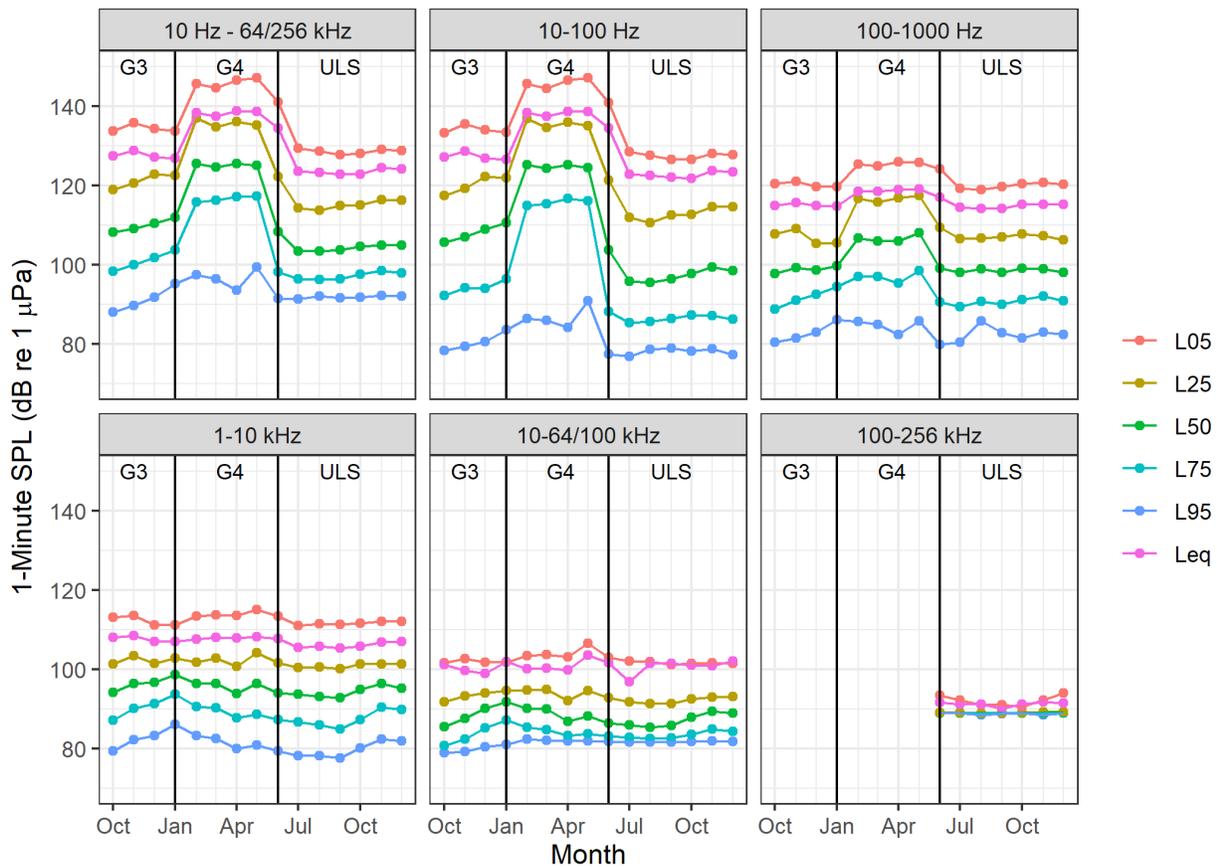


Figure 13. Monthly sound level statistics as functions of time in each indicated frequency band before filtering out periods with current speeds greater than 0.5 m/s. Data start in October 2019 and end in December 2020.

To reduce some of the effect of mooring noise, we recomputed the monthly sound level statistics after filtering out periods when current speeds were greater than 0.5 m/s (Figure 14). The filtering appeared to remove some of the mooring-related artefacts in the 100–1000 Hz band, but the broadband and 10–100 Hz levels were still substantially affected. The filtering also stabilized the highest frequency band (100–256 kHz) levels recorded on the ULS.

Aside from the equipment-related trends, the sound level statistics were generally consistent over time periods with consistent recording equipment; however, there was some variability. The L_{05} , L_{95} , and L_{eq} generally had more variability than other statistics because they are more sensitive to infrequent events. Some of the increases in levels during the AMAR G3 recording period (October 2019 to January 2020) were likely associated with increasing wind speed (see Section 3.1.4). The higher levels for the L_{95} , L_{75} , and L_{50} statistics in Oct – Dec 2020 for the 1–10 and 10–100 kHz bands were also likely due to faster winds during that period. The relatively small increase in the higher-level statistics (e.g., L_{95} , L_{eq}) in November to December 2020 compared to July to October 2020 for 10–10,000 Hz may have been related to the end of the ECHO program’s 2020 Haro Strait and Boundary Pass voluntary slowdown.

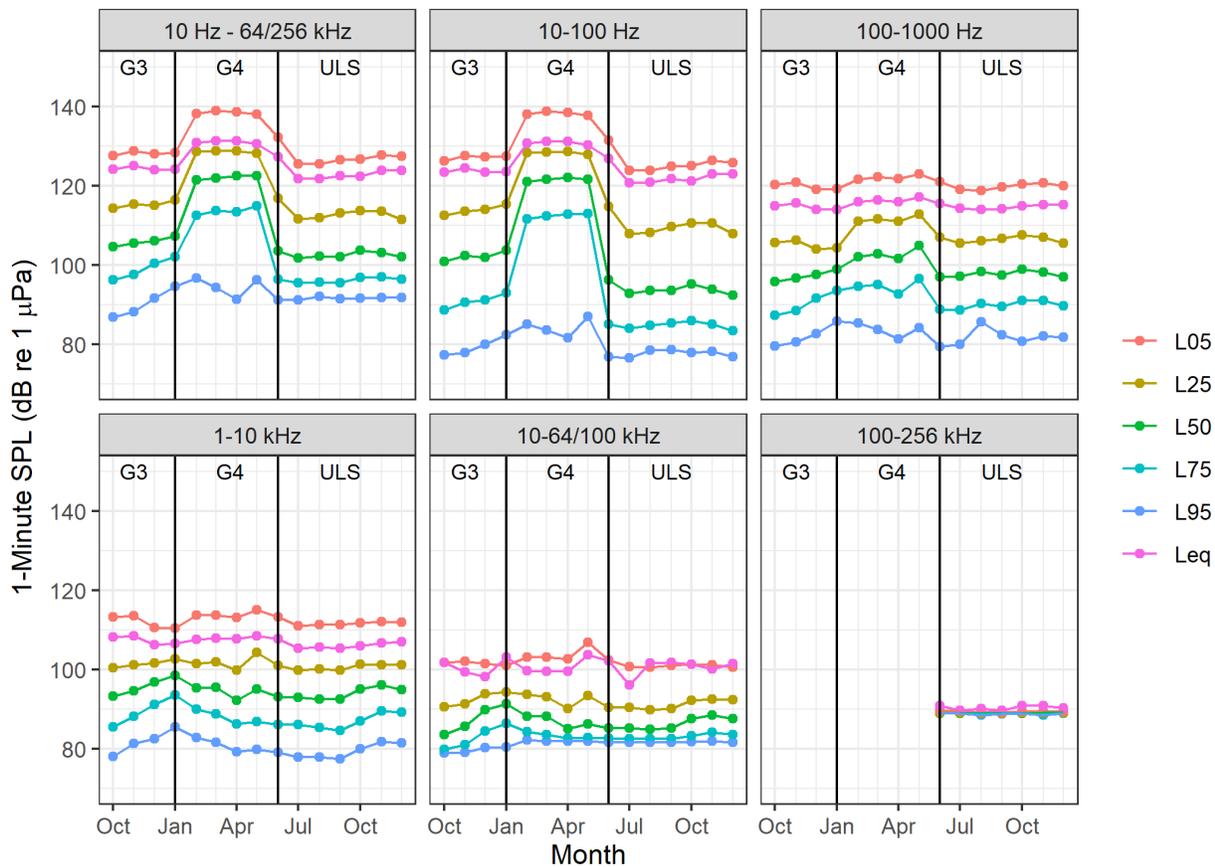


Figure 14. Monthly sound level statistics as functions of time in each indicated frequency band after filtering out periods with current speeds greater than 0.5 m/s. Data start in October 2019 and end in December 2020.

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 for the analysis period, and they did not show a strong weekday/weekend difference. Figure 15 shows an example from July 2020. There were some trends over the course of each day in June through September, when sound levels were higher during daylight hours. Figure 16 shows an example from July 2020 where sound levels were elevated between approximately 08:00 and 21:00. This trend was likely caused by seasonal recreational vessel traffic.

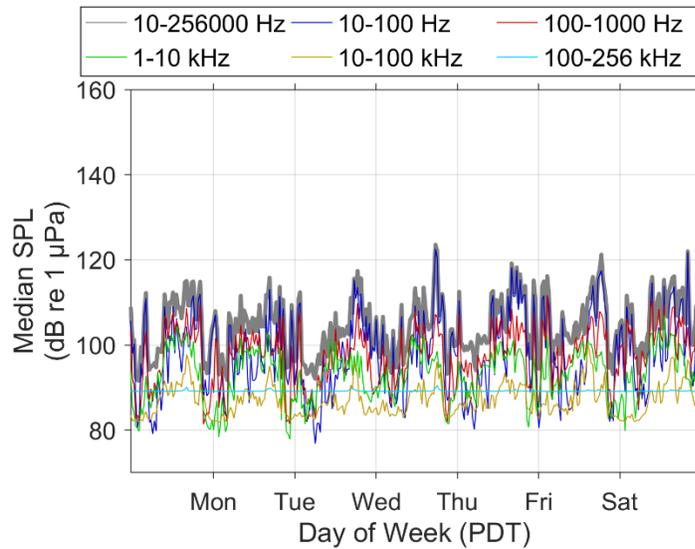


Figure 15. Weekly rhythm plot showing the median sound pressure level (SPL) during July 2020 measured by the Underwater Listening Station (ULS).

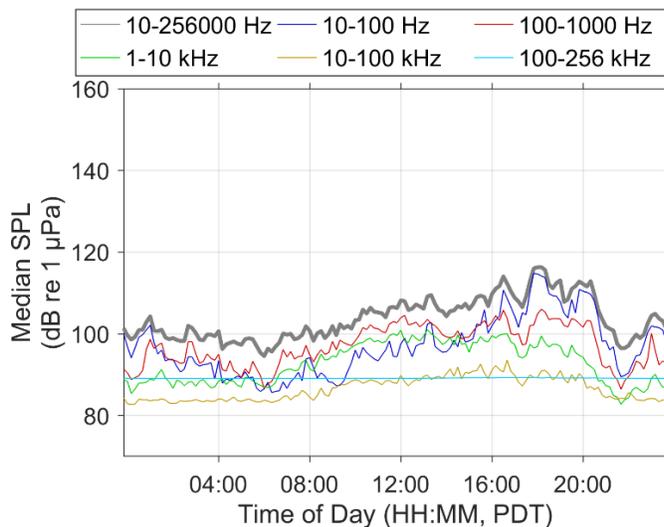


Figure 16. Daily rhythm plot showing median sound pressure level (SPL) during July 2020 measured by the Underwater Listening Station (ULS).

3.1.3. Influence of Water Currents

Water currents were measured using an ADCP deployed either autonomously (October 2019 to June 2020) or on the ULS frame A (June 2020 to December 2020). The most influential currents on ambient sound levels were those passing over the hydrophones, which were deployed near the seafloor. A secondary effect is that vessels travelling with a constant speed over ground, may be quieter or louder if they are travelling with or against currents, respectively.

The nearest-to-seafloor ADCP measurements varied between 8 and 16 m above the seafloor for the autonomous ADCPs (92 m water depth for the October 2019 and January 2020 deployments), and were ~9 m above the seafloor for the cabled ADCP (184 m water depth). Figure 17 shows the probability density of the near-seafloor current speed from all available ADCP measurements during the analysis period. The maximum recorded current was 2.4 m/s (4.7 knots), recorded from the autonomous ADCP that was located approximately 1.5 km southwest of the ULS.

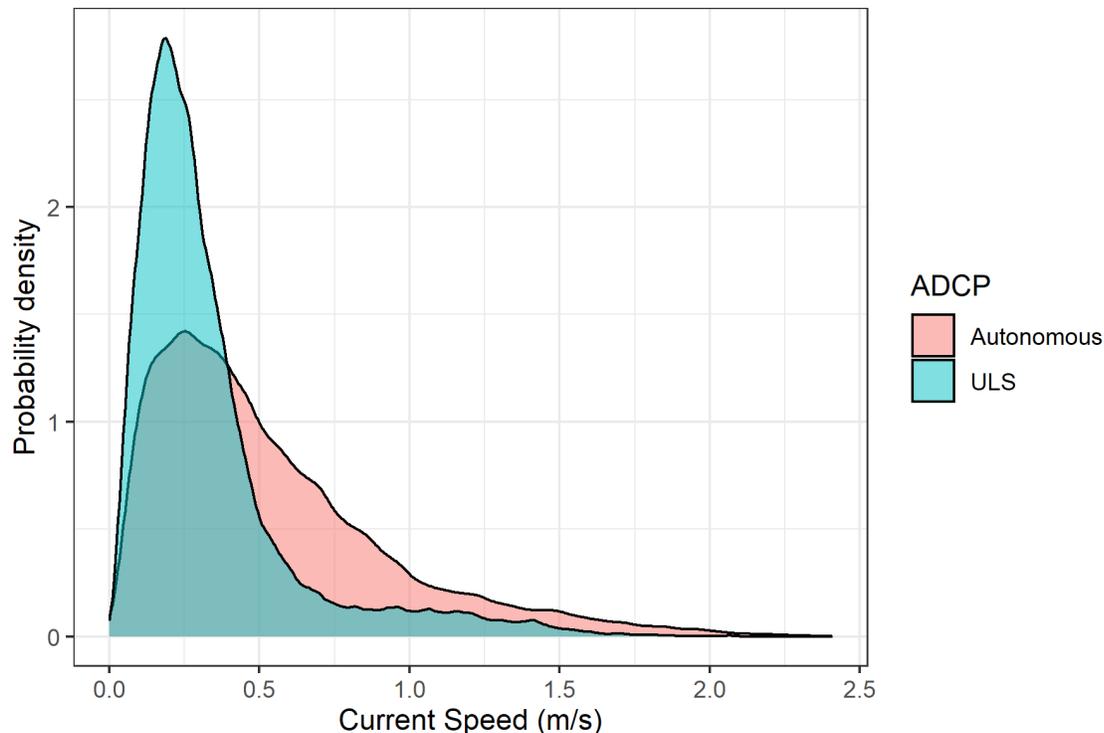


Figure 17. Probability density of near-seafloor current speed magnitude from all available Acoustic Doppler Current Profiler (ADCP) measurements. ADCP measurements were made every 10–15 minutes. The autonomous ADCP current speed distribution is from October 2019 to June 2020 while the ULS ADCP distribution is from June 2020 to December 2020.

There was a period of overlap, from 9–16 Jun 2020, during which both the autonomous and ULS ADCPs were operating. A comparison of the magnitude of near-seafloor current speeds during this overlap period revealed that, in general, the ULS ADCP recorded lower current speeds than the autonomous ADCP (Figure 18). During this period, the average current speed recorded by the ULS was 0.32 m/s, whereas the average current speed recorded by the autonomous ADCP was 0.51 m/s. This trend was more pronounced towards the end of the overlapping period and was driven primarily by differences in Northing current speed (Figure 19). This overlapping period did not cover a full synodic month, so these findings may not necessarily be representative of the differences between currents at the two measurement locations (Figure 1); however, the current speed probability density plot (Figure 17) suggests the near-seafloor currents were generally lower at the ULS location than at the autonomous ADCP location.

A similar analysis was performed on the near-surface currents (Appendix C). The differences between near-surface currents from the autonomous and ULS ADCPs were found to be similar to those of the near-seafloor currents, although the long-term distributions for the autonomous and ULS measurements were more similar to each other near the surface than near the seafloor. Near-surface currents at the autonomous ADCP location were generally faster than those at the ULS location.

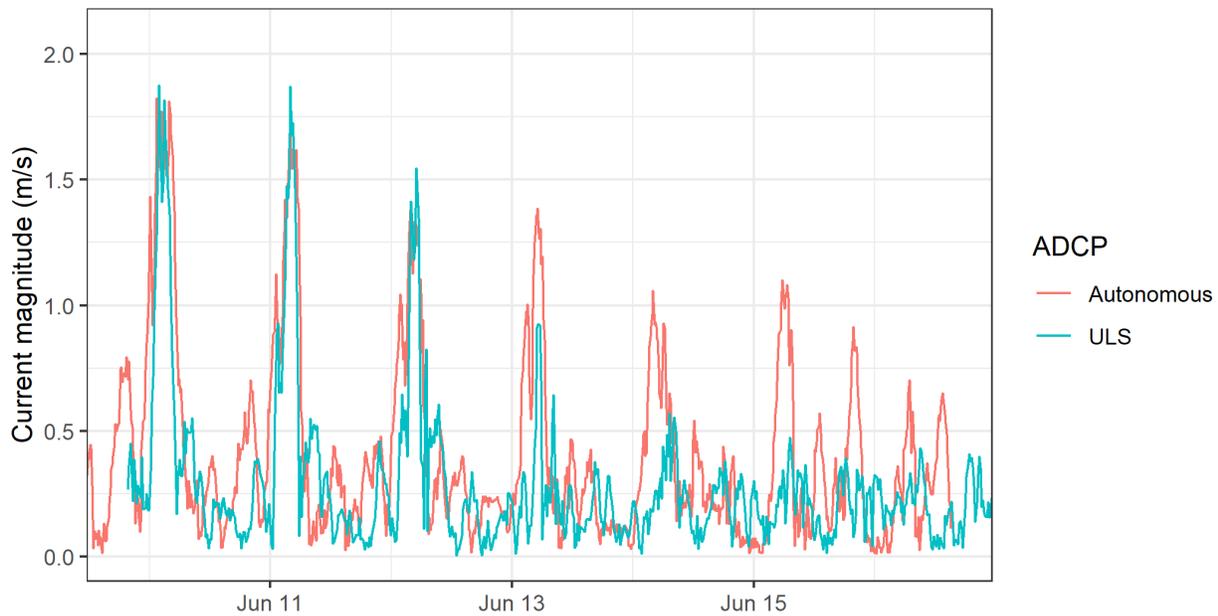


Figure 18. Comparison of near-seafloor current speed magnitude during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs).

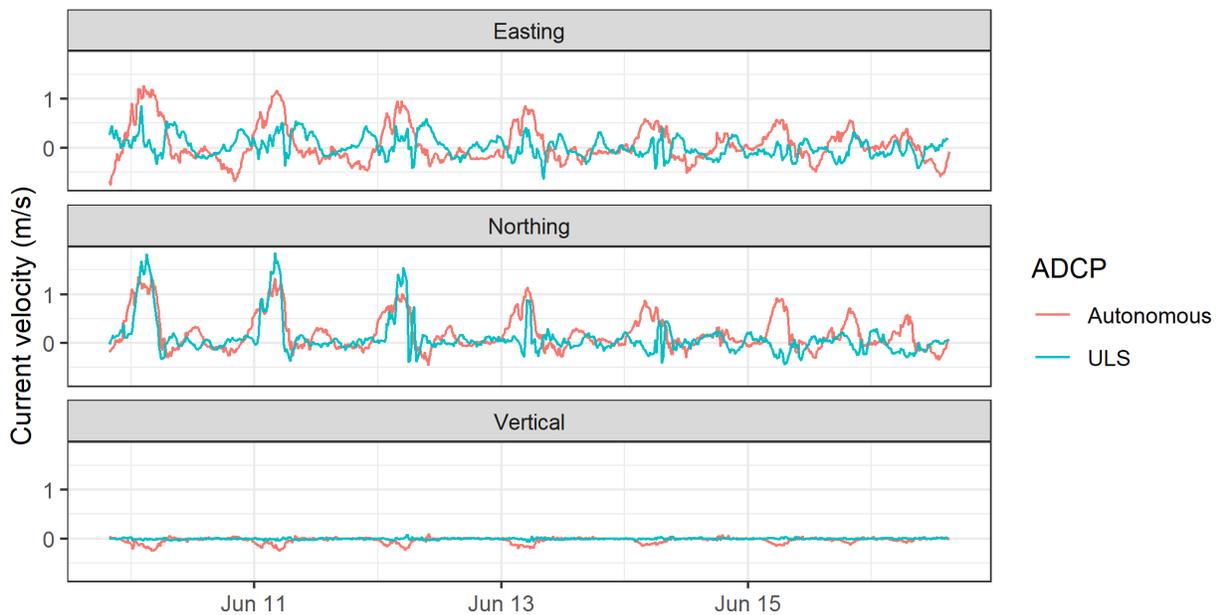


Figure 19. Comparison of near-seafloor current speed broken down by directional component during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs).

Sound levels were affected by noise artefacts from current flow around the hydrophones at certain times throughout the analysis period. The effects of water current speed (as measured by the ADCP near the seafloor) on sound levels are shown with a 2-dimensional (2-D) histogram of SPL (1-minute average) for each decade band for the AMAR G3 (Figure 20), G4 (Figure 21), and ULS (Figure 22). There were relatively few measurements at higher current speeds. Therefore, to better reveal the trends at higher current speeds, the data were normalized by the total number of counts at a given speed. Unnormalized 2-D histograms can be found in Appendix C.

The effects of current speed were strongest in the 10–100 Hz band for all recorders (panel ‘a’ in Figures 20–22). The trends were clearest in the cabled ULS recordings, likely because of the co-located ADCP and hydrophone. The effect was most clearly observed for current speeds greater than ~0.5 m/s, although the effect was noticeable in the ULS data starting at speeds as low as ~0.2 m/s.

The AMAR G4 data in the 10–100 Hz band had a bimodal distribution, which was atypical of those from the other recorders, and suggests some kind of instability of the mooring in currents. Furthermore, sound pressure levels (SPL) at low current speeds were higher on the AMARs, particularly the AMAR G4 (Figures 20 and 21), compared to the ULS (Figure 22). This may indicate that movement of the floating moorings, even in low-current conditions, produced an increase in low-frequency sound levels.

The current speed/SPL correlation could also be seen in the 100–1000 Hz band, and in the higher frequency bands (10–64, 10–100, and 100–256 kHz); however, the 1–10 kHz band was essentially independent of current speed. It is difficult to say how much of this effect is due to turbulence creating pseudonoise and how much is real sound from sediment particles moving around. One way to investigate this would be to analyze the noise coherence function between two hydrophones on the same ULS frame, and see how it varies with current speed. Pseudonoise would not be correlated between sensors but real sounds would.

Given that the near-seafloor currents measured at the autonomous ADCP location likely underestimated those at the AMAR locations (Figures 17–19), the effect of current speed on SPL may be underestimated for the AMAR moorings and is likely the reason that the trends are less clear for the AMAR data than for the ULS data.

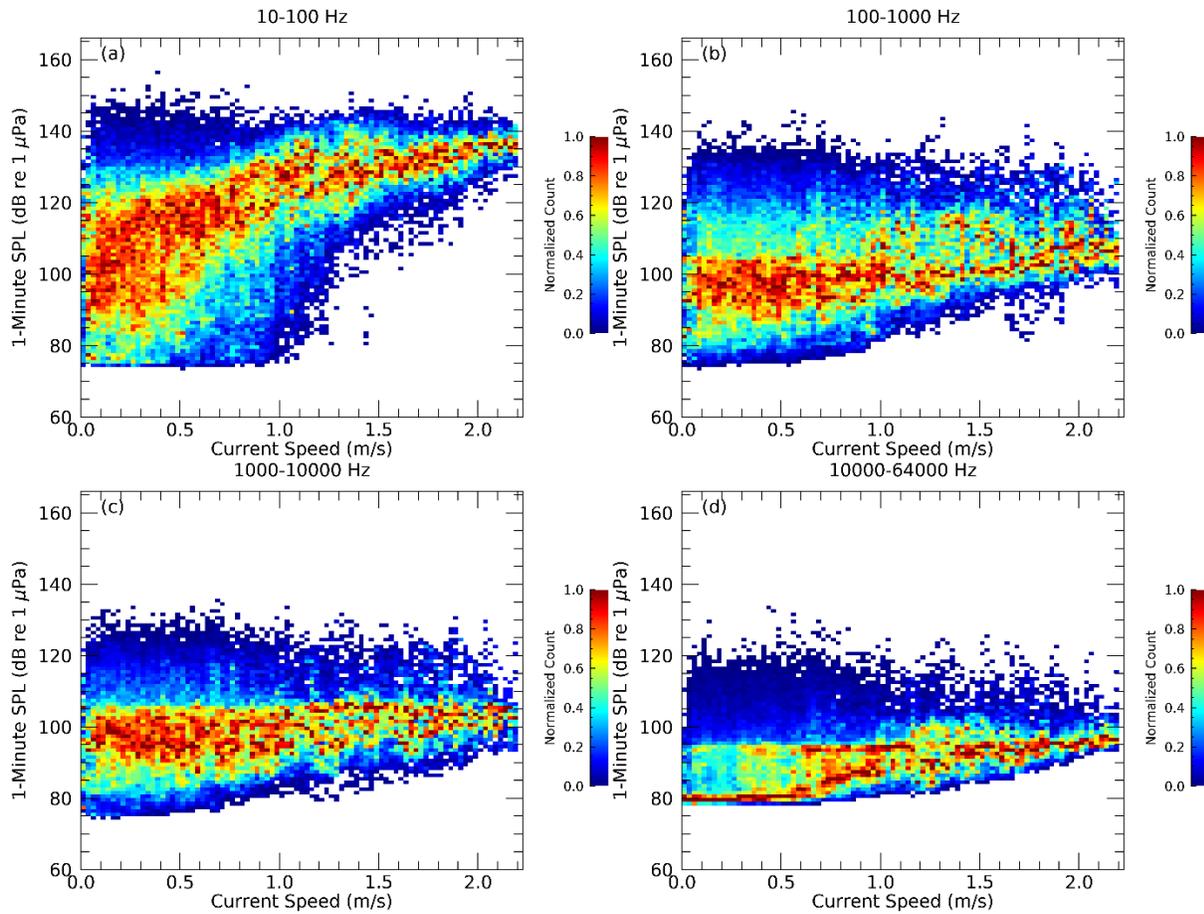


Figure 20. AMAR G3 (2019 Oct 15 to 2020 Jan 31): Two-dimensional (2-D) normalized histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler- (ADCP)-measured seafloor current speed. The counts for each SPL-current bin have been normalized (divided by) the maximum count within the corresponding current speed interval. The narrow sound level distributions at low current speeds and high frequencies (panel 'd') are due to sound levels being lower than the noise floor of the hydrophone.

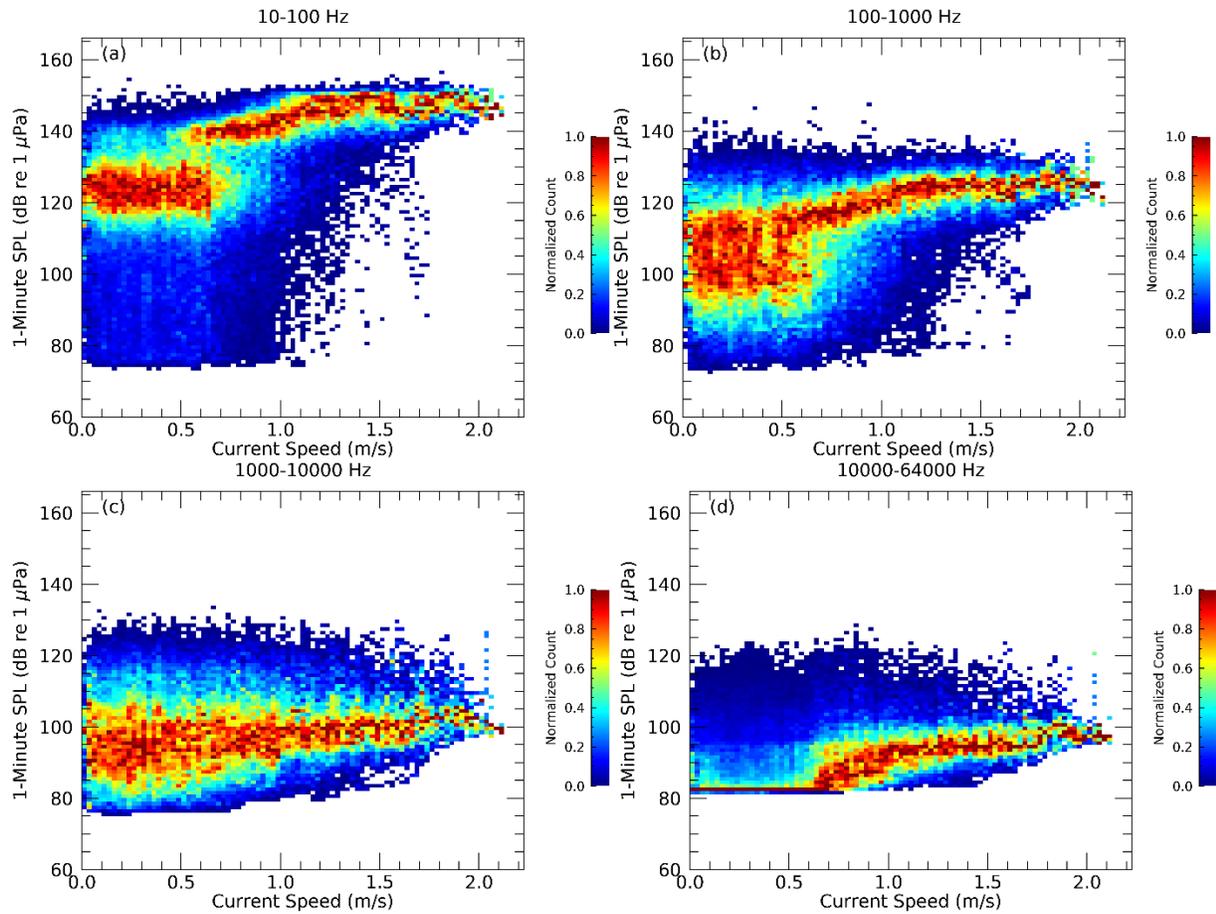


Figure 21. AMAR G4 (2020 Jan 31 to 2020 Jun 09): Two-dimensional (2-D) normalized histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler- (ADCP)-measured seafloor current speed. The counts for each SPL-current bin have been normalized (divided by) the maximum count within the corresponding current speed interval. The narrow sound level distributions at low current speeds and high frequencies (panel 'd') are due to sound levels being lower than the noise floor of the hydrophone.

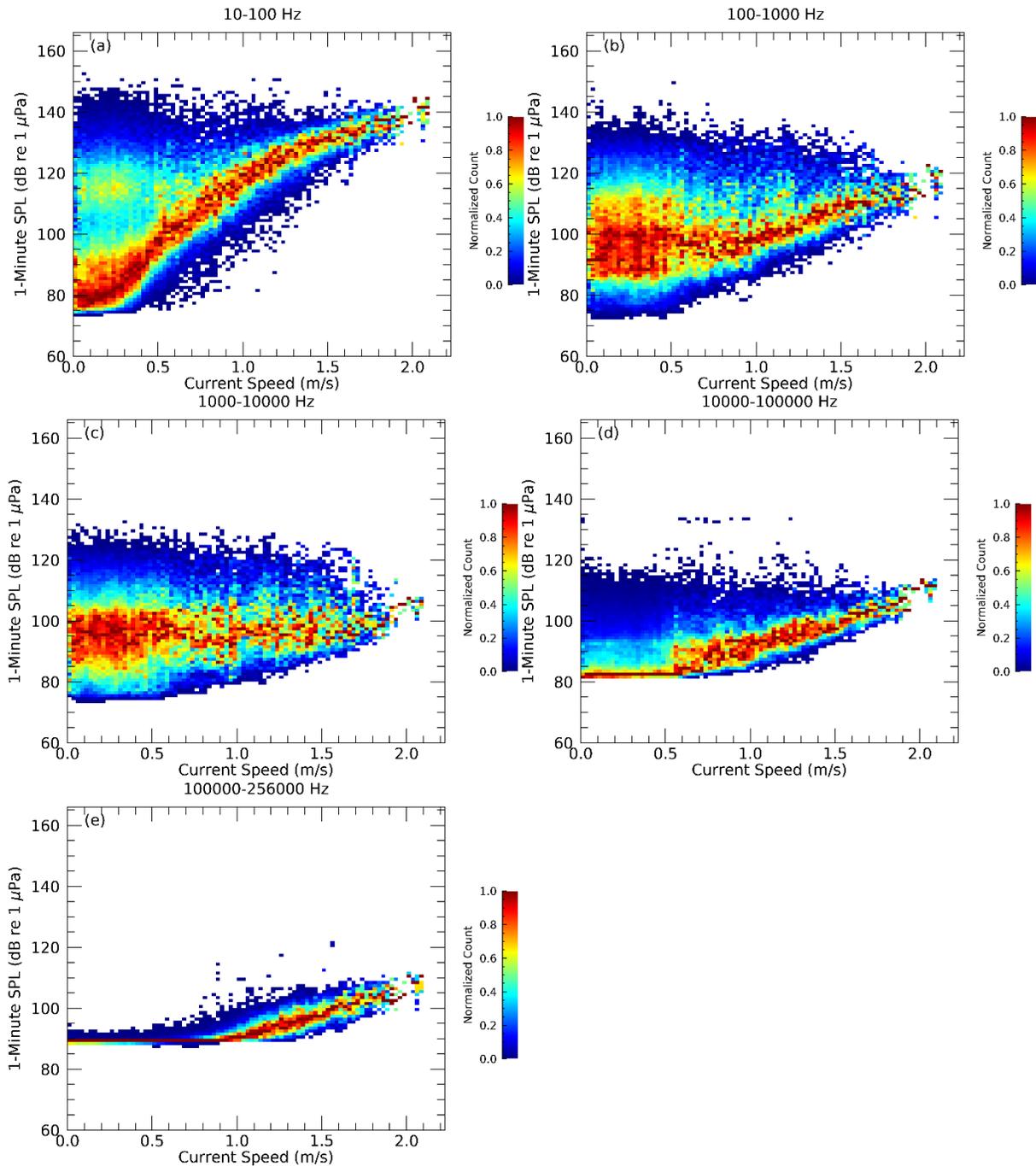


Figure 22. Cabled ULS (2020 Jun 09 to 2020 Dec 31): Two-dimensional (2-D) normalized histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler- (ADCP)-measured seafloor current speed. The counts for each SPL-current bin have been normalized (divided by) the maximum count within the corresponding current speed interval. The narrow sound level distributions at low current speeds and high frequencies (panels 'd' and 'e') are due to sound levels being lower than the noise floor of the hydrophone.

3.1.4. Influence of Wind Speed

Figure 23 shows a histogram of recorded wind speeds over the analysis period. Figure 24 shows a box-and-whisker plot of the wind speeds by month. Wind speeds were generally higher in winter, with the highest average wind speed in January 2020 (7.4 m/s) and lowest average wind speed in May 2020 (2.9 m/s). A detailed explanation of box-and-whisker plots can be found in the Glossary.

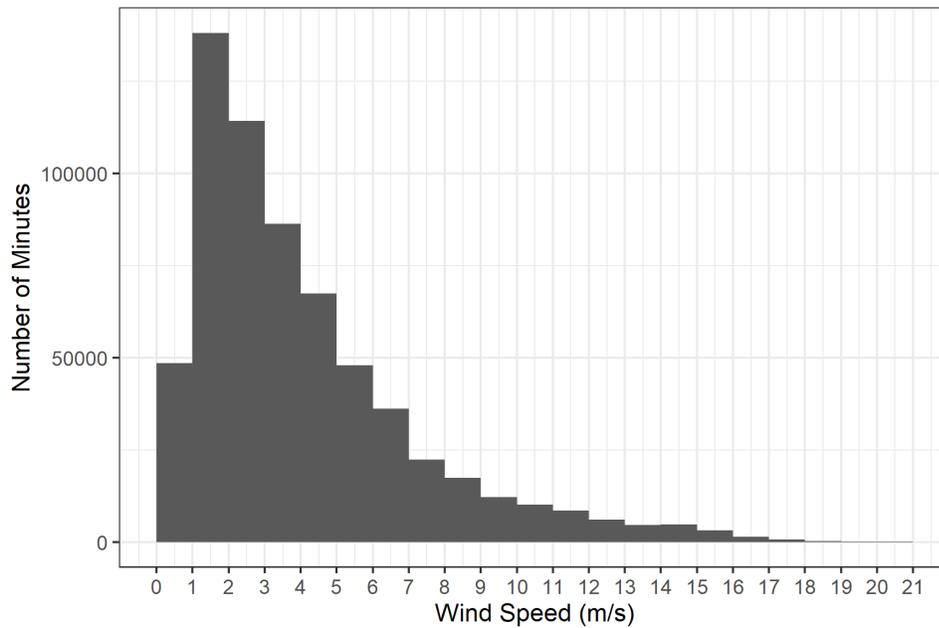


Figure 23. Histogram of wind speed during the analysis period. Wind speed was linearly interpolated from hourly measurements to 1-minute intervals.

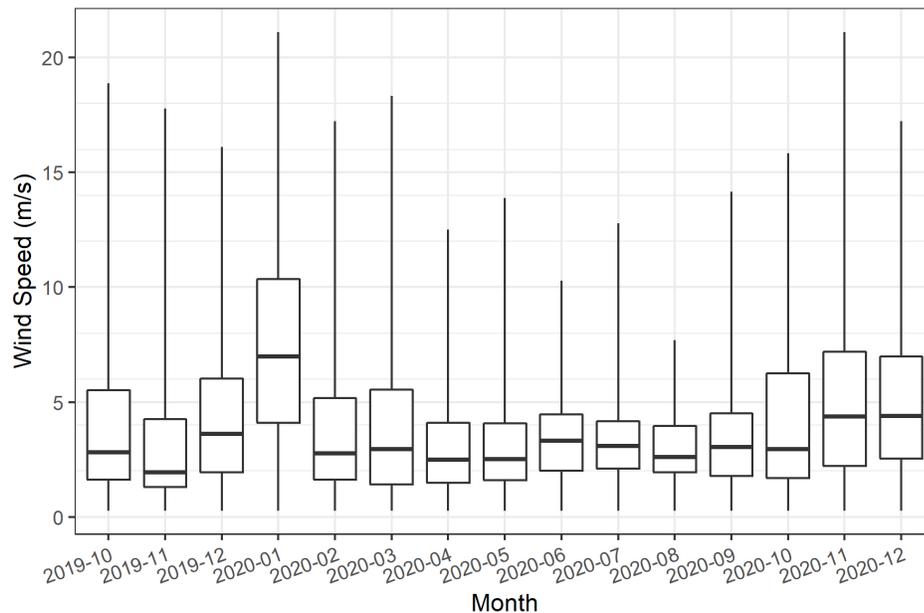


Figure 24. Box-and-whisker plot of wind speed as a function of month during the analysis period. Wind speed was linearly interpolated from hourly measurements to 1-minute intervals. The box edges represent the 25th and 75th percentiles, the horizontal line within the box represents the median (50th percentile), and the whiskers show the highest and lowest observations.

Two-dimensional (2-D) histograms of SPL versus wind speed are shown in Figures 25 and 26 for AMAR and ULS recordings, respectively. The plots also show the L_{90} , the sound level exceeded 90% of the time, in each wind speed bin and the expected wind-driven ambient noise levels based on the Knudsen curves (Knudsen et al. 1948). The SPL distributions in the 10–100 Hz band differ between the recorder types, primarily because of low-frequency mooring noise (see Sections 3.1.2 and 3.1.1).

There does not appear to be an effect of wind speed on the 10–100 Hz sound levels on the AMARs (top left panel in Figure 25), or the 100–256 kHz sound levels on the ULS (last panel in Figure 26). For the remaining frequency bands, however, wind speed appears to influence the lower sound levels which generally match the Knudsen trends well.

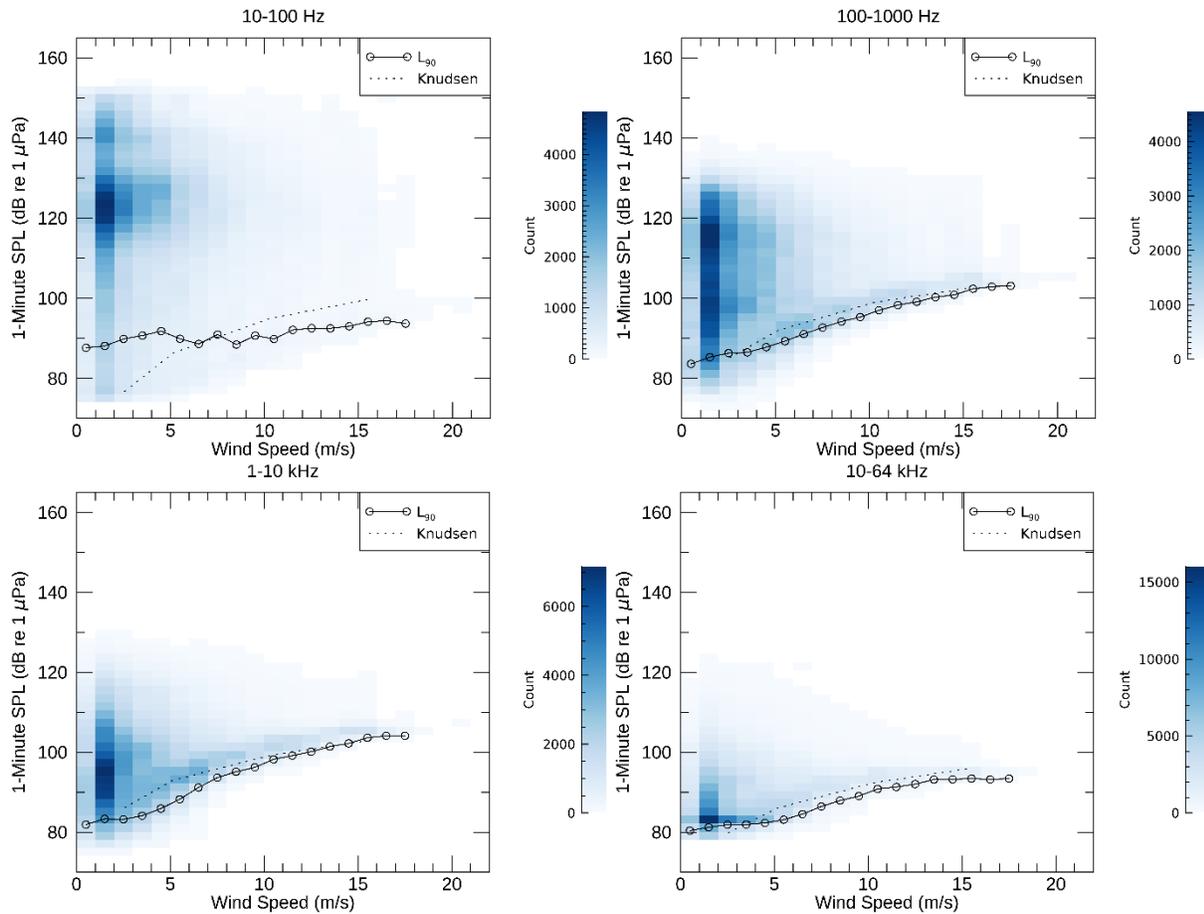


Figure 25. AMARs G3 and G4: Two-dimensional (2-D) histograms of decade-band sound pressure level (SPL) versus wind speed. The L_{90} within each wind speed bin is shown with a solid black and circled line (where there are at least 500 SPL measurements in the wind speed bin). The predicted sound levels from Knudsen et al. (1948) are shown as a dotted line.

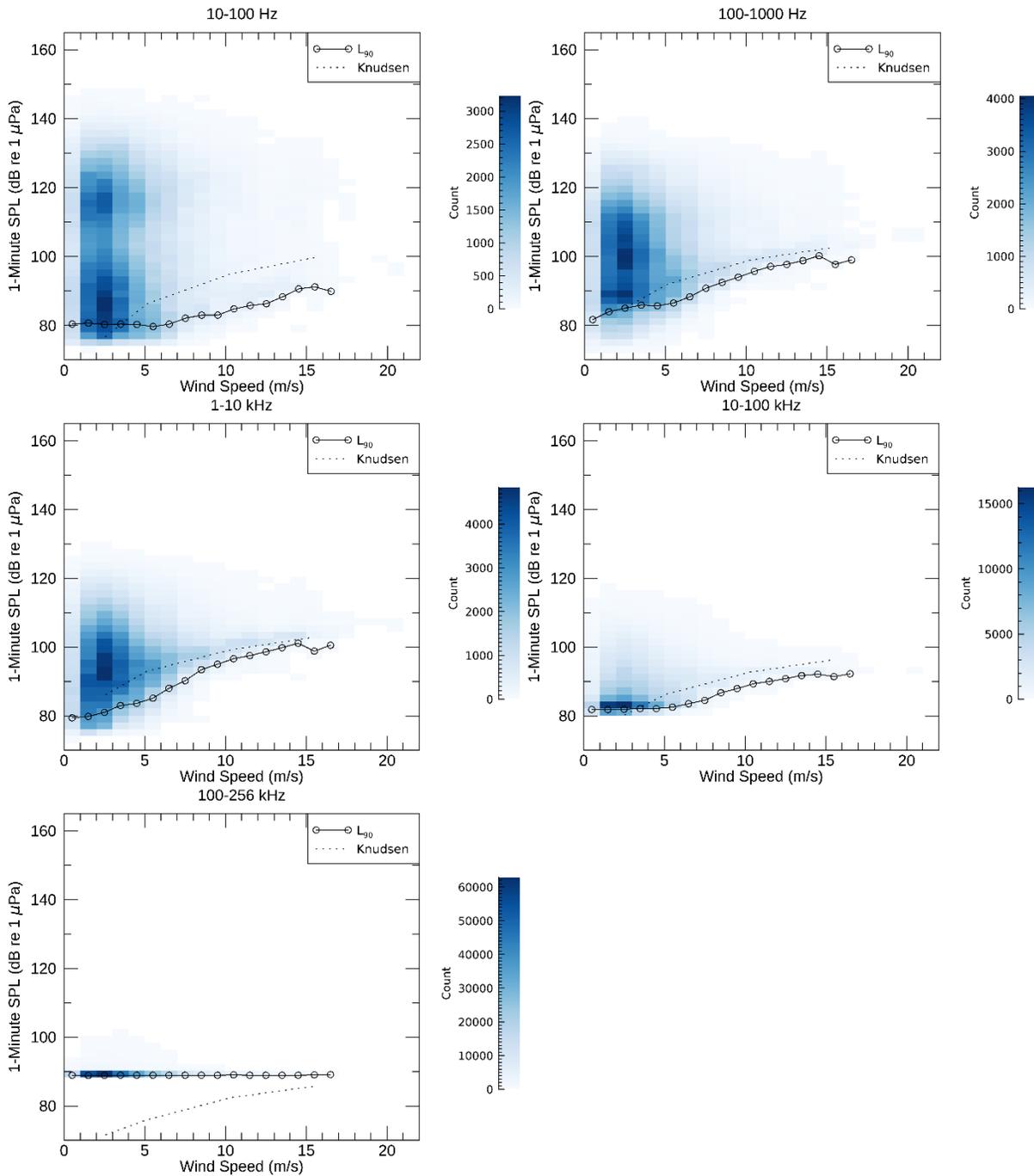


Figure 26. Underwater Listening Station (ULS): Two-dimensional (2-D) histograms of decade-band sound pressure level (SPL) versus wind speed. The L_{90} within each wind speed bin is shown with a solid black and circled line (where there are at least 500 SPL measurements in the wind speed bin). The predicted sound levels from Knudsen et al. (1948) are shown as a dotted line.

3.1.5. Influence of Vessel Traffic

Vessel traffic (as determined from AIS) substantially increased sound levels in Boundary Pass across a wide frequency range. To assess the influence of AIS vessel traffic on sound levels, we investigated time periods with and without AIS-broadcasting vessels within 6 km of the hydrophone. For this analysis, we also filtered out time periods when seafloor current speeds exceeded 0.5 m/s to reduce the effect of current-induced flow noise (see Section 3.1.3). Figure 27 shows cumulative distribution functions (CDF) for broadband and decade-band SPL from AMARs G3 and G4 for time periods with and without AIS-broadcasting vessels. Figure 28 shows the CDFs recorded from the ULS, again for time periods with and without AIS-broadcasting vessels. Sound levels in all frequency bands increased by several decibels due to vessel presence for nearly all percentiles, with the exception of the highest frequency band recorded on the ULS (100–256 kHz, Table 3), which only appeared affected above the L_5 . The increases in sound levels for the 10–64, 10–100, and 100–256 kHz bands during quiet times were likely underestimated because the noise floor of the hydrophones limited the ability to quantify low levels of high-frequency sounds.

For some frequency bands, the increase in SPL due to AIS vessel presence differed substantially based on the recorder. For example, the smaller increase in the broadband L_{95} on ULS measurements was partly due to the larger bandwidth of the ULS system and the high-frequency noise floor of the system limiting the quietest broadband sound level that was measured. For the higher-level statistics (e.g., L_{25} , L_5 , and L_{eq}), the larger increase for the ULS measurements was influenced by the lower mooring noise on the ULS. This effect also applied to the 10–100 Hz band. The smaller increase for the 10–100 Hz L_{95} on the ULS compared to the AMAR was largely because the sound level with AIS vessel presence was higher for the AMAR measurements. The reason for this is unknown.

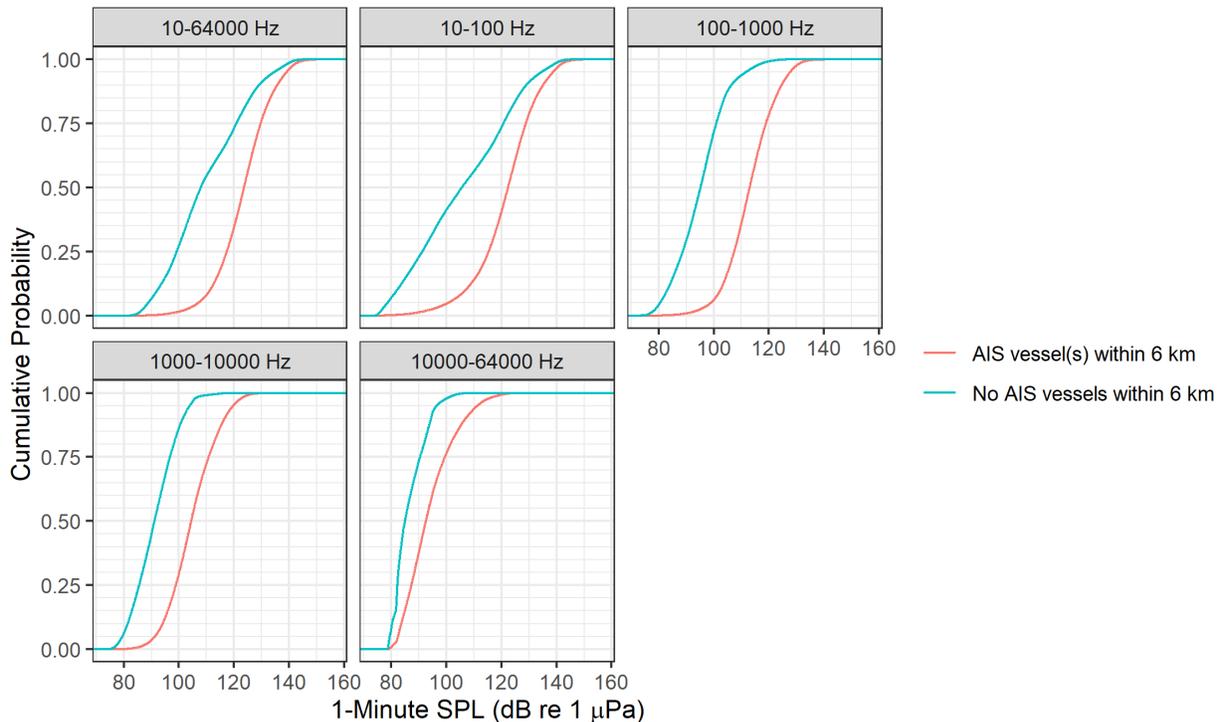


Figure 27. AMARs G3 and G4: Cumulative distribution functions (CDFs) for periods with and without Automatic Identification System (AIS) vessel traffic within 6 km of the hydrophone in broadband and decade bands during the analysis period. Time periods when seafloor current speed exceeded 0.5 m/s were excluded before calculating the CDFs. Table 3 lists the differences in percentiles and the L_{eq} .

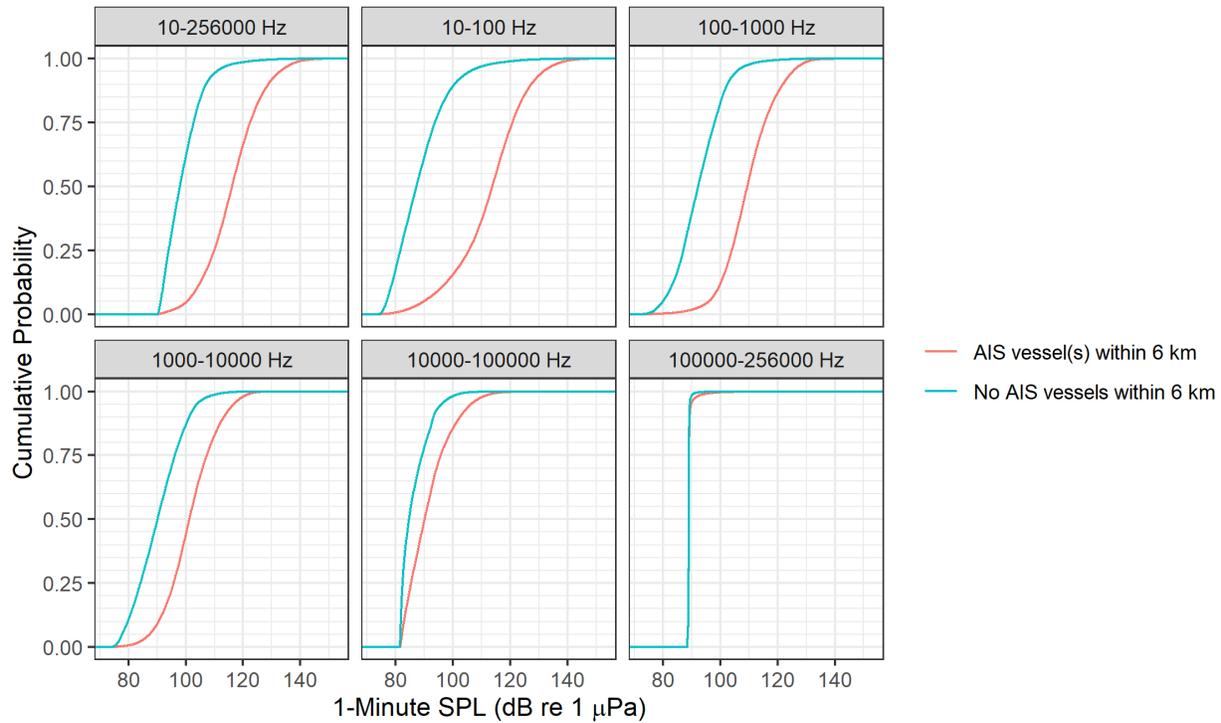


Figure 28. Underwater Listening Station (ULS): Cumulative distribution functions (CDFs) for periods with and without Automatic Identification System (AIS) vessel traffic within 6 km of the hydrophone in broadband and decade bands during the analysis period from ULS recordings. Time periods when seafloor current speed exceeded 0.5 m/s were excluded before calculating the CDFs. Table 3 lists the differences in percentiles and the L_{eq} .

Table 3. Increases in sound levels due to Automatic Identification System (AIS) vessel presence within 6 km of the hydrophone for different frequency bands during the analysis period. Differences were calculated for time periods when seafloor current speed was less than 0.5 m/s. Most differences between the AMAR and ULS statistics in the 10–100 Hz band were due to mooring noise (see Sections 3.1.1 and 3.1.2).

Recorder	Band (Hz)	Increase in SPL due to AIS vessel presence (dB)					
		L_{95}	L_{75}	L_{50}	L_{25}	L_5	L_{eq}
AMARs G3 and G4	10–64,000	17.2	17.3	14.9	8.1	4.3	4.5
	10–100	20.6	23.0	15.9	7.4	4.0	4.1
	100–1,000	17.5	17.9	16.9	17.0	15.4	14.3
	1,000–10,000	11.0	12.4	12.2	12.7	14.9	13.8
	10,000–64,000	2.8	4.4	6.7	7.7	14.0	9.0
ULS	10–256,000	9.1	15.8	18.2	19.7	22.2	13.8
	10–100	12.9	23.8	26.4	27.0	25.7	14.2
	100–1,000	16.0	17.0	17.2	17.5	19.6	13.4
	1,000–10,000	9.5	11.6	11.1	11.1	12.8	10.6
	10,000–100,000	0.6	2.9	5.4	6.5	10.3	3.9
	100,000–256,000	0.0	0.0	0.0	0.0	0.5	2.7

3.2. Marine Fauna Detection Results

A total of 12,303 killer whale vocalizations and 15,161 humpback whale vocalizations were reported by the automated detector at Boundary Pass from 16 Oct 2019 to 31 Dec 2020. No Pacific white-sided dolphin vocalizations were detected at Boundary Pass during this period. The automated detector identified nearly 90,000 potential fish sounds from 16 Oct 2019 to 1 Jul 2020. There were too many detections to review all of them manually, so an experienced analyst reviewed a selection of detections using PAMLab. No true fish sounds were identified by the analyst in the selected fish detections for the recording period from 16 Oct 2019 to 1 Jul 2020. However, after that period, there were fewer fish detections so it was feasible for an analyst to review all of the detections, and a total of 403 true fish sounds were verified within the set of automated detections at Boundary Pass from 1 Jul to 31 Dec 2020 (ULS only). We suspect that AMAR mooring noise contributed to the large number of false fish-sound detections and the quieter ULS moorings allowed for better automated detector performance and made it easier to observe true fish sounds above background noise levels. Figure 29 shows the proportion of detections by species from 16 Oct 2019 to 31 Dec 2020 (humpback and killer whales only). The hourly and daily detection counts of killer whale vocalizations, humpback whale vocalizations, and fish sounds are illustrated in Figures 30, 31, and 32, respectively.

In total, killer whale vocalizations were detected on 83 days (19% of the recording period, Table 4). The month with the most days of these detections was December 2019 (15 days). In total, humpback whale vocalizations were detected on 148 days (33% of the recording period, Table 4). November and December 2019 were the months with the most days of humpback whale detections (21 and 25 days, respectively). No Pacific white-sided dolphins were detected on Boundary Pass recordings during the reporting period (16 Oct 2019 to 31 Dec 2020). In total, fish sounds were detected on 29 days (15% of the analyzed period for fish sounds, Table 4). Most of these were in fall 2020 (October, November, and December; 21 days).

Some spectrograms of killer whale vocalizations, humpback whale vocalizations, and fish sounds are illustrated in Figure 33.

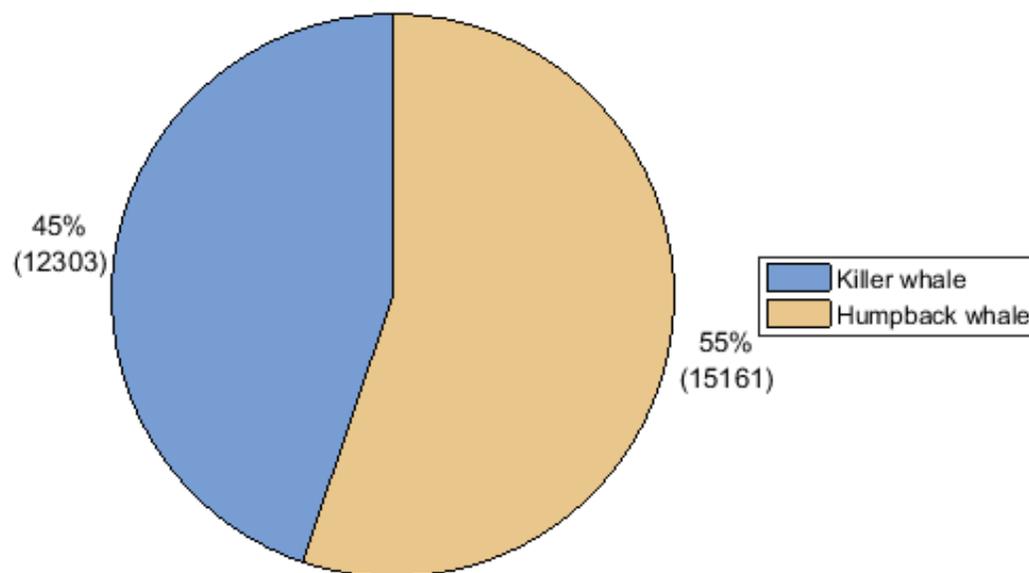


Figure 29. Proportion of detections by marine mammal species for Year 2 (16 Oct 2019 to 31 Dec 2020).

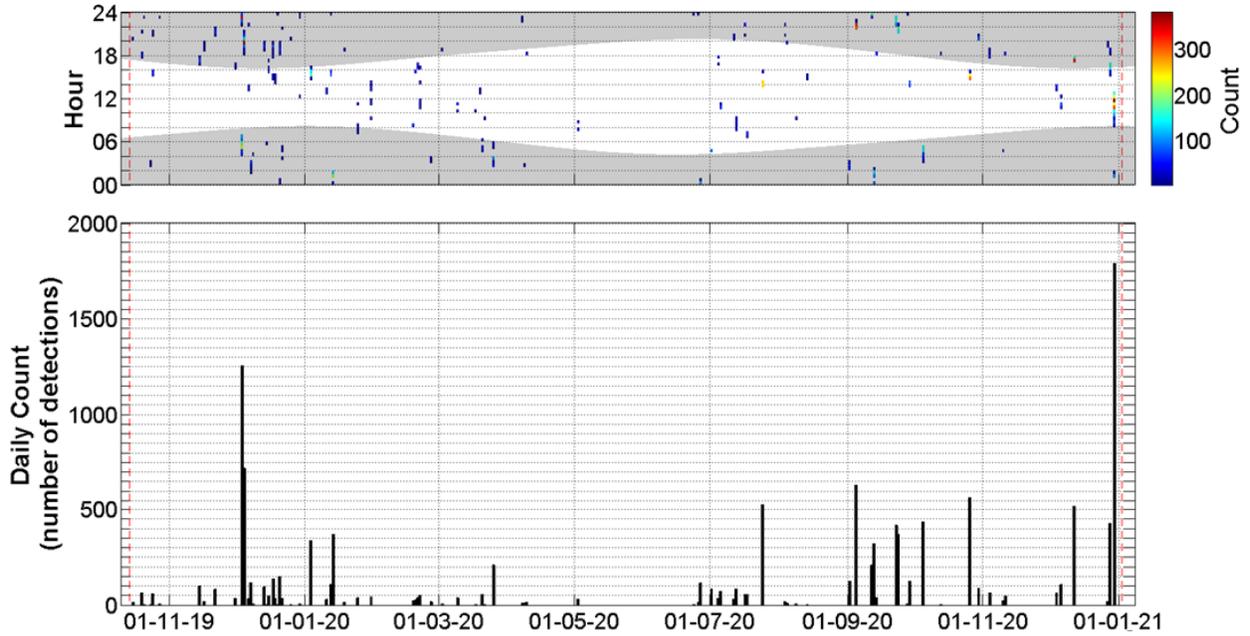


Figure 30. (Top) Hourly and (bottom) daily detection counts (PST) of killer whale vocalizations for Year 2 (16 Oct 2019 to 31 Dec 2020). In the top panel, sunset to sunrise hours are shaded in grey.

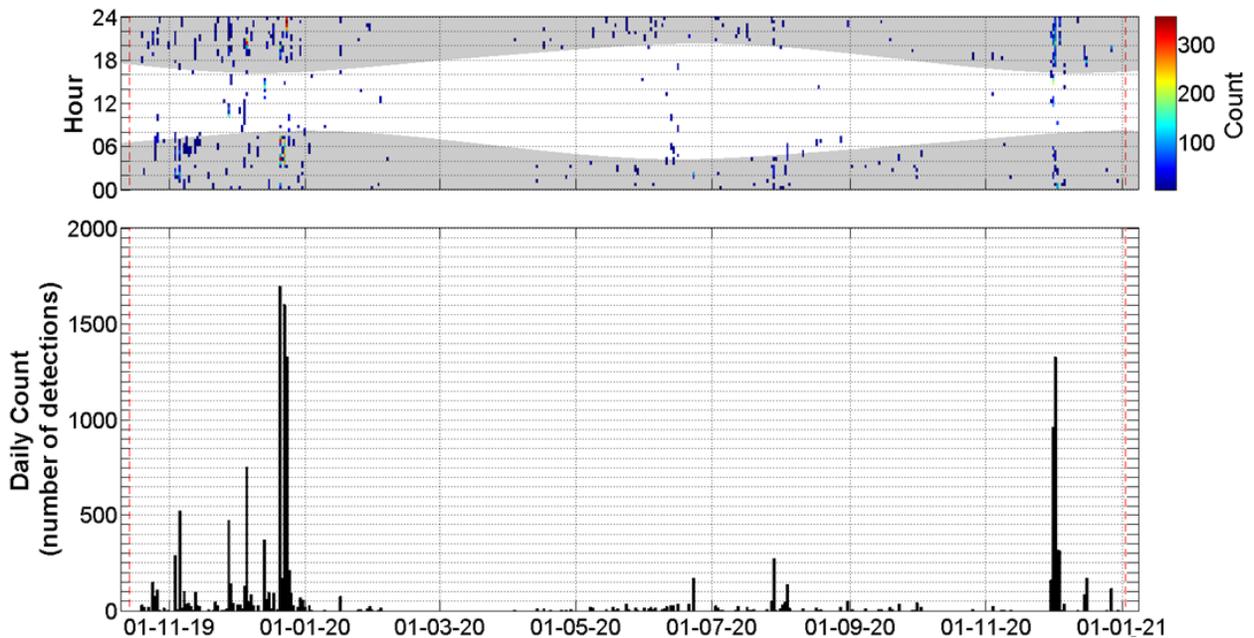


Figure 31. (Top) Hourly and (bottom) daily detection counts (PST) of humpback whale vocalizations for Year 2 (16 Oct 2019 to 31 Dec 2020). In the top panel, sunset to sunrise hours are shaded in grey.

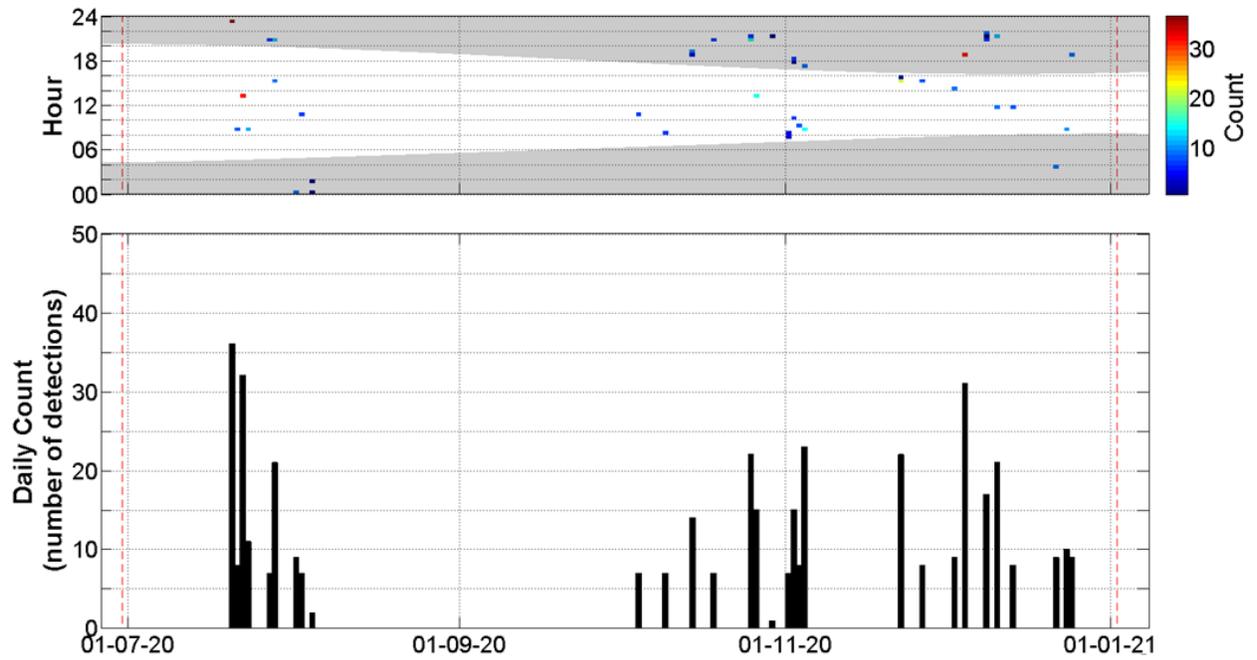


Figure 32. (Top) Hourly and (bottom) daily detection counts (PST) of fish sounds for Year 2 (ULS only, 1 Jul to 31 Dec 2020). In the top panel, sunset to sunrise hours are shaded in grey.

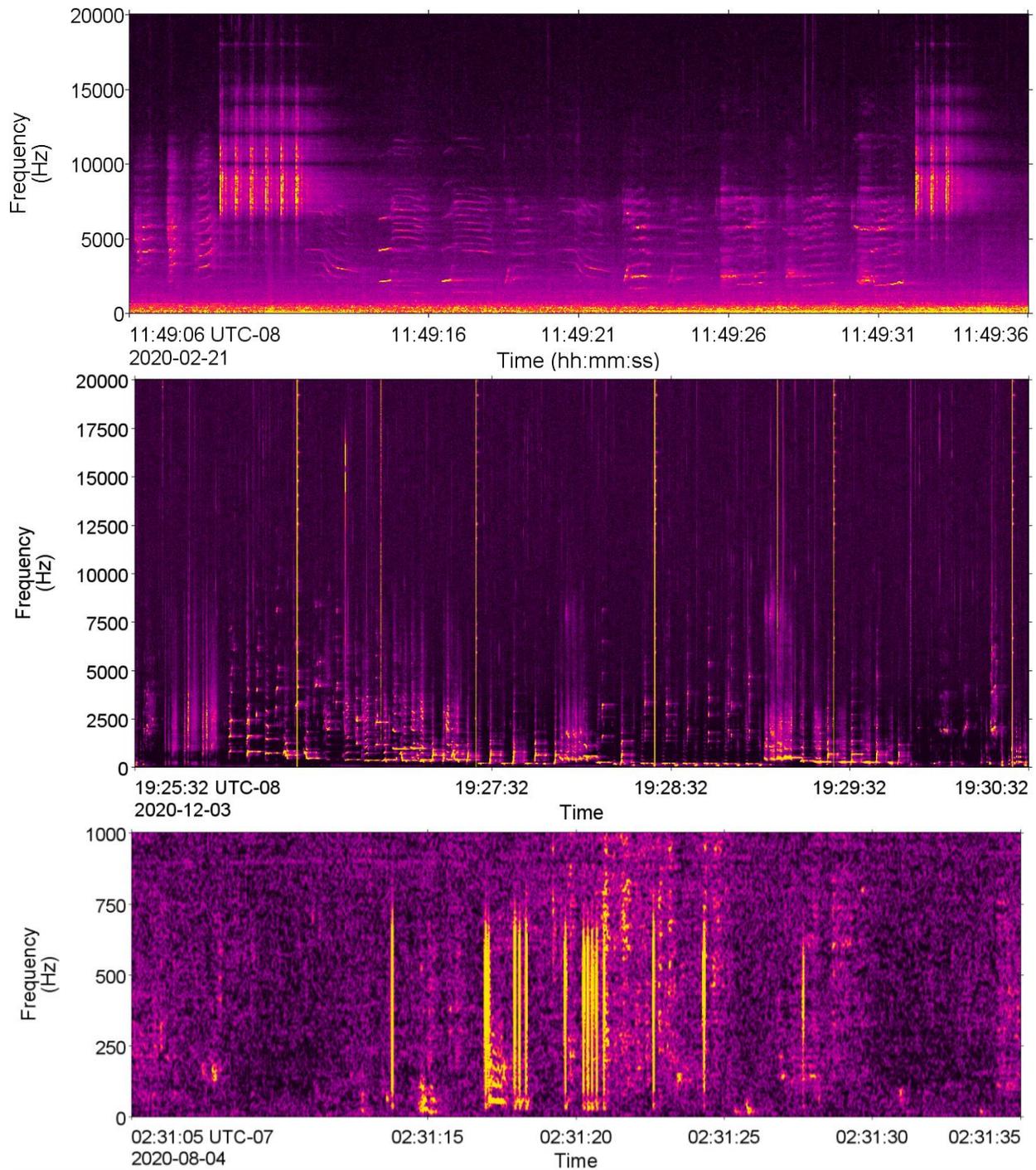


Figure 33. Spectrogram of vocalizations from (top) killer whales on 21 Feb 2020 (PST), (middle) humpback whales on 3 Dec 2020 (PST), and (bottom) fish sounds on 4 Aug 2020 (PDT). Both top and bottom panels show 30 seconds of data, and the middle panel shows 300 seconds of data.

Table 4. Number of marine mammal detections and days with detections by calendar month and species for Year 2 (16 Oct 2019 to 31 Dec 2020).

Month	Humpback whale		Killer whale		Pacific white-sided dolphin		Fish	
	Number of detections	Days with detections	Number of detections	Days with detections	Number of detections	Days with detections	Number of detections	Days with detections
Oct 2019*	452	9/15	176	6/15	0	0/15	NA	NA
Nov 2019	2009	21/30	251	4/30	0	0/30	NA	NA
Dec 2019	7137	25/31	2685	15/31	0	0/31	NA	NA
Jan 2020	188	8/31	967	7/31	0	0/31	NA	NA
Feb 2020	29	3/29	177	5/29	0	0/29	NA	NA
Mar 2020	0	0/31	343	7/31	0	0/31	NA	NA
Apr 2020	67	7/30	51	3/30	0	0/30	NA	NA
May 2020	172	11/31	37	1/31	0	0/31	NA	NA
Jun 2020	447	12/30	145	3/30	0	0/30	NA	NA
Jul 2020	502	14/31	974	8/31	0	0/31	115	5/31
Aug 2020	368	10/31	52	4/31	0	0/31	18	3/31
Sep 2020	178	9/31	2267	7/30	0	0/30	0	0/31
Oct 2020	32	2/31	1102	4/31	0	0/31	73	7/31
Nov 2020	1170	6/30	145	3/30	0	0/30	83	6/30
Dec 2020	2403	11/31	2938	6/31	0	0/31	114	8/31

* Total number of recording days for this report was only 15 because the previous reporting period ended on 16 Oct 2019 (see Table 2).

3.3. Vessel Source Level Measurement Summary

A total of 8069 vessel source level measurements were made using JASCO's ShipSound application during this study period. Of these, 5751 (approximately 71%) passed the manual quality control checks. Figure 34 shows the number of accepted measurements 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". The number of measurements are lower for the first month (October 2019) because measurements reported are for only 15 days of that month. Appendix F contains tables of the number of accepted measurements and the acceptance rates corresponding to the data shown in Figure 34. Table 5 lists radiated noise levels (RNL) statistics by vessel category for all accepted measurements during the study period. Monopole source levels (MSL) for vessel categories with more than 50 accepted measurements during the study period are shown in Figure 35.

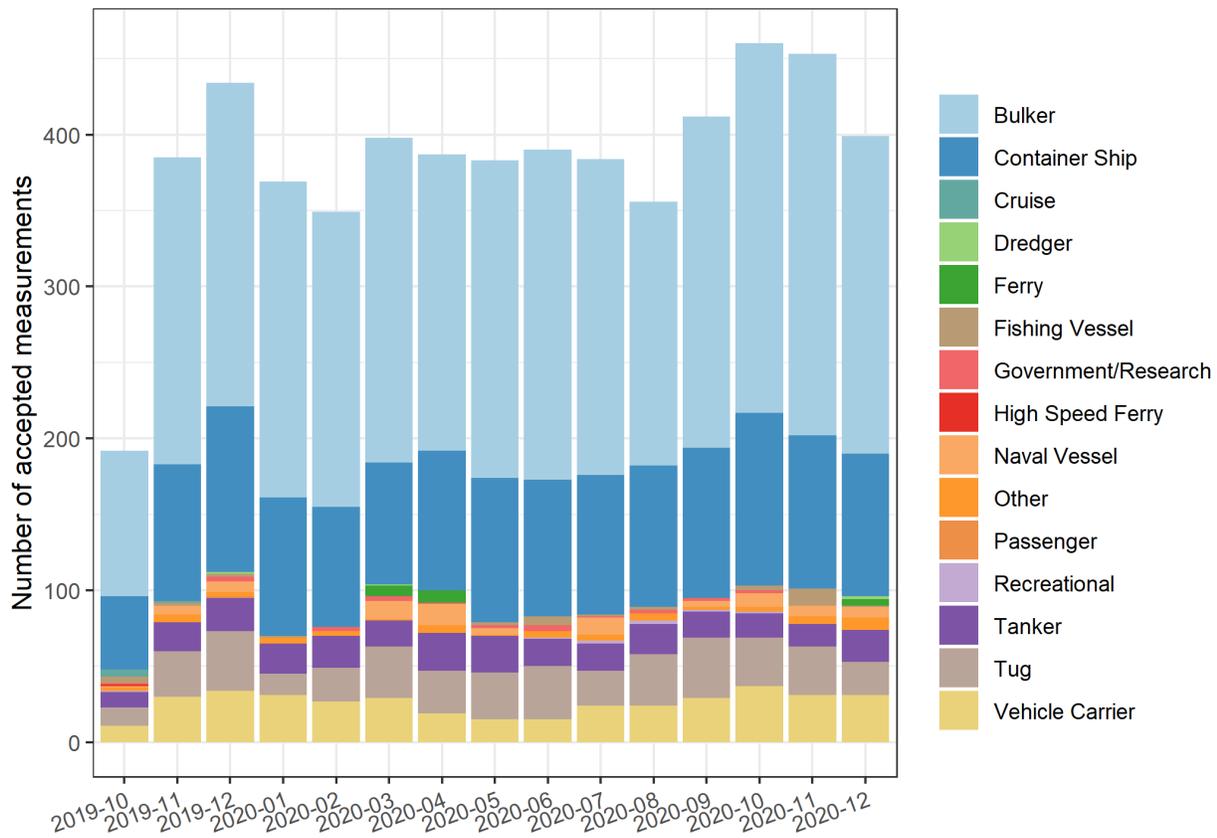


Figure 34. Number of vessel source level measurements, by vessel category, that passed the manual quality control checks for each calendar month.

Table 5. Summary of broadband radiated noise levels (RNL) by vessel category.

Vessel class	Max RNL (dB re 1 μ Pa m)	Average RNL (dB re 1 μ Pa m)	Min RNL (dB re 1 μ Pa m)	Number of accepted measurements	Percent of accepted measurements
Bulker <200 m	202.5	188.3	169.5	1441	25.1
Bulker \geq 200 m	204.0	188.8	174.7	1610	28.0
Container Ship <200 m	190.7	186.2	181.8	2	<0.1
Container Ship \geq 200 m	205.4	192.1	177.2	1365	23.7
Dredger	186.7	184.6	181.2	4	0.1
Ferry \geq 50 m	191.2	180.9	168.4	19	0.3
Fishing Vessel	189.3	180.8	170.7	35	0.6
Government/Research	192.1	177.1	163.0	24	0.4
High Speed Ferry	177.8	177.8	177.8	1	<0.1
Naval Vessel	201.8	169.6	156.8	82	1.4
Other	198.4	185.3	168.4	55	1.0
Passenger \geq 100 m	170.9	170.9	170.9	1	<0.1
Passenger <100 m	192.6	182.6	171.6	6	0.1
Recreational	188.9	175.1	165.1	8	0.1
Tanker	197.8	187.9	176.0	283	4.9
Tug <50 m	200.8	181.8	168.7	362	6.3
Tug \geq 50 m	194.4	186.5	175.3	66	1.1
Vehicle Carrier	202.2	189.5	174.8	387	6.7
All vessels	205.4	188.5	156.8	5751	100.0

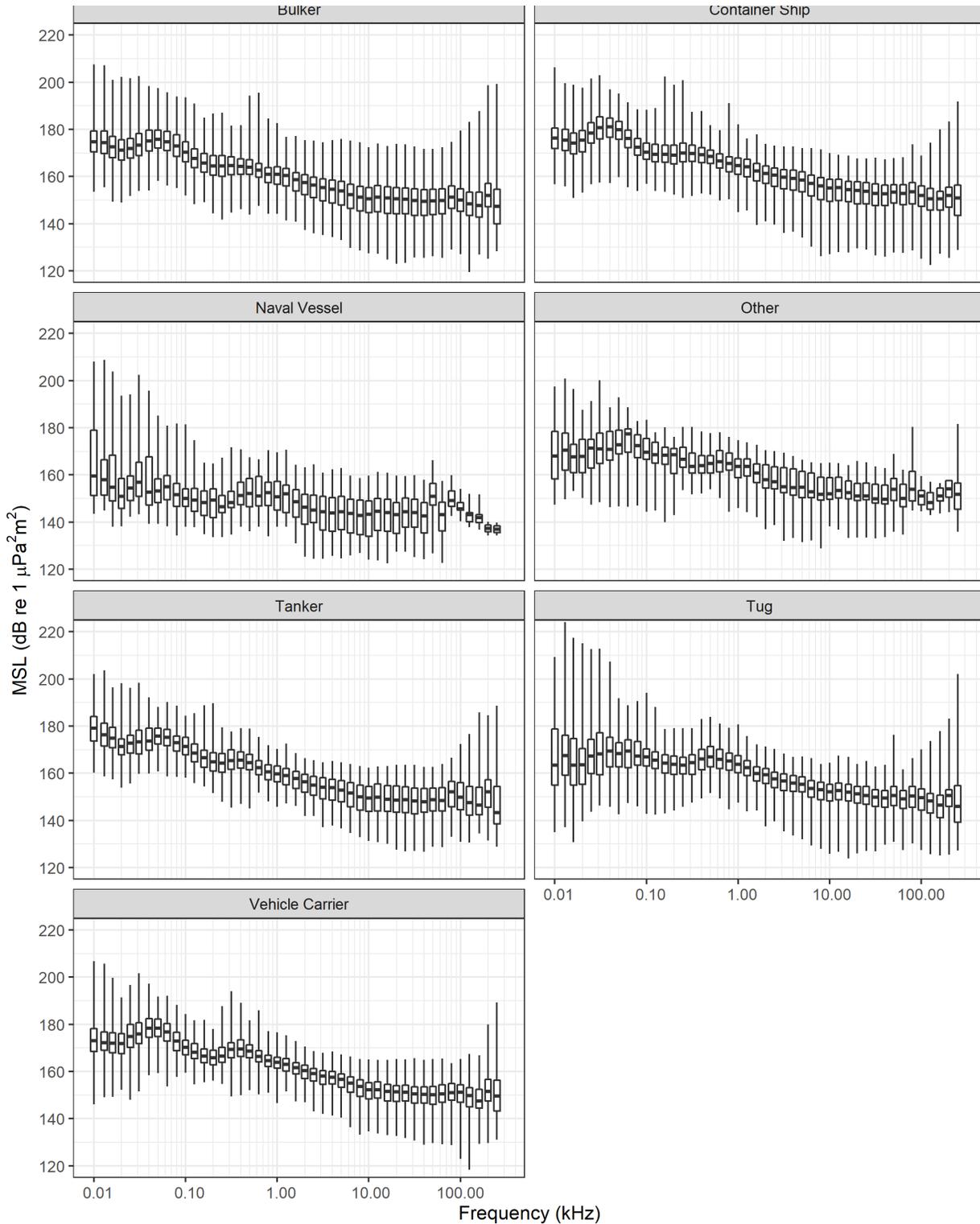


Figure 35. Box-and-whisker plots of monopole source levels (MSL) for vessel categories with more than 50 accepted measurements during the study period. The abrupt change in the Naval Vessel MSL distributions above 63 kHz is because relatively few Naval Vessel measurements were made on the ULS (the only recording system to provide source levels above this frequency).

The vessel's CPA distance was correlated with the probability of failing the manual quality control checks. Figure 36 shows the cumulative density functions for accepted and rejected measurements. Figure 37 shows the acceptance and rejection rates as a function of CPA distance.

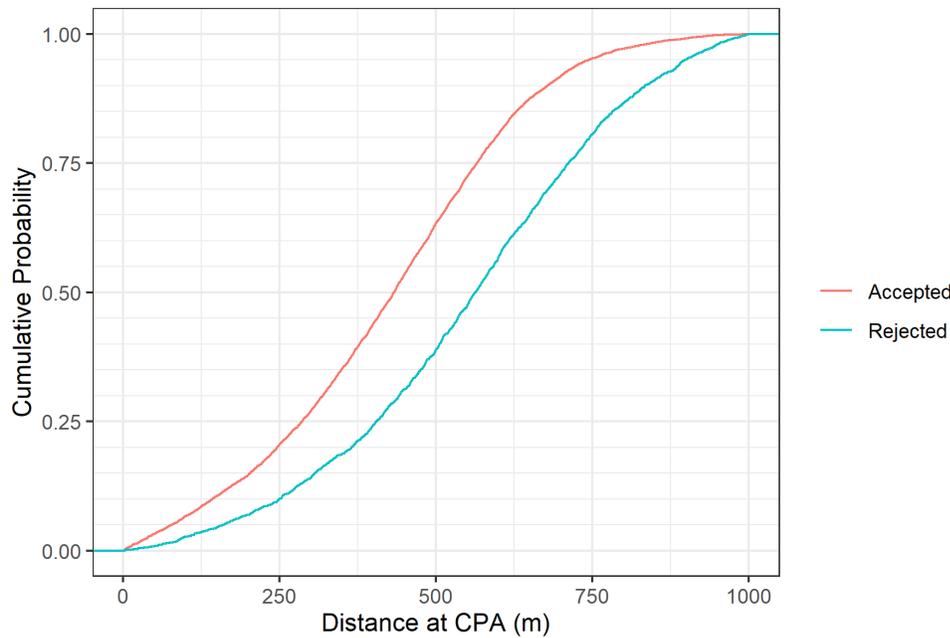


Figure 36. Cumulative distribution functions (CDFs) for distance at the closest point of approach (CPA) for vessels which were accepted (passed manual quality control) and rejected (did not pass quality control checks).

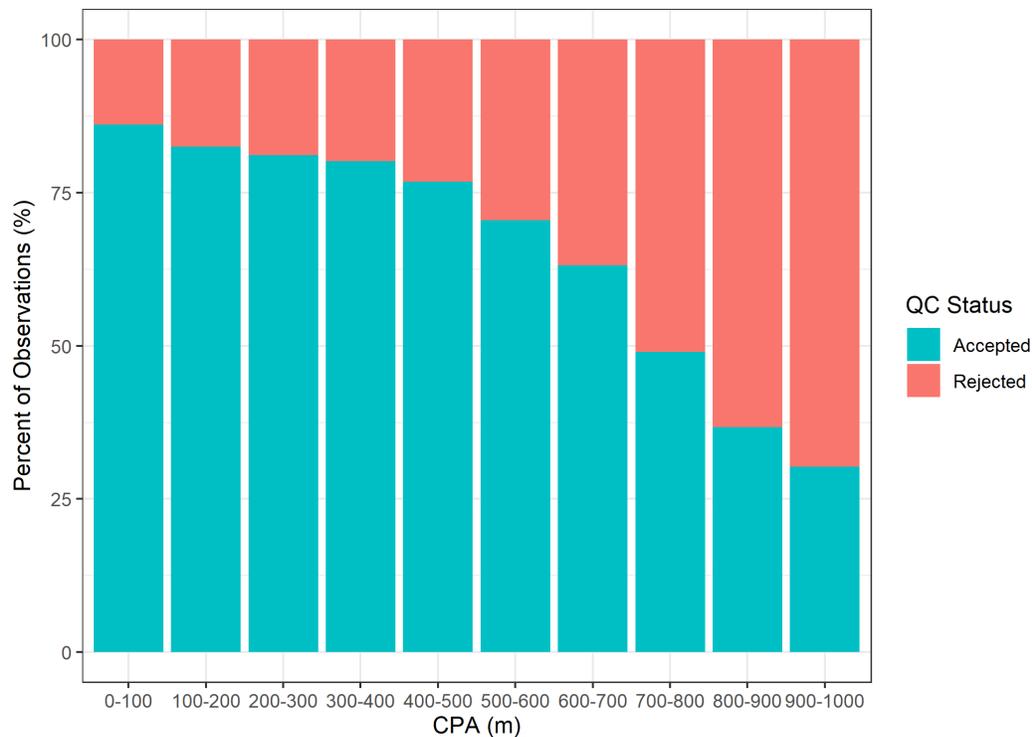


Figure 37. Acceptance and rejection rates of vessels by (horizontal) closest point of approach (CPA) distance.

The hydrophone location was originally chosen to minimize the average distance of vessel tracks from the ULS based on the historic distributions of inbound and outbound traffic. Figure 38 shows histograms of the CPA distances for accepted and rejected measurements along a line in the cross-track direction. The figure is limited to CPA distances of 1 km because that is the maximum measurement distance criterion used here in ShipSound. The histograms show that the vessels have a more constrained outbound route than when they are inbound. 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.

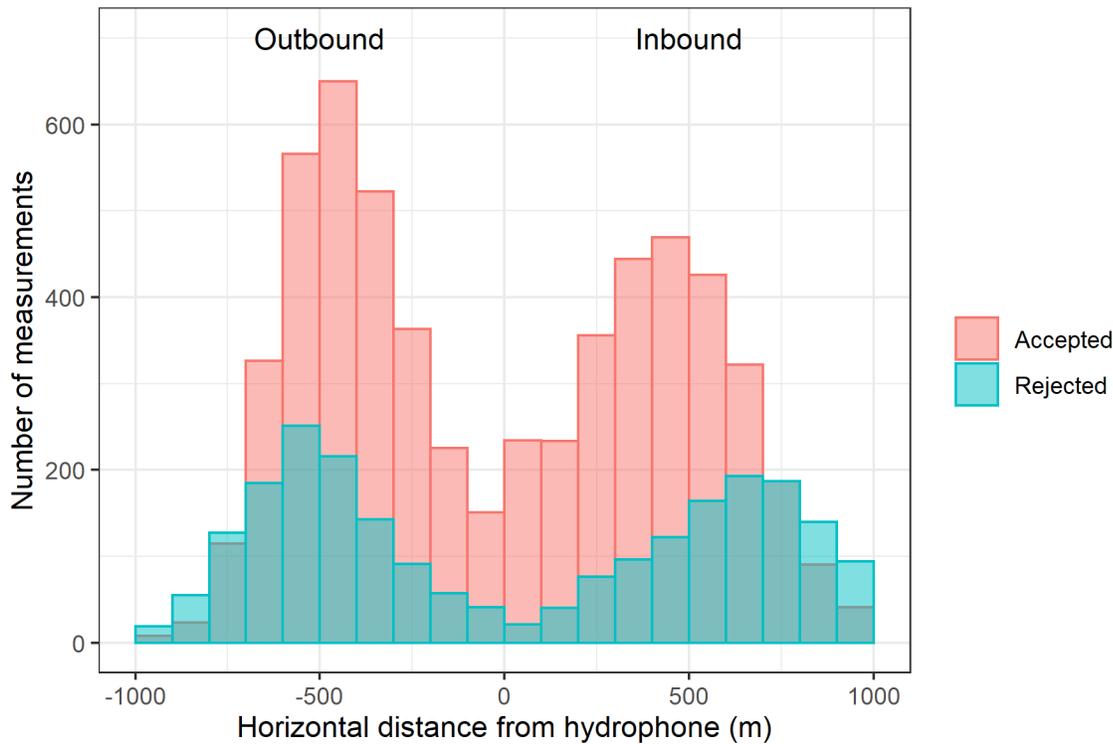


Figure 38. Histogram of closest point of approach (CPA) distances in the cross-track direction.

Table 6 lists the measurement rejection reasons from the manual quality review phase and the corresponding percent of rejected measurements for each reason. “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. These measurements were generally rejected during manual quality review.

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. Approximately 6% of the rejected measurements were for this reason.

Oscillating interference patterns in the spectrogram were the cause for rejection of approximately 4% of the rejected measurements. Figure 39 shows an example spectrogram of a measurement that was rejected for this reason. The CPA cannot be determined accurately for these measurements, and there is a potential for errors due to incorrect propagation loss distance correction. This effect was only observed on the autonomous hydrophones, and it was likely due to fluctuating water currents and turbulence

pushing the mooring over and oscillating the hydrophone height above seabed during the vessel measurement. Some of these measurements may be recoverable by a more detailed manual analysis. This is no longer a problem as the cabled ULS hydrophones are mounted on rigid frames.

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 (%)
Other vessels nearby	66
Many frequency bands contaminated by background noise	24
Vessel sound levels saturated the recording system	6
Oscillating spectrogram interference pattern	4
Other	2

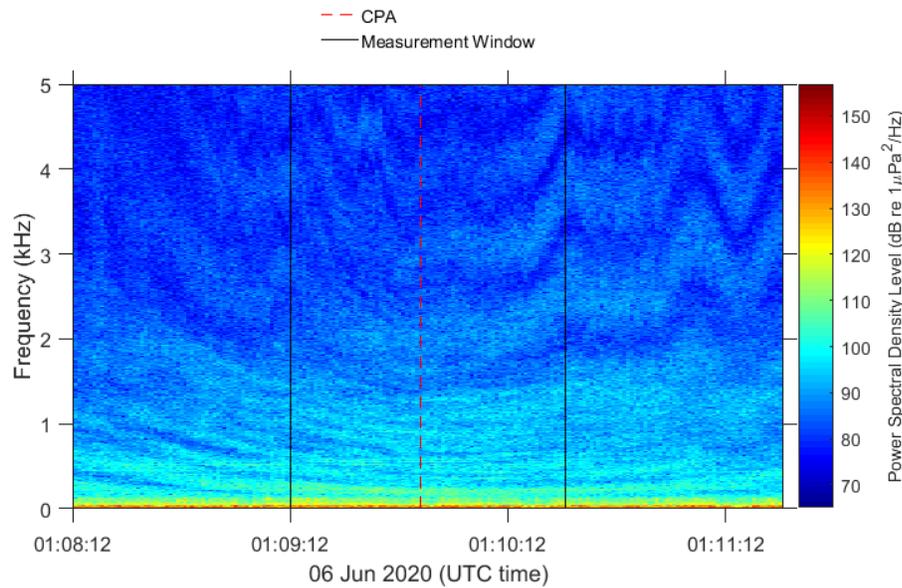


Figure 39. Oscillating interference patterns in a spectrogram for a tug passing AMAR 629 in Boundary Pass. This measurement was rejected because of the spectrogram oscillation, which is most visible in this spectrogram at frequencies above 2 kHz.

4. Discussion and Conclusion

Ambient noise in Boundary Pass was found to be affected by current-induced water flow and mooring noise, wind speed, and vessel traffic. The fast currents in Boundary Pass are up to 2.4 m/s (4.7 knots) and these caused elevated sound levels in all decade bands except the 1–10 kHz band. The mooring design had a large influence on the severity of the current-related noise. In terms of flow noise, the solid ULS frames had the best performance and the mooring for the AMAR G4 629 had the worst performance, with the latter producing sound throughout its recording period (31 Jan to 14 Jun 2020) that affected both the high and low sound level statistics (Figure 13). Low-frequency sound levels from the G4 recordings appeared elevated even at low current speeds and had a bi-modal distribution, suggesting there may be some instability in the mooring design used for that deployment.

The near-seafloor and near-surface current speeds measured at the autonomous ADCP deployment location, at approximately 1.5 km from the AMARs, appeared higher than those at the hydrophones. The autonomous ADCPs were deployed on a bathymetric pinnacle at ~100 m depth, while the AMARs were deployed in 190 m depth. In contrast, the ADCP deployed in conjunction with the ULS was attached to the same frame as the hydrophones. This is likely why the trends of sound levels with current speed were clearest for the ULS recordings.

AMAR 629 recordings overlapped with the ULS recordings from 8–14 Jun 2020, allowing for a comparison in noise levels. The differences in ambient noise levels were largest in the first two decades (10–1000 Hz), which was largely due to mooring noise on the AMAR. During louder periods (e.g., with vessel presence), the decade distributions were in much better agreement because the mooring noise was masked by the higher level ship noise. At higher frequencies (above ~10 kHz), the differences were largely due to different noise floor characteristics of the hydrophones. The HTI hydrophones (used on ULS frame B) had a higher noise floor than the GTI hydrophones (ULS frame A and AMAR 629).

Vessel traffic presence, assessed using AIS records, led to substantial increases in ambient sound levels. Sound levels in all frequency bands increased by several decibels when AIS vessels were within 6 km of the hydrophone, with the exception of the highest frequency band recorded on the ULS (100–256 kHz). Median broadband sound levels increased by ~15 and ~18 dB when AIS vessels were within 6 km of the AMAR hydrophones or ULS, respectively (Table 3). The increases were largest in the 10–100, 100–1000, and 1–10 kHz bands on both the AMARs and the ULS. The higher frequency 10–64 kHz band on the AMARs, and the 10–100 kHz band on the ULS also increased substantially for the L_5 percentile (i.e., the loudest 5% of time). This may have been caused by hull-mounted high-frequency sonars elevating ambient sound levels during relatively brief periods as the vessels transited over the recorders. There was only a small increase in 100–256 kHz levels measured by the ULS, likely because sound energy at those frequencies is absorbed quickly by seawater. We expect the influence of vessel traffic on higher frequency levels would be important if the distance limit was set to much shorter than 6 km.

Long-term trends in ambient sound levels were influenced largely by changes in mooring noise, even after filtering out time periods when current speeds exceeded 0.5 m/s. Across time periods with consistent equipment, sound levels appeared to increase during winter when wind speeds were higher. A small increase in high-level percentiles was observed in November and December 2020, the start of which coincided with the end of the ECHO program's 2020 voluntary slowdown in Haro Strait and Boundary Pass. Sound levels did not appear to be dependent on the day of the week but were found to increase during daylight hours in summer.

Over 27,800 marine fauna detections were found in the acoustic data for the ~15 month study period. Most (55%) of these were from humpback whales, and the detections occurred throughout all seasons of the study period, but not all months, with no humpback detections in March 2020 (Figure 31). The remaining marine mammal detections were from killer whales, which were found in all months (Figure 30). There was a substantial increase in marine fauna detections in Year 2 of the study compared with Year 1 (Warner and Frouin-Mouy 2019). As mentioned earlier, the ULS produced less mooring noise than the AMARs, allowing for better detection of quieter marine mammal calls and fish sounds after its deployment. Fish detections were limited to the ULS recordings (July to December 2020). No fish sounds were detected in the previous year of the study. These results indicate that the lack of detections prior to

the deployment of the ULS were likely due to masking by mooring-related noise rather than a true absence of fish.

Over 8000 vessel source level measurements were analyzed with JASCO's ShipSound application for this analysis period. A large proportion of these measurements were of bulker (53%) and container ships (24%). Container ships had the highest average radiated noise levels (RNL), followed by vehicle carriers, bulkers, tankers, and large tugs. The quietest vessel type was naval vessels. Source level measurements are dependent on receiving AIS data from the vessels, so recreational vessels may be underrepresented in the database because they are less likely to carry AIS transmitters. The hydrophone locations were suitable for processing source level measurements for vessels travelling in both the incoming and outgoing international shipping lanes (Figure 38). The rate at which vessels passed the manual quality control checks was found to decrease for vessels that had larger CPA distances. The overall measurement acceptance rate was 71% and was greater than 50% for vessels passing within 700 m of the hydrophones (Figure 37). The most frequent reason for rejection of source level measurements was the presence of other vessels nearby (66%) followed by contamination by background noise in multiple frequency bands, especially in the 50–1000 Hz range (24%). 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.

5. Acknowledgements

We thank Greg Bellavance and the crew of the *Moving Experience* for their assistance with deploying and retrieving the autonomous underwater monitoring equipment. We thank David Osborne for allowing us to install our shore-based AIS logger at his home on Saturna Island. JASCO's field teams included Connor Grooms, H elo ise Frouin-Mouy, Jennifer Wladichuk, and Graham Warner.

The cabled ULS was designed by JASCO's engineering personnel: John Moloney, Art Cole, Craig Hillis, Ron Burke, and Jack Hennessey, several of whom participated in its final assembly, testing and deployment in May 2020. JASCO's IT team led by Jason Reym set up the sophisticated data management and backup systems at Saturna Island. Mike Shaw and the crew at Island Tug and Barge provided expert cable lay services including the lowering of the ULS hydrophone frames to the seabed. This has been a wonderful group effort performed by a highly talented group of people.

Glossary

1/3-octave

One third of an octave. Note: A one-third octave is approximately equal to one decidecade ($1/3 \text{ oct} \approx 1.003 \text{ ddec}$; 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.

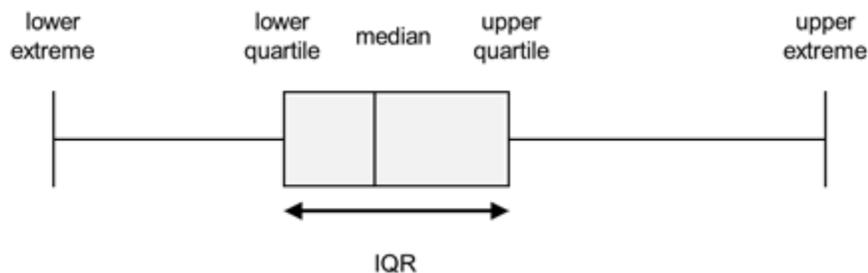


Figure 40. Diagram showing how quantiles are displayed on a box-and-whisker plot. IQR = interquartile range (i.e., the range between the 25th and 75th percentile).

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 ($1 \text{ ddec} \approx 0.3322 \text{ oct}$) 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.

Leq

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: $\mu\text{Pa}^2/\text{Hz}$.

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 ($p_0 = 1 \mu\text{Pa}$) and the unit for SPL is dB re $1 \mu\text{Pa}^2$:

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

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 $1 \mu\text{Pa}^2 \cdot \text{m}^2$ (pressure level) or dB re $1 \mu\text{Pa}^2 \cdot \text{s} \cdot \text{m}$ (exposure level).

spectral density level

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

spectrogram

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

spectrum

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

synodic month

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

transmission loss (TL)

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

Literature Cited

- [ANSI] American National Standards Institute. 12.64-2009 (R2014). *Grade C – Survey Method - Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements*.
- [ANSI] American National Standards Institute. S1.1-1994 (R2004). *American National Standard: Acoustical Terminology*. NY, USA. <https://webstore.ansi.org/Standards/ASA/ANSIS11994R2004>.
- [ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.13-2005 (R2010). *American National Standard: Measurement of Sound Pressure Levels in Air*. NY, USA. <https://webstore.ansi.org/Standards/ASA/ANSIASAS1132005R2010>.
- [ANSI] American National Standards Institute. S12.7-1986 (R2006). *American National Standard: Methods for Measurements of Impulsive Noise*. NY, USA. <https://webstore.ansi.org/Standards/ASA/ANSIS121986R2006>.
- [ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S12.64-2009. *American National Standard: Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements*. NY, USA. <https://webstore.ansi.org/Standards/ASA/ANSIASAS12642009Part>.
- [ISO] International Organization for Standardization. 2006. *ISO 80000-3:2006 Quantities and units – Part 3: Space and time*. <https://www.iso.org/standard/31888.html>.
- [ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. <https://www.iso.org/standard/62406.html>.
- [NOAA] National Oceanic and Atmospheric Administration (US). 2013. *Draft guidance for assessing the effects of anthropogenic sound on marine mammals: Acoustic threshold levels for onset of permanent and temporary threshold shifts*. National Oceanic and Atmospheric Administration, US Department of Commerce, and NMFS Office of Protected Resources, Silver Spring, MD, USA. 76 p.
- Breiman, L. 2001. Random Forests. *Machine Learning* 45(1): 5-32. <https://doi.org/10.1023/A:1010933404324>.
- Dewey, R., T. Dakin, X. Mouy, and I.R. Urazghildiiev. 2015. A regional hydrophone network: Monitor, detect and track. *Underwater Acoustics Conference and Exhibition*. 21-26 Jun 2015, Crete, Greece.
- Fristrup, K.M. and W.A. Watkins. 1993. *Marine animal sound classification*. Report Number WHOI-94-13. Woods Hole Oceanographic Institution. 32 p. <http://darchive.mblwhoilibrary.org:8080/bitstream/handle/1912/546/WHOI-94-13.pdf?sequence=1>.
- Frouin-Mouy, H. 2019a. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from Dec 2018 to June 2019*. Document Number 01942, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Frouin-Mouy, H. 2019b. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from June to October 2019*. Document Number 01968, Version 2.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Frouin-Mouy, H. 2020a. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from October 2019 to January 2020*. Document Number 02030, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Frouin-Mouy, H. 2020b. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from January to June 2020*. Document Number 02149, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

- Frouin-Mouy, H. 2020c. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from July to September 2020*. Document Number 02236, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Frouin-Mouy, H. 2020d. *ECHO Program Boundary Pass Hydroacoustic Measurements: Marine Mammal Detections from October to December 2020*. Document Number 02303, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Gray, L.M. and D.S. Greeley. 1980. Source level model for propeller blade rate radiation for the world's merchant fleet. *Journal of the Acoustical Society of America* 67(2): 516-522. <https://doi.org/10.1121/1.383916>.
- Grooms, C. and G.A. Warner. 2019a. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from Dec 2018 to June 2019*. Document Number 01941, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Grooms, C. and G.A. Warner. 2019b. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from June 2019 to October 2019*. Document Number 01967, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Grooms, C.H. and G.A. Warner. 2020. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from October to December, 2020*. Document Number 02294, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Knudsen, V.O., R.S. Alford, and J.W. Emling. 1948. Underwater ambient noise. *Journal of Marine Research* 7: 410-429.
- Mellinger, D.K. and J.W. Bradbury. 2007. Acoustic measurement of marine mammal sounds in noisy environments. *2nd International Conference on Underwater Acoustic Measurements: Technologies and Results*. Heraklion, Greece. pp. 273-280. <ftp://ftp.pmel.noaa.gov/newport/mellinger/papers/Mellinger+Bradbury07-BioacousticMeasurementInNoise-UAM,Crete.pdf>.
- Moloney, J., C.A. Hillis, X. Mouy, I.R. Urazghildiev, and T. Dakin. 2014. Autonomous Multichannel Acoustic Recorders on the VENUS Ocean Observatory. *OCEANS 2014*. 14-19 Sep 2014. IEEE, St. John's, NL, Canada. pp. 1-6. <https://doi.org/10.1109/OCEANS.2014.7003201>.
- Mouy, X., J. Ford, J. Pilkington, K. Kanis, A. Riera, T. Dakin, and P.-A. Mouy. 2015. Automatic Marine Mammal Monitoring off British Columbia, Canada. *7th International DCLDE Workshop*. 13-16 Jul 2015, La Jolla, CA, USA.
- Warner, G.A. and H. Frouin-Mouy. 2019. *Annual Report of Boundary Pass Acoustic Monitoring: Year 1, December 2018 to October 2019*. Document Number 02020, Version 2.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority.
- Warner, G.A. 2020a. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from October 2019 to January 2020*. Document Number 02055, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Warner, G.A. 2020b. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from January to March, 2020*. Document Number 02164, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Warner, G.A. 2021. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from July to September, 2020*. Document Number 02220, Version 2.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).
- Warner, G.A. and T. Dofher. 2021. *ECHO Program Boundary Pass Hydroacoustic Measurements: Ambient Noise from April to June, 2020*. Document Number 02148, Version 2.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority (VFPA).

Appendix A. Example Ambient Noise Report for One Month

A.1. Introduction

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

This report contains analysis of data collected from July to September 2020¹. The acoustic data were processed to compute ambient noise statistics.

A.2. Report Schedule

Table A-1. The analysis was conducted over calendar month periods from July to September 2020. Table A-2 lists the report schedule for the Boundary Pass data.

Month start	Month end	Weeks reported
1 Jul 2020, 00:00 PDT	1 Aug 2020, 00:00 PDT	Sun 5 Jul to Sun 12 Jul Sun 12 Jul to Sun 19 Jul Sun 19 Jul to Sun 26 Jul Sun 26 Jul to Sun 2 Aug
1 Aug 2020, 00:00 PDT	1 Sep 2020, 00:00 PDT	Sun 2 Aug to Sun 9 Aug Sun 9 Aug to Sun 16 Aug Sun 16 Aug to Sun 23 Aug Sun 23 Aug to Sun 30 Aug Sun 30 Aug to Sun 6 Sep
1 Sep 2020, 00:00 PDT	1 Oct 2020, 00:00 PDT	Sun 6 Sep to Sun 13 Sep Sun 13 Sep to Sun 20 Sep Sun 20 Sep to Sun 27 Sep Sun 27 Sep to Sun 4 Oct

A.3. Ambient Noise Data Processing Methods

Location Name: Boundary Pass

Analysis Period: 1 Jul 2020 to 30 Sep 2020

Table A-2. ULS locations and periods used for analysis.

ULS	Hydrophone	Start	End	Latitude	Longitude	Water depth (m)
A1	GTI M36-V35-100	2020-07-01 00:00	2020-09-30 23:59	48° 45.64598' N	123° 3.663361' W	195

ULS A1 has a 150 kHz ADCP that emits pings once every minute. These pings saturate the A1 hydrophones for less than one second each minute. When computing 1-min sound levels, the second that contained saturated ADCP pings were excluded from the averages. The second following the ADCP ping

¹ This report has been truncated for this appendix to only show one month of results

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.

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. 1/3-octave-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 larger 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 1/3-octave levels are calculated similarly to the spectral levels, except the 1-minute spectra are first integrated within the 1/3-octave-bands with centre frequencies between 10 Hz and 50 kHz, which are then displayed at 5th, 25th, 50th, 75th, and 95th percentile levels. The mean band and spectral levels are also shown.
3. One-third-octave-band levels: A tabular presentation of the 1/3-octave-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.

A.4. Results: July 2020

A.4.1. Ambient Sound Pressure Level versus Time

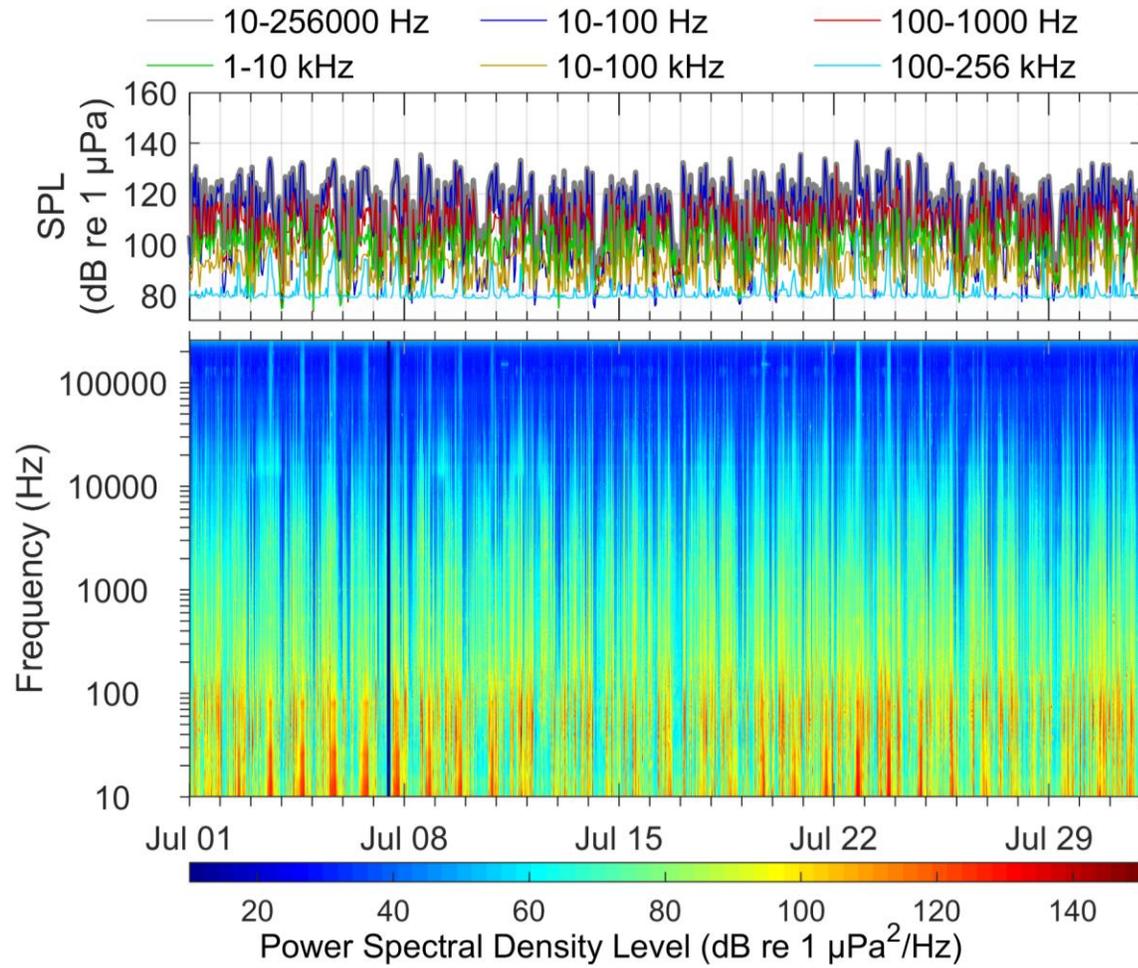


Figure A-1. Broadband, decade band sound pressure level (SPL) versus time and spectrogram through the analysis period (1-hour resolution).

A.4.2. Spectral Levels and 1/3-Octave Band Levels

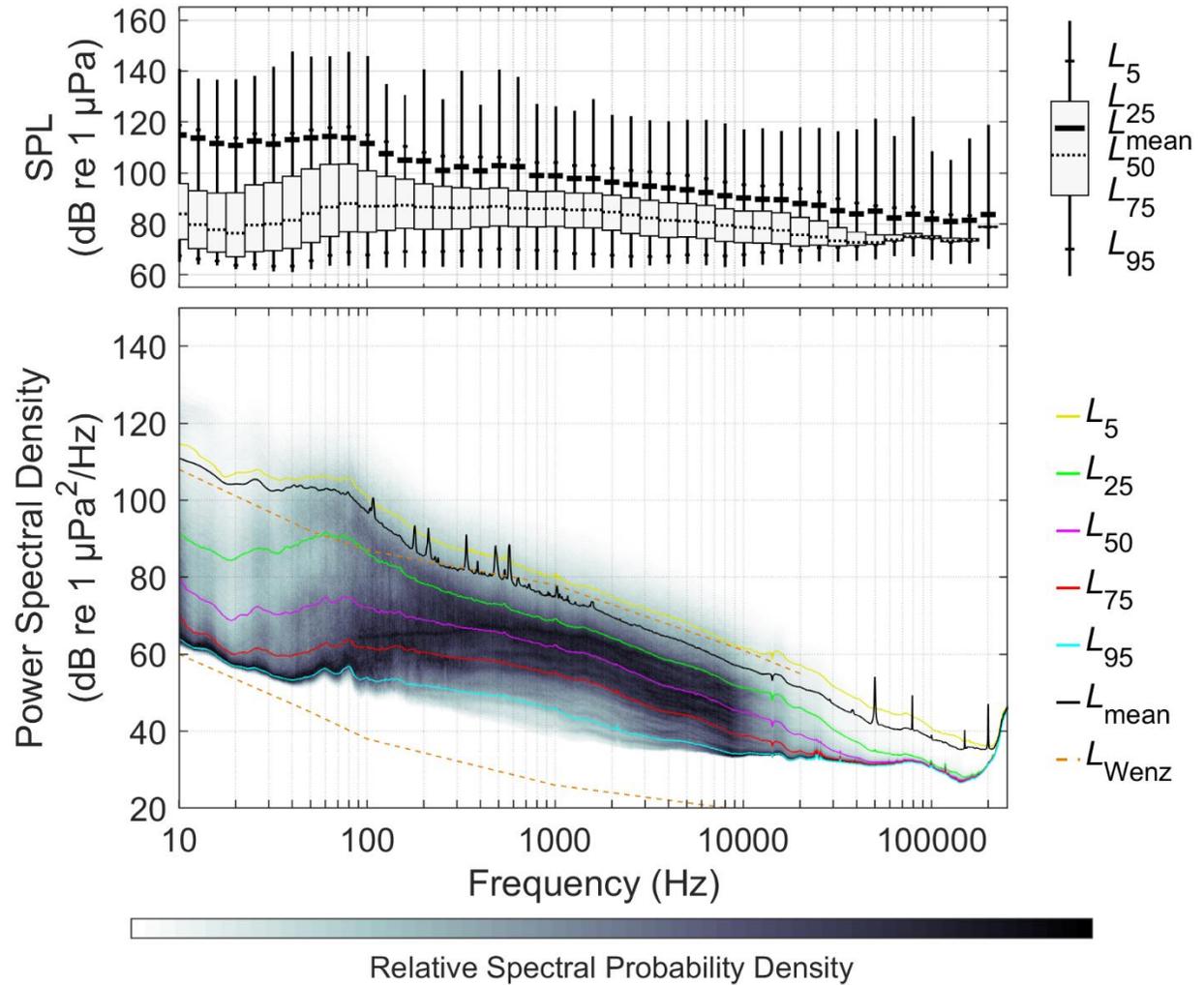


Figure A-2. The top panel shows percentiles and mean 1/3-octave-band sound pressure level (SPL) (1 minute) over the analysis period. The bottom panel shows percentiles and mean power spectral density levels over the same time period.

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

Table A-3. Broadband and 1/3-octave-band sound levels (dB re 1 µPa) for the 95th, 75th, 50th, 25th, and 5th percentiles. Levels correspond to 1-minute SPL.

Frequency (Hz)	L ₉₅	L ₇₅	L ₅₀	L ₂₅	L ₅
Broadband	91.5	96.5	103.5	114.4	129.4
10	67.5	73.9	83.9	95.8	118.8
12.6	66.3	70.3	79.7	93.0	116.9
15.8	65.5	68.9	77.8	92.1	114.0
20	63.8	67.2	76.4	92.2	113.7
25.1	64.0	69.1	79.5	95.4	115.4
31.6	63.4	69.5	80.0	96.2	114.9
39.8	63.4	70.4	81.5	98.7	115.6
50.1	65.6	72.7	84.1	101.6	116.9
63.1	67.7	75.1	86.6	103.4	117.8
79.4	69.0	76.9	88.0	103.5	118.1
100	67.8	76.8	87.0	100.8	115.0
125.9	68.7	77.5	87.0	98.7	112.3
158.5	69.2	78.3	87.3	97.6	110.4
199.5	69.0	77.9	86.7	95.7	108.1
251.2	69.2	77.9	86.5	94.8	106.6
316.2	69.4	78.0	86.3	94.2	106.3
398.1	69.7	78.8	86.6	93.8	106.2
501.2	70.2	79.2	86.9	94.1	106.2
631	70.0	78.9	86.2	93.0	105.2
794.3	69.7	78.8	85.9	92.7	104.1
1000	69.4	79.0	86.0	92.8	104.1
1258.9	68.3	78.5	85.5	92.1	102.9

Frequency (Hz)	L ₉₅	L ₇₅	L ₅₀	L ₂₅	L ₅
1584.9	68.2	78.5	85.5	92.1	103.0
1995.3	67.8	77.5	84.6	91.3	101.9
2511.9	67.3	76.2	83.5	90.2	101.0
3162.3	67.2	75.3	82.3	89.2	100.4
3981.1	67.4	74.7	81.4	88.3	99.8
5011.9	67.8	74.9	81.1	88.0	99.0
6309.6	67.8	74.3	80.6	87.3	97.8
7943.3	67.5	73.1	79.4	86.0	96.4
10000	68.0	72.6	78.7	85.1	95.4
12589.3	68.9	72.5	78.3	85.1	94.9
15848.9	69.4	72.2	77.4	84.4	95.5
19952.6	69.6	71.3	75.7	82.6	93.8
25118.9	70.7	71.7	74.9	81.2	92.5
31622.8	70.8	71.4	73.3	78.6	89.9
39810.7	71.2	71.7	72.8	76.9	88.2
50118.7	71.8	72.1	72.8	75.7	87.1
63095.7	73.1	73.4	73.8	75.7	86.4
79432.8	74.6	74.7	75.1	76.3	86.7
100000	74.2	74.3	74.6	75.3	84.7
125892.5	72.8	73.0	73.4	74.5	83.6
158489.3	73.1	73.3	73.6	74.3	83.3
199526.2	78.7	78.8	78.8	79.0	83.6

A.4.4. Daily Rhythm Plot

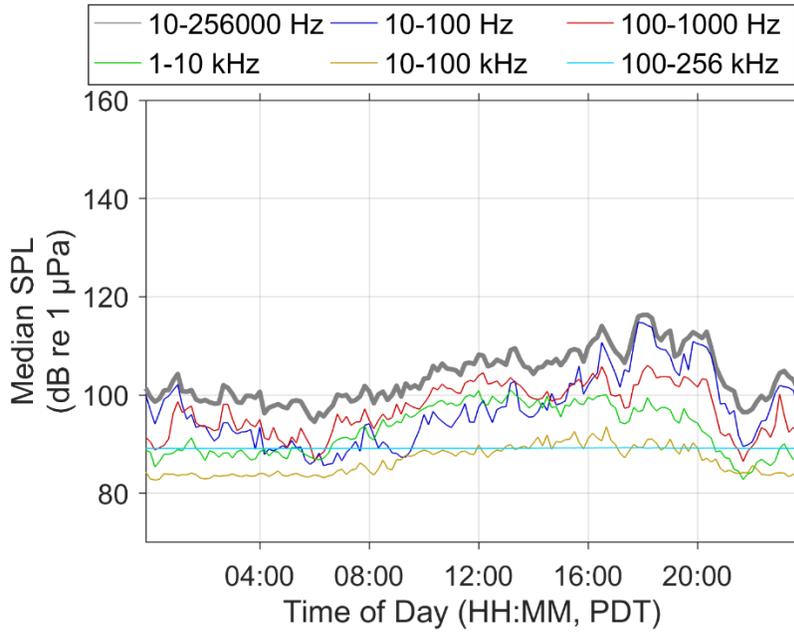


Figure A-3. The median 1-minute sound pressure level (SPL) versus time of day (10-minute resolution) over the analysis period.

A.4.5. Weekly Rhythm Plot

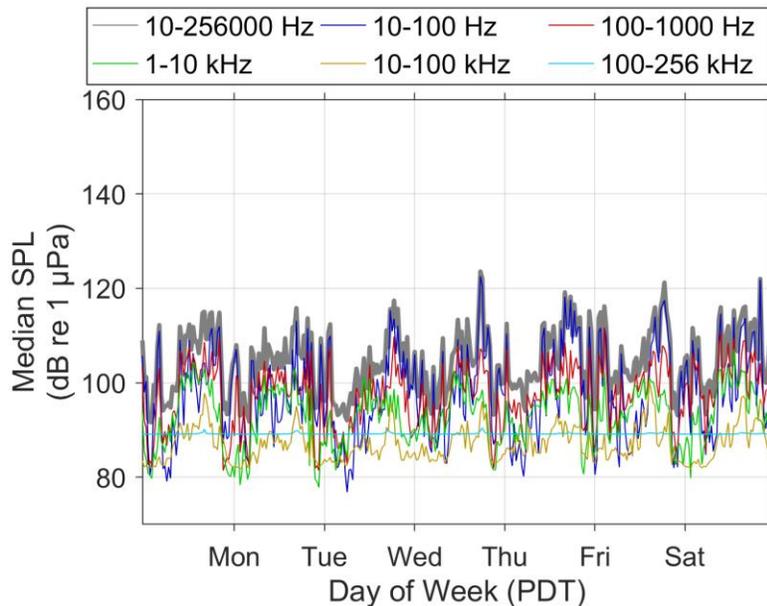


Figure A-4. The median 1-minute sound pressure level (SPL) versus day of week (30-minute resolution) over the analysis period.

A.4.6. SPL Box Plot

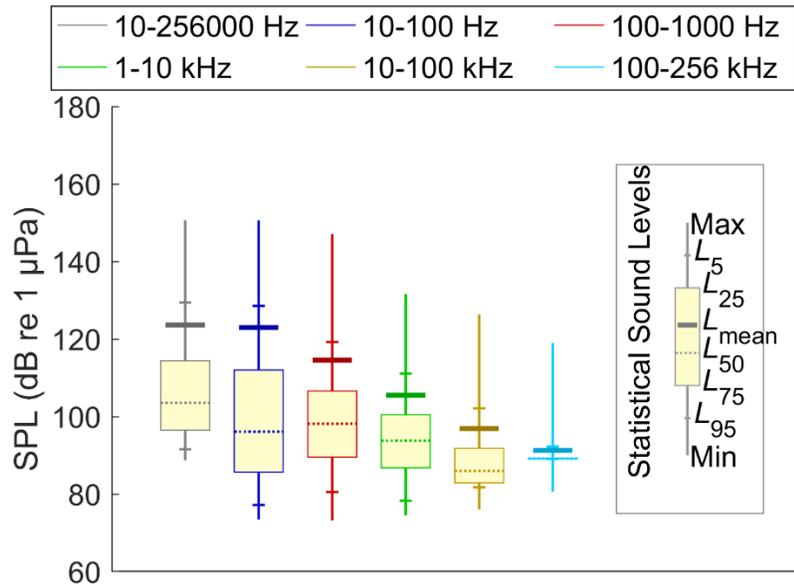


Figure A-5. The broadband and decade-band sound pressure level (1 minute) statistics over the analysis period.

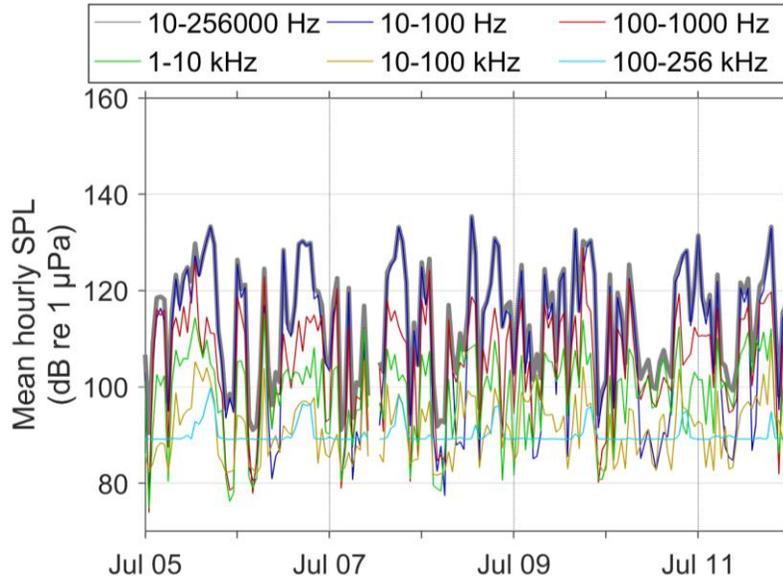
A.4.7. Table of Values

Table A-4. Sound pressure level (1 minute) statistics (dB re 1 µPa) used to generate the sound pressure level (SPL) box plot in Appendix A.4.6.

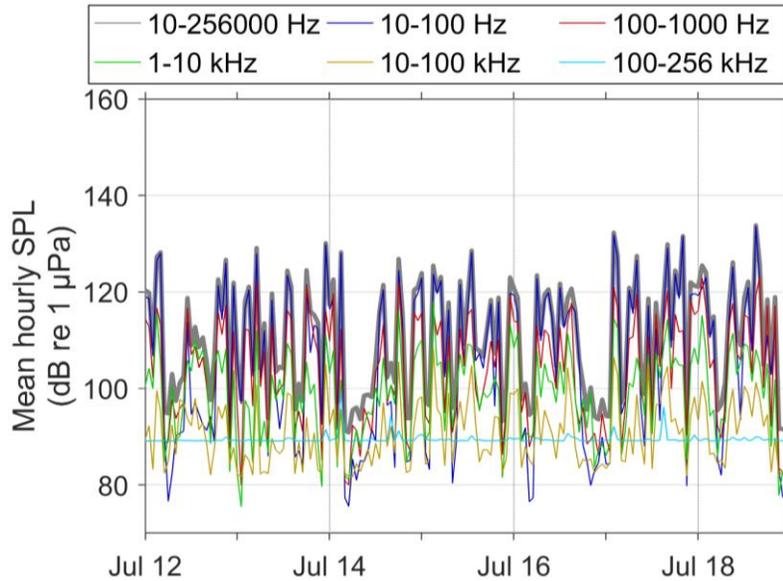
Sound level statistic	10–256,000 Hz	10–100 Hz	100–1000 Hz	1000–10,000 Hz	10–100 kHz	100–256 kHz
Min	88.7	73.4	73.2	74.5	76	80.6
L ₉₅	91.5	77.2	80.5	78.3	81.7	89.1
L ₇₅	96.5	85.7	89.5	86.8	82.9	89.1
L ₅₀	103.5	96.1	98.1	93.8	86	89.1
L ₂₅	114.4	112	106.6	100.4	91.8	89.2
L ₅	129.4	128.6	119.2	111.1	102.1	92.3
Max	150.6	150.6	147.1	131.6	126.4	119
Mean	123.6	123	114.5	105.5	96.9	91.3

A.4.8. Weekly Band Levels

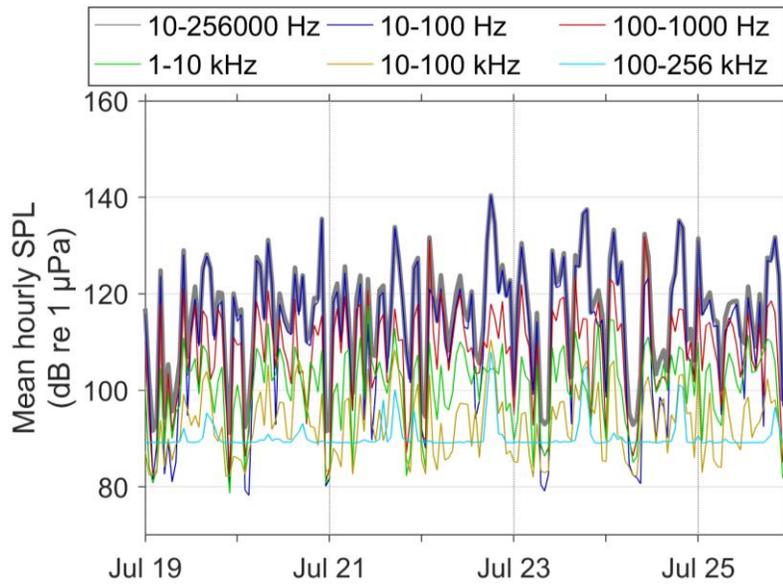
A.4.8.1. Sun 5 Jul to Sun 12 Jul



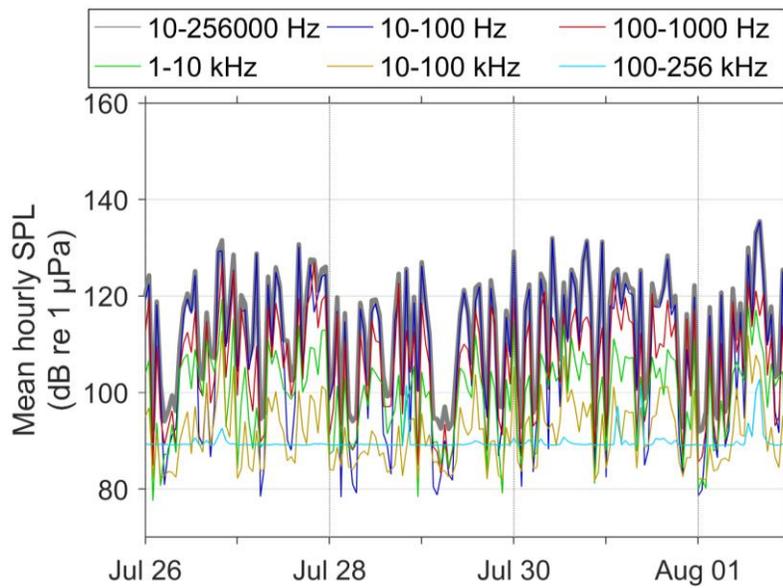
A.4.8.2. Sun 12 Jul to Sun 19 Jul



A.4.8.3. Sun 19 Jul to Sun 26 Jul

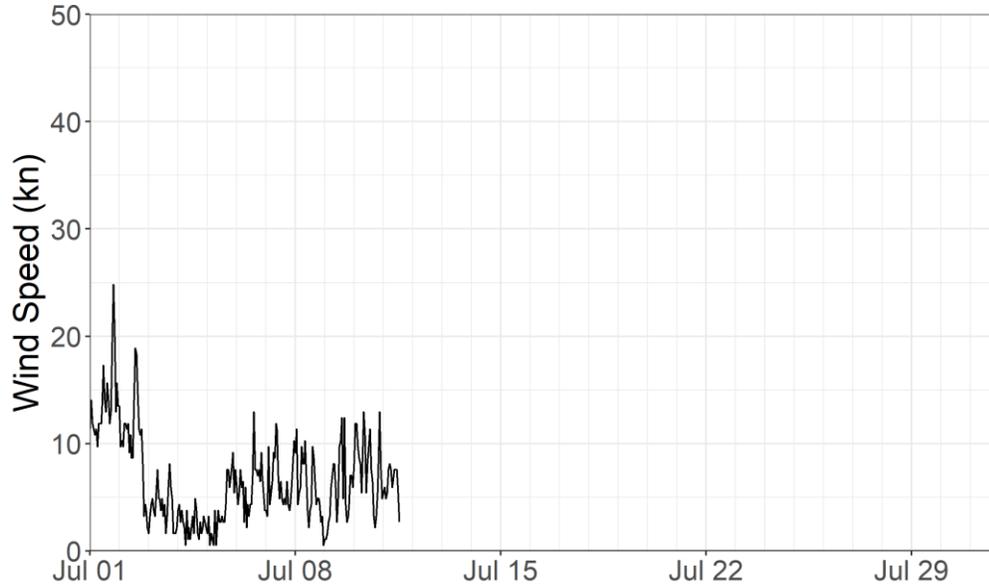


A.4.8.4. Sun 26 Jul to Sun 2 Aug

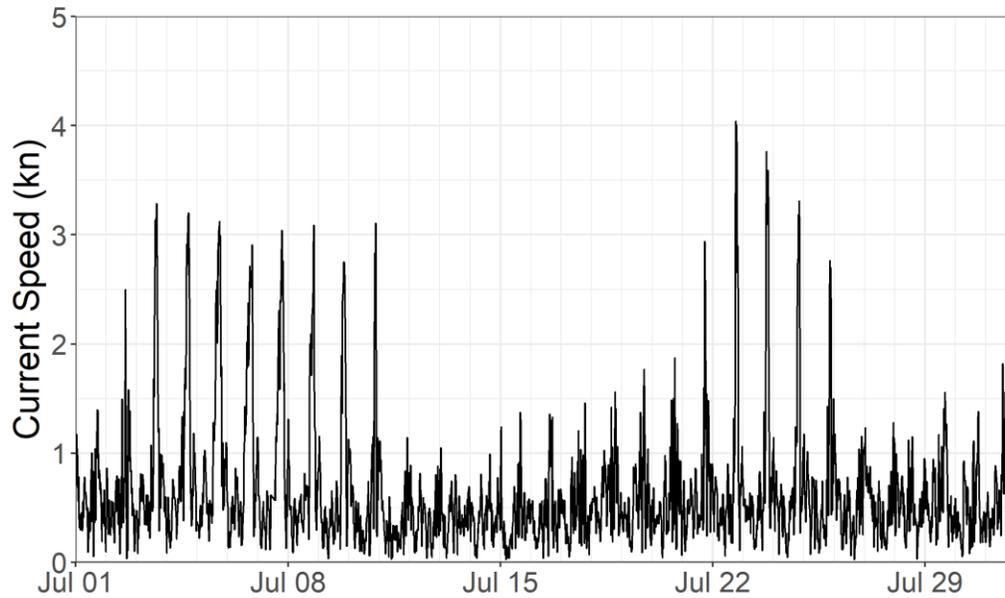


A.4.9. Hourly Wind Speed

Wind data from both the Saturna Island CS and Kelp Reefs weather stations were unavailable after 11 Jul.



A.4.10. Near-seafloor Current Speed



Appendix B. Example Marine Mammal Detection Report for One Month

B.1. Introduction

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

The acoustic data were processed to detect marine mammal vocalizations. This report presents the results of data collected from July to September 2020², in the following three formats:

- Pie charts of the relative number of automatic vocalizations 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 number of detections for each hour and per day for each species. All graphs are in Pacific Standard Time unless otherwise indicated.
- Spectrograms showing how animal-vocalization frequencies varied in time.

B.2. Methods

B.2.1. Acoustic Data

Acoustic data were collected in Boundary Pass using JASCO's ULS. Table B-1 lists the deployment coordinates and recording start/end times.

Table B-1. The ULS deployment coordinates and recording start/end times used for analysis.

ULS	Latitude	Longitude	Water depth (m)	Start	End
A1	48 45.64598' N	123 3.66336' W	193	2020-07-01 00:00	2020-09-30 23:59

² This report has been truncated for this appendix to only show one month of results

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 fish sounds from acoustic recordings. The algorithm employed was similar to the one described in Moloney et al. (2014) and Dewey et al. (2015). Figure B-1 shows the various processing steps of the detector.

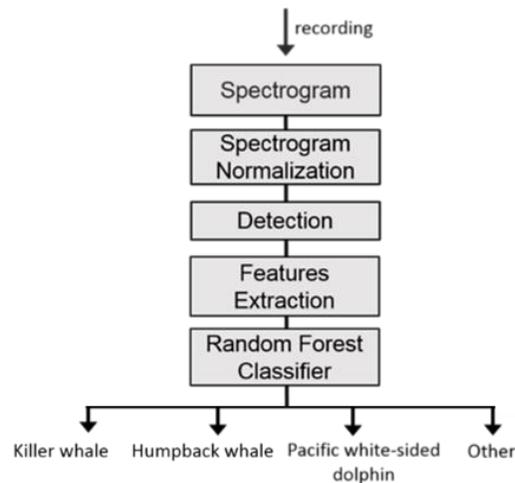


Figure B-1. The process for automatic detections of killer whales, humpback whales, Pacific white-side dolphins, and fish sounds.

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

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

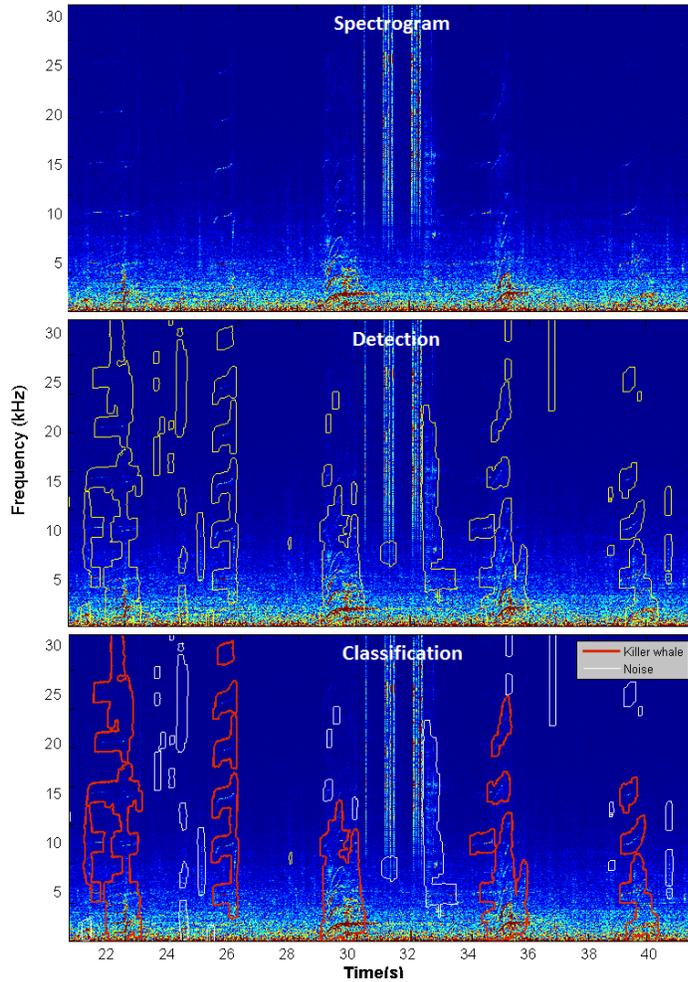


Figure B-2. Key processing steps of the detector. Top panel: Spectrogram with killer whale vocalizations. Middle panel: Acoustic events detected in the spectrogram. Bottom panel: Killer whale vocalizations classified using a random forest classifier.

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 PAMlab. All false detections for these species were excluded from the graphs in this report.

B.3. Results: 1 Jul to 31 Jul 2020

B.3.1. Relative Vocalization Detections by Species

A total of 974 killer whale vocalizations, 502 humpback whale vocalizations and 115 fish sounds were reported by the automated detector from 1 Jul to 31 Jul 2020. No Pacific white-sided dolphin vocalizations were detected at ULS A1 during this period. Figure B-3 shows the proportion of detections by species for this period.

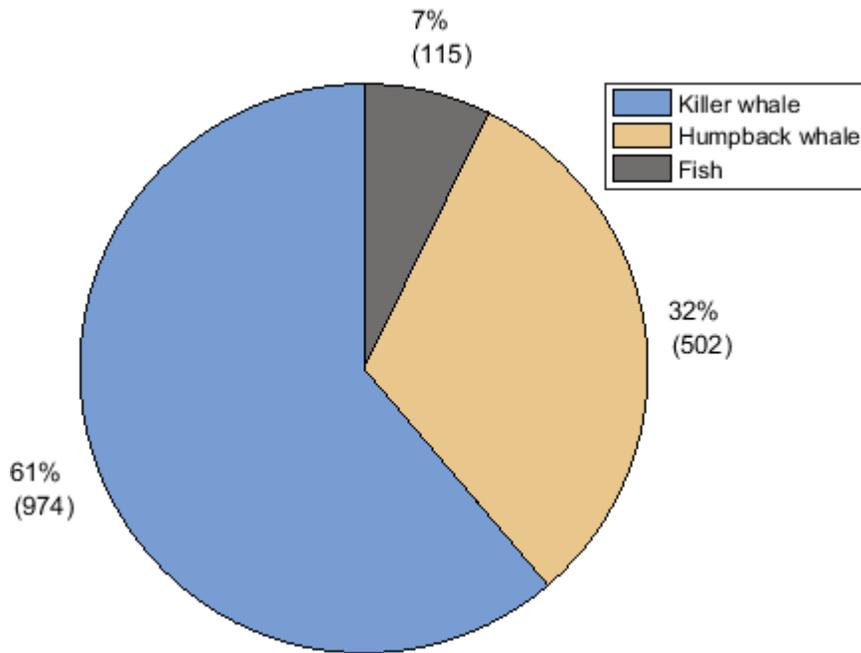


Figure B-3. Relative vocalization detections from 1 Jul to 31 Jul 2020.

B.3.2. Killer Whales

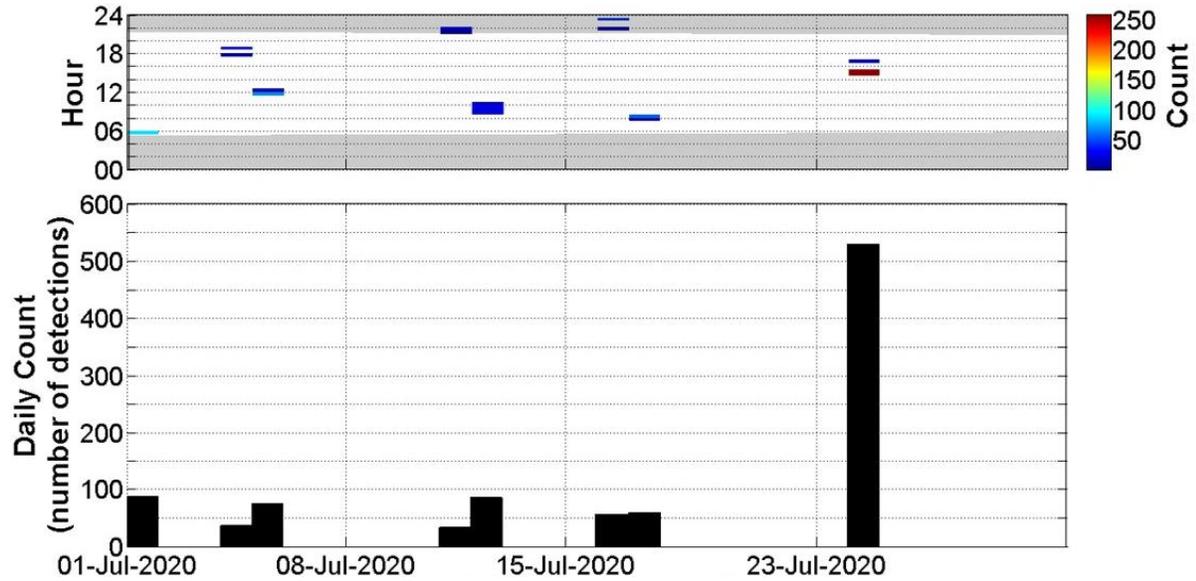


Figure B-4. Hourly and daily detection counts (PDT) of killer whale vocalizations at ULS A1 from 1 Jul to 31 Jul 2020. Grey areas indicate darkness period.

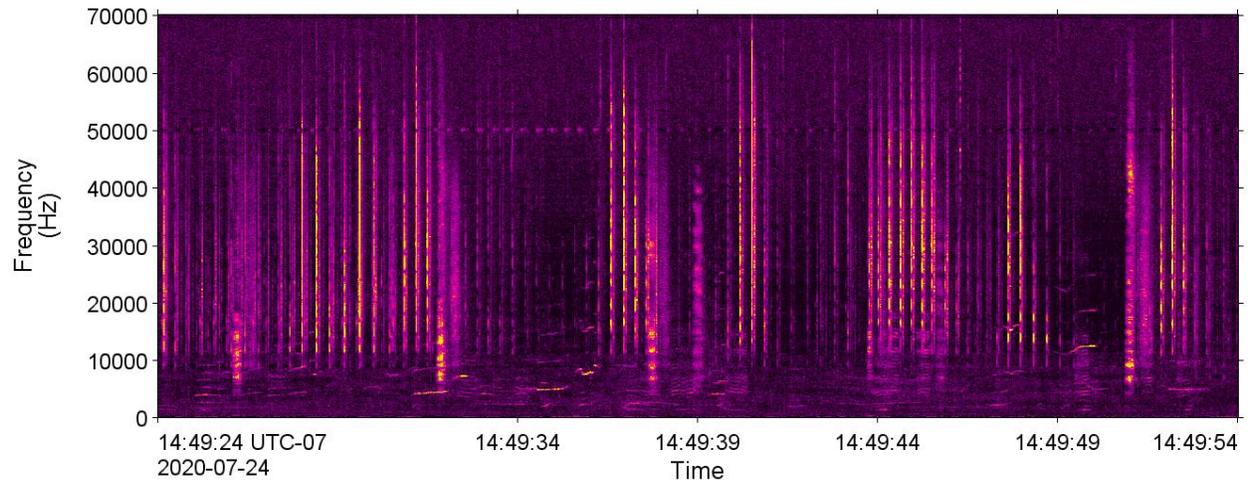


Figure B-5. Spectrogram of killer whale vocalizations at ULS A1 on 24 Jul 2020 (PDT, UTC-7h).

B.3.3. Humpback Whales

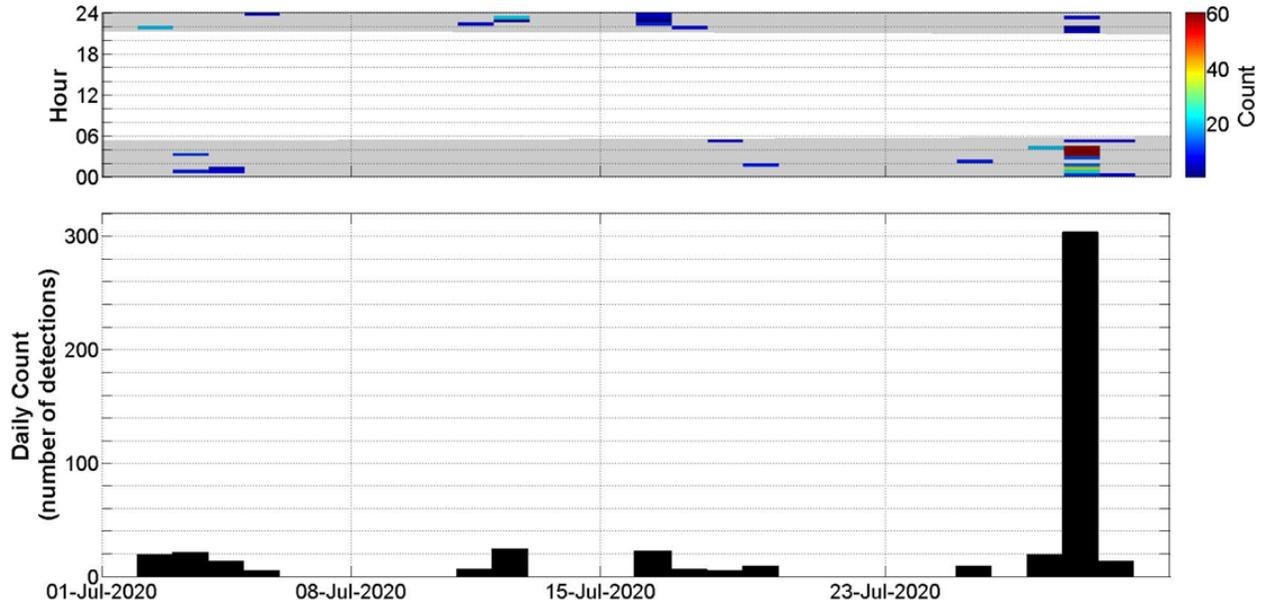


Figure B-6. Hourly and daily detection counts (PDT) of humpback whale vocalizations at ULS A1 from 1 Jul to 31 Jul 2020. Grey areas indicate darkness period.

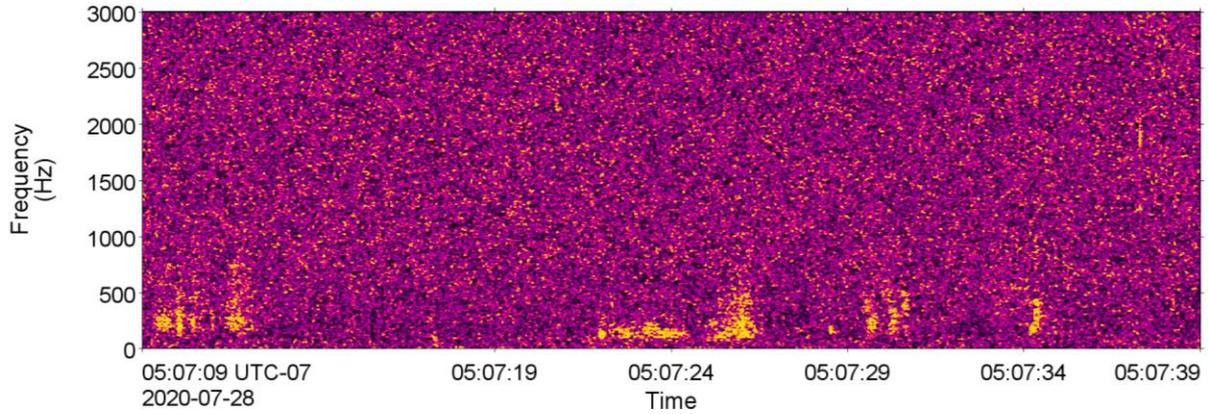


Figure B-7. Spectrogram of humpback whale vocalizations at ULS A1 on 28 Jul 2020 (PDT, UTC-7h).

B.3.4. Pacific White-Sided Dolphins

No Pacific white-sided dolphins were detected on ULS A1 recordings during the analysis period.

B.3.5. Fish

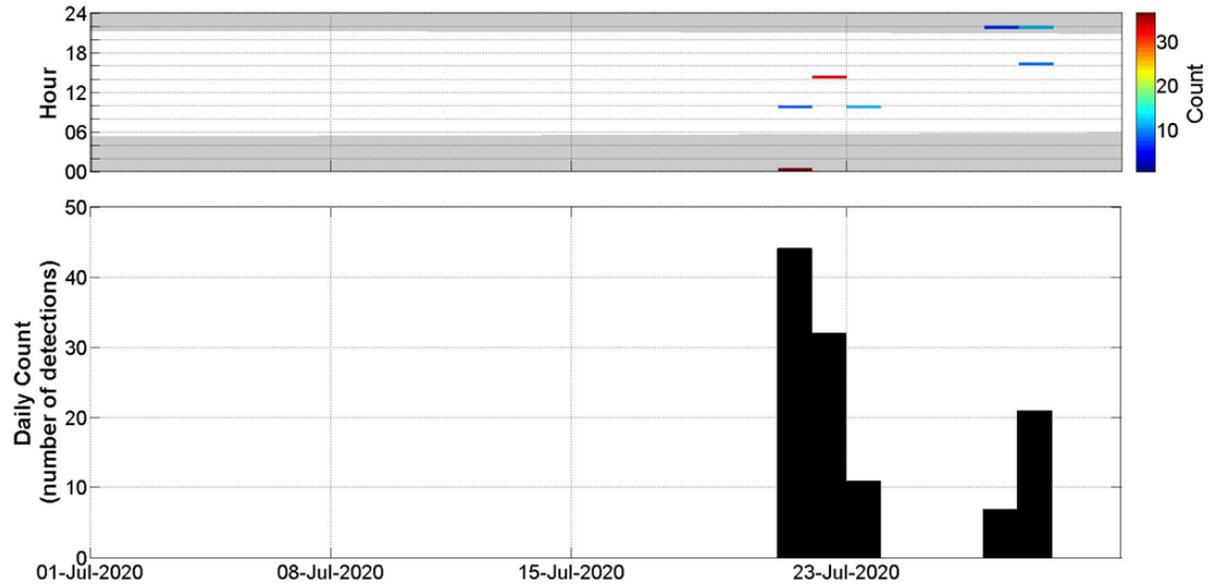


Figure B-8. Hourly and daily detection counts (PDT) of fish sounds at ULS A1 from 1 Jul to 31 Jul 2020. Grey areas indicate darkness period.

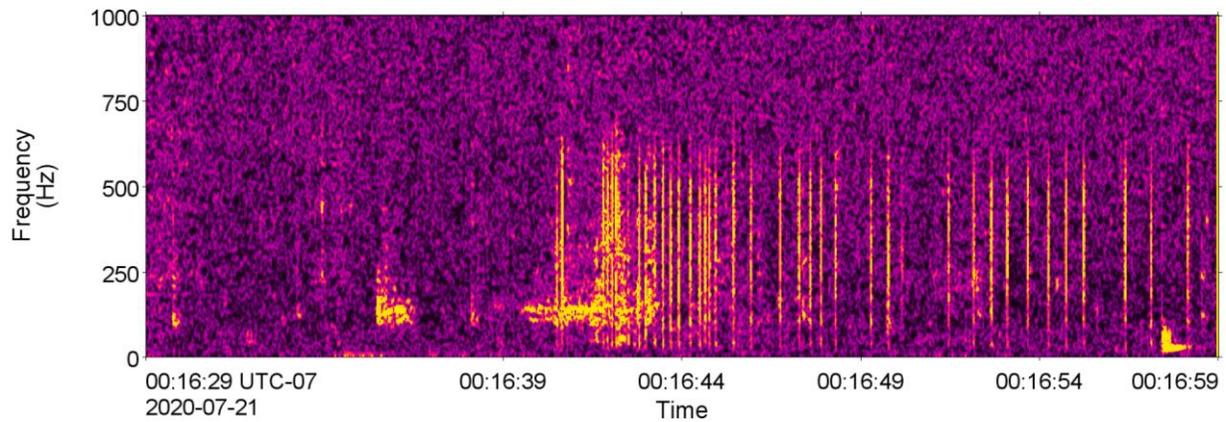


Figure B-9. Spectrogram of fish sounds at ULS A1 on 21 Jul 2020 (PDT, UTC-7h).

Appendix C. Near-surface Water Currents

Near-surface water currents (~20 m depth) were analyzed because they were used in the vessel source level analysis (Appendix E). See Section 3.1.3 for analysis of the near-seabed currents, which are relevant for flow and mooring noise.

Figure C-1 shows the probability density of the near-surface current speed from all available ADCP measurements during the analysis period. Figure C-2 shows the near-surface current speed during a period of overlap, 9–16 Jun 2020, during which both the autonomous and ULS ADCPs were operating. Figure C-3 shows the near-surface current velocity in the easting, northing, and vertical directions during the overlapping period.

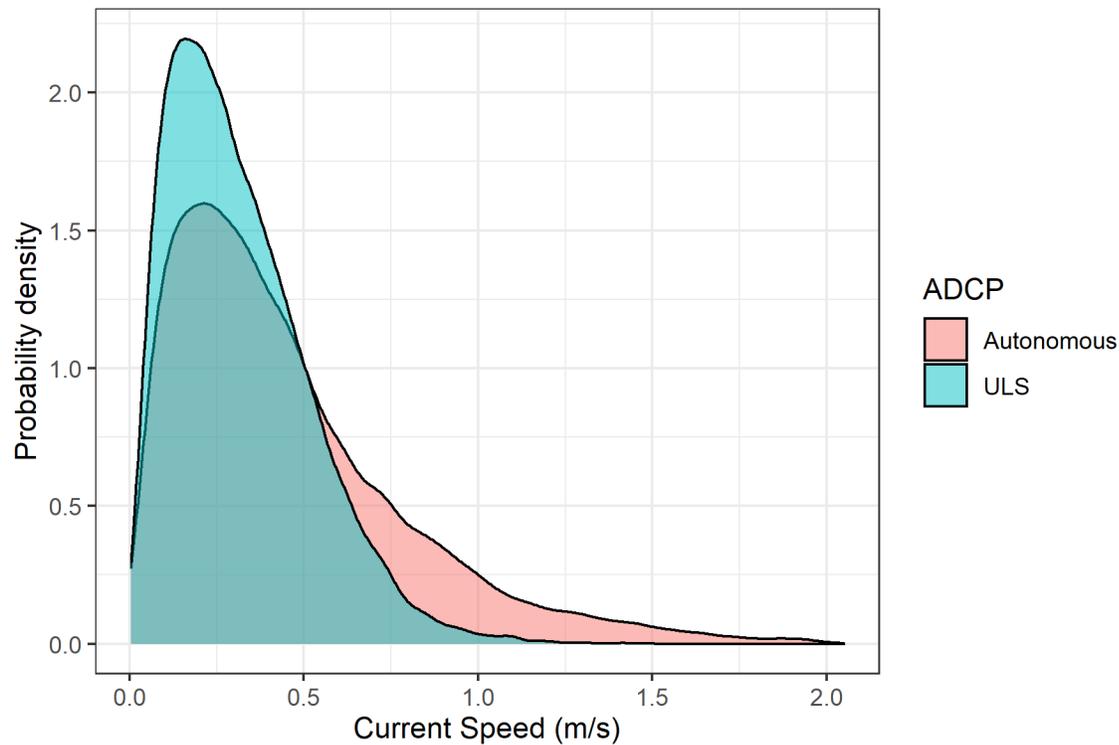


Figure C-1. Probability density of near-surface (~20 m depth) current speed magnitude from all available Acoustic Doppler Current Profiler (ADCP) measurements. ADCP measurements were made every 10–15 minutes. The autonomous ADCP current speed distribution is from October 2019 to June 2020 while the ULS ADCP distribution is from June 2020 to December 2020.

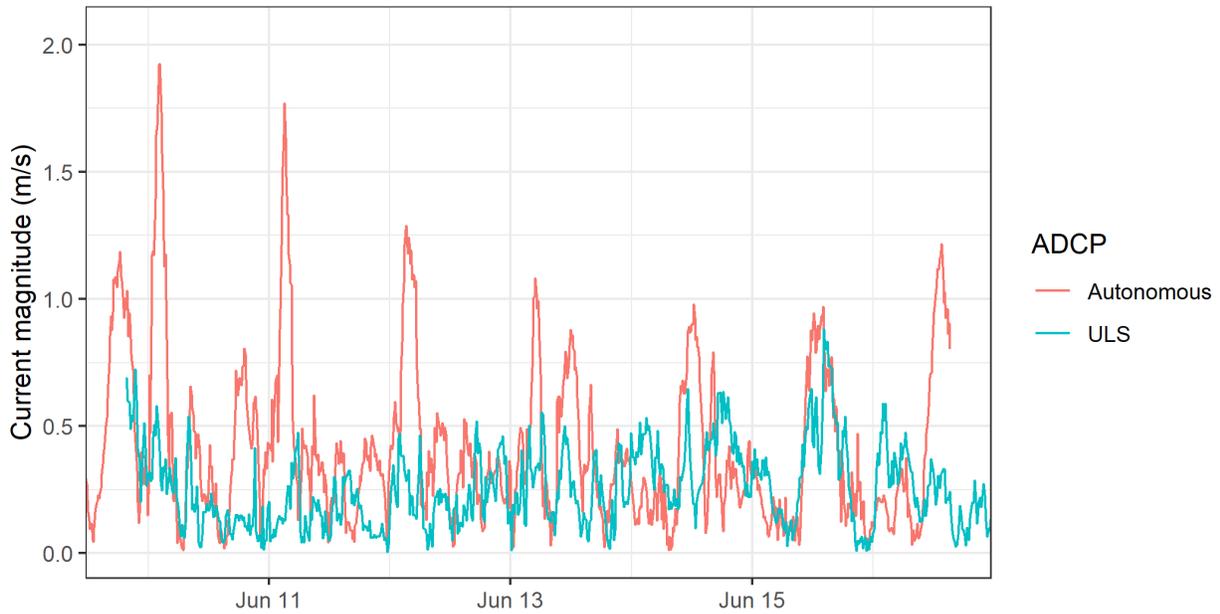


Figure C-2. Comparison of near-surface (~20 m depth) current speed magnitude during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs).

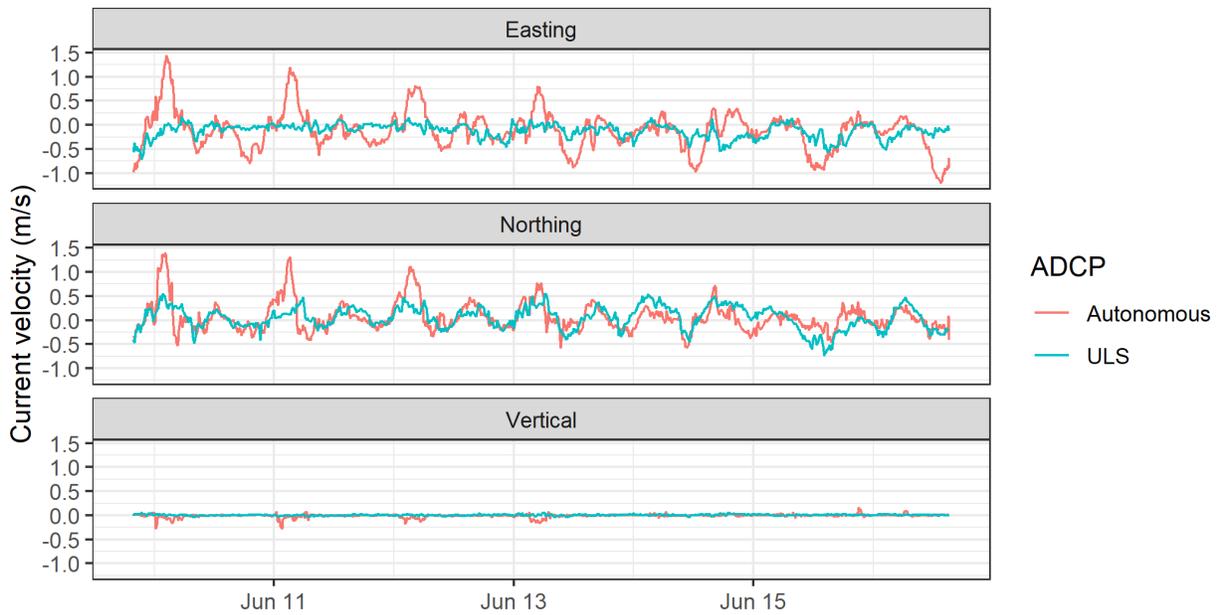


Figure C-3. Comparison of near-surface (~20 m depth) current speed broken down by directional component during the eight-day overlapping period for the autonomous and Underwater Listening Station (ULS) Acoustic Doppler Current Profilers (ADCPs).

Appendix D. Additional Ambient Noise Results

The effects of near-seafloor water current speed (as measured by an ADCP) on sound levels shown as 2-dimensional (2-D) histograms of SPL (1-minute average) for each decade band for the AMAR G3 (Figure D-1), G4 (Figure D-2), and ULS (Figure D-3) recordings. The data presented here are not normalized by the total number of counts at a given speed, in contrast to the corresponding figures in Section 3.1.1.

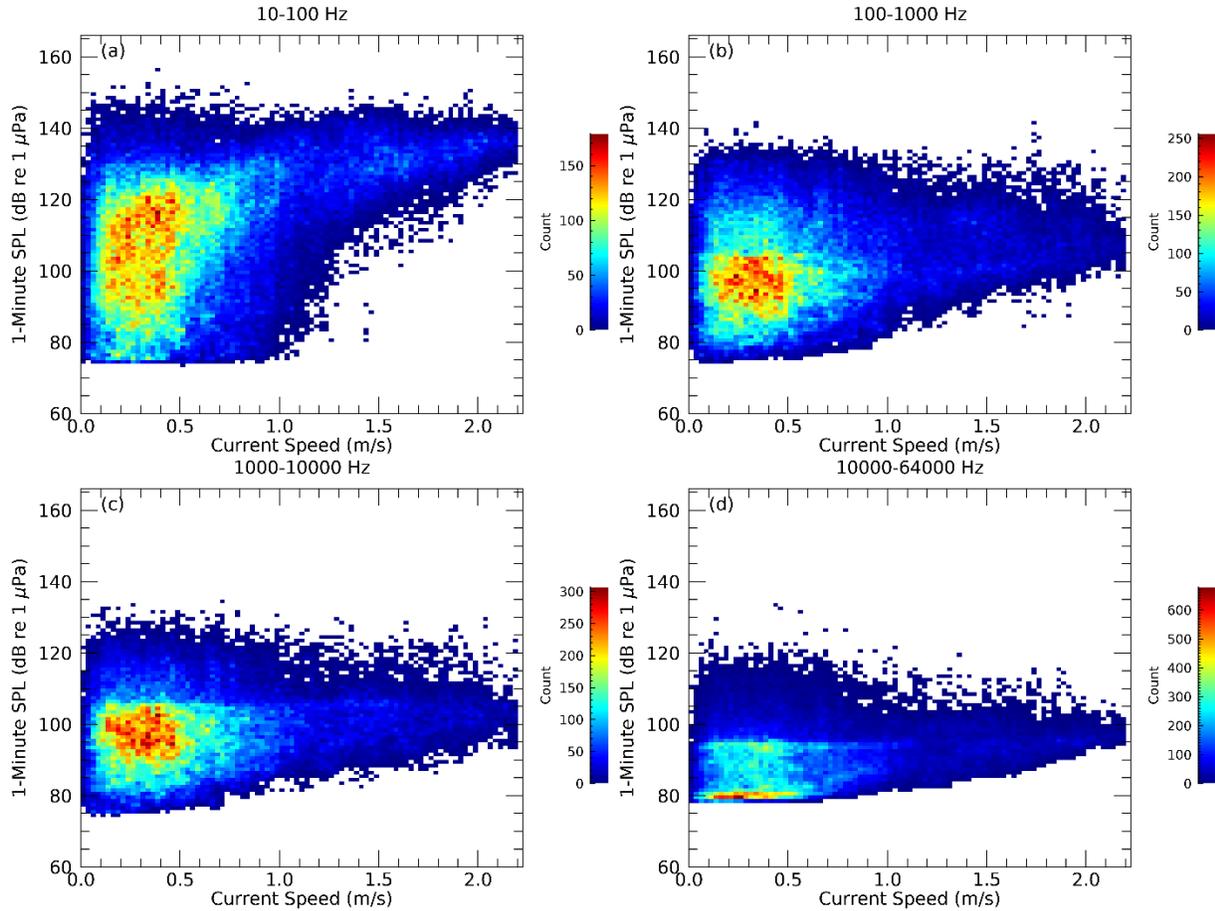


Figure D-1. AMAR G3 (2019 Oct 15 to 2020 Jan 31): Two-dimensional (2-D) histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler (ADCP)-measured seafloor current speed.

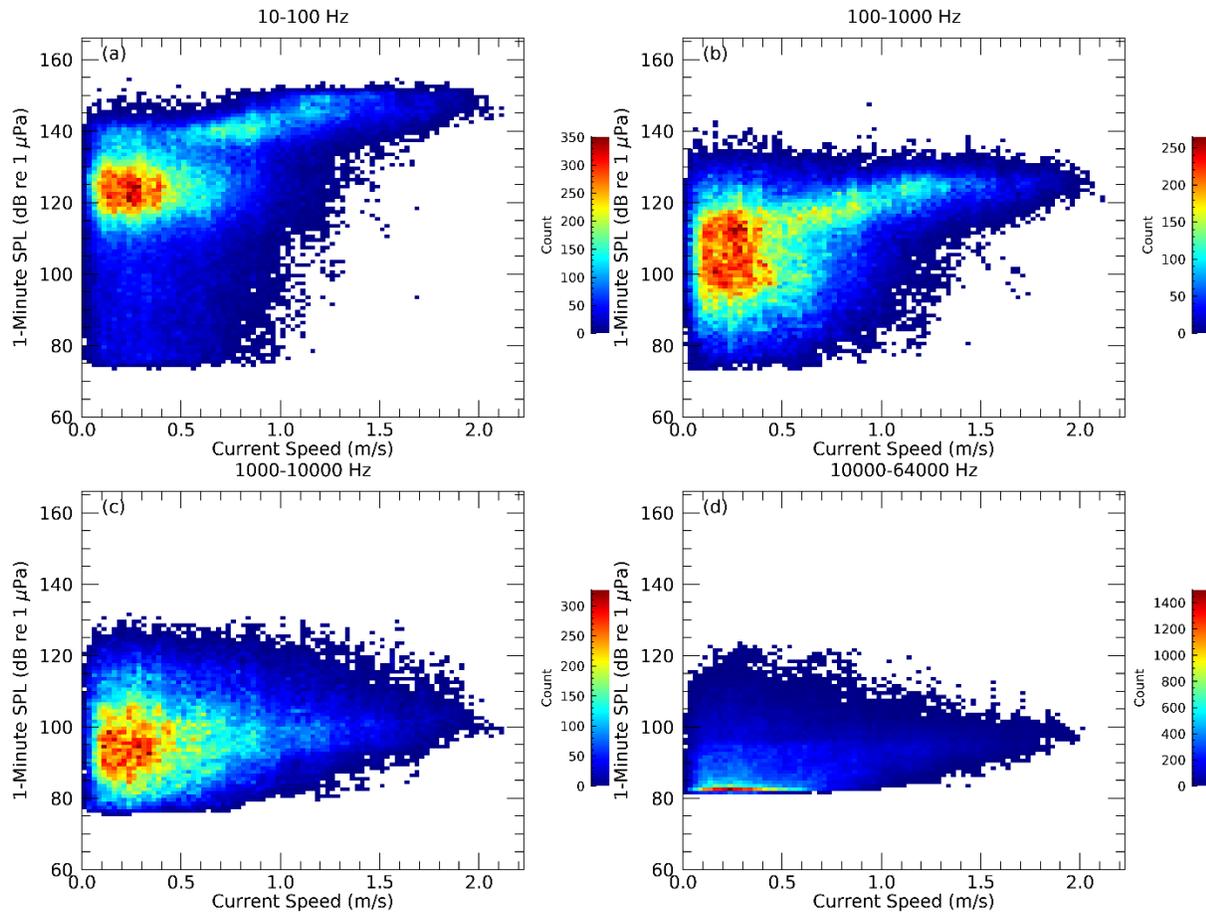


Figure D-2. AMAR G4 (2020 Jan 31 to 2020 Jun 09): Two-dimensional (2-D) histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler (ADCP)-measured seafloor current speed.

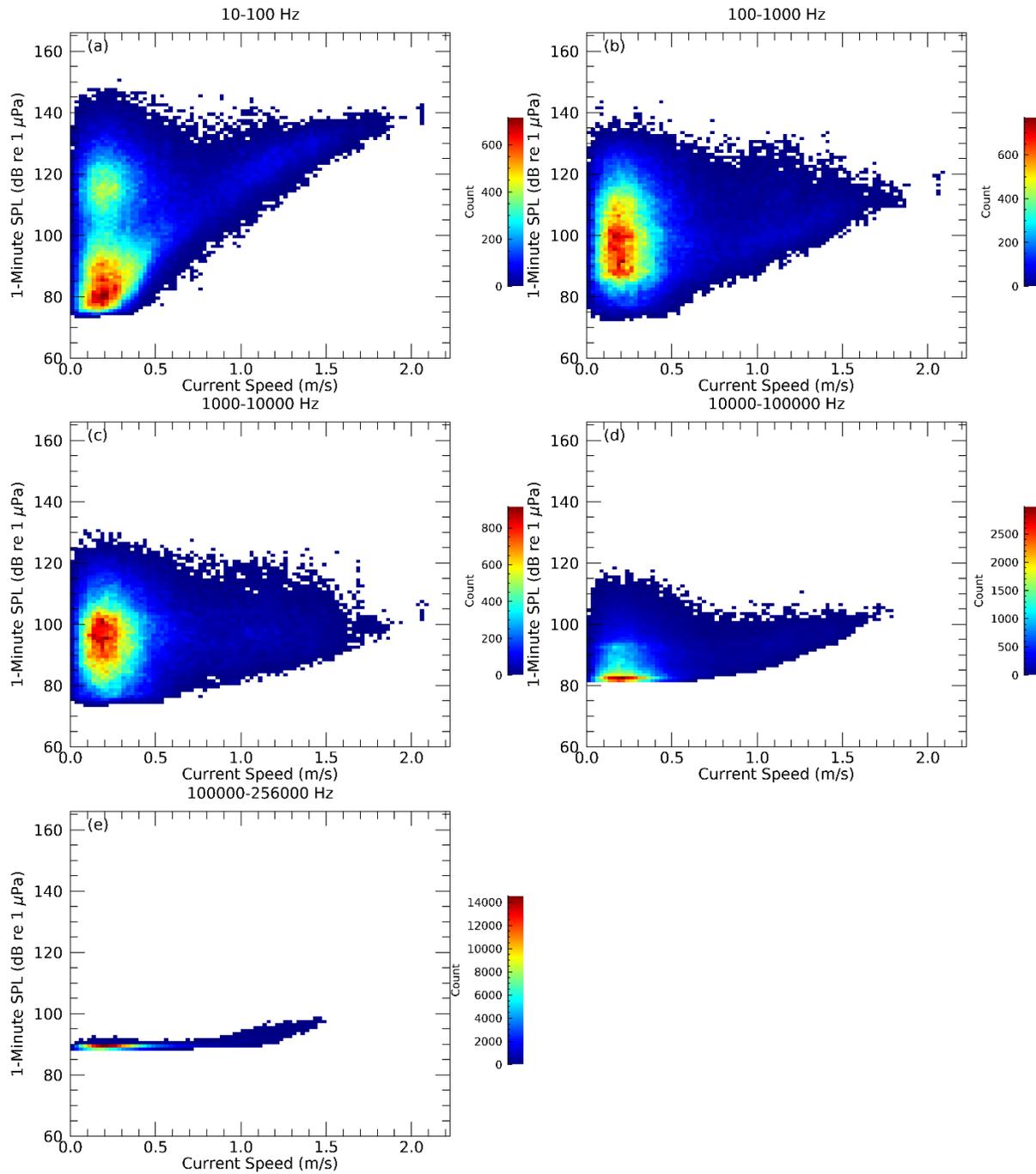


Figure D-3. ULS (2020 Jun 09 to 2020 Dec 31): Two-dimensional (2-D) histograms by decade band of 1-minute averaged sound pressure level (SPL) versus Acoustic Doppler Current Profiler (ADCP)-measured seafloor current speed.

Appendix E. 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 $\pm 30^\circ$ 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 E-1). Spectrum measurements are calculated using 1-second fast Fourier transforms, shaded using a Hanning window.

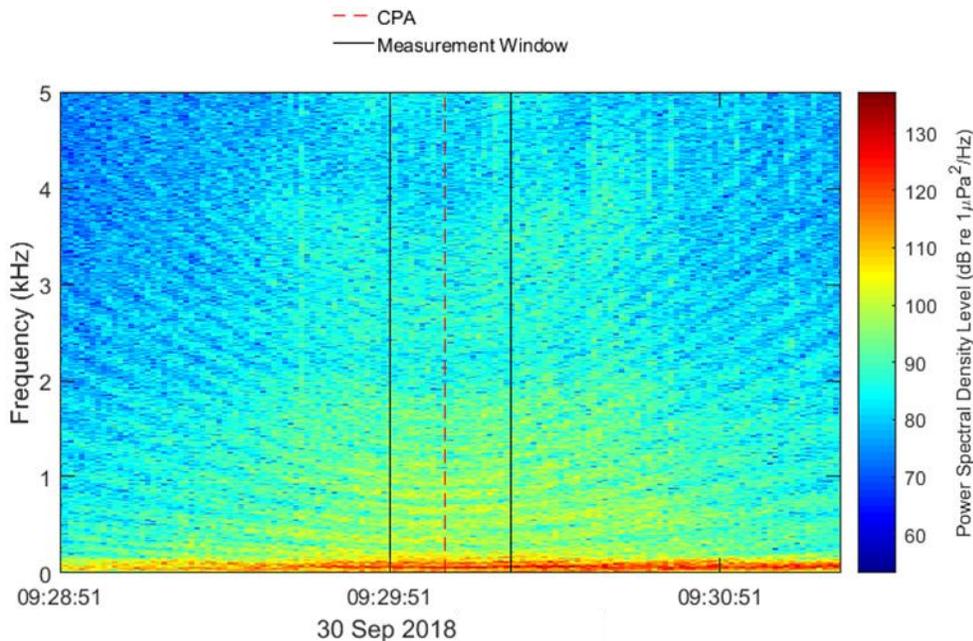


Figure E-1. Spectrogram of a single vessel measurement from ShipSound, showing the closest point of approach (CPA) time (dashed red line) and the measurement window (black box) used for calculating vessel source levels. The spectrogram shows the spectrum of the underwater sound pressure recorded on the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

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

requires a source depth, which is defined in ShipSound as a Gaussian distribution centred at the draft minus 0.85 of the propeller diameter (Gray and Greeley 1980). If the propeller diameter is unknown, it is calculated from the vessel draft as,

$$p = 0.3d/0.85,$$

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

Environmental conditions (wind speed and current speed) were also recorded for each measurement. Meteorological data for Boundary Pass were obtained from Environment Canada weather stations (see 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 E-2 summarizes this approach. The overall vessel measurement was not necessarily rejected if some of the decidecade-band source levels were rejected during the automated quality review phase.

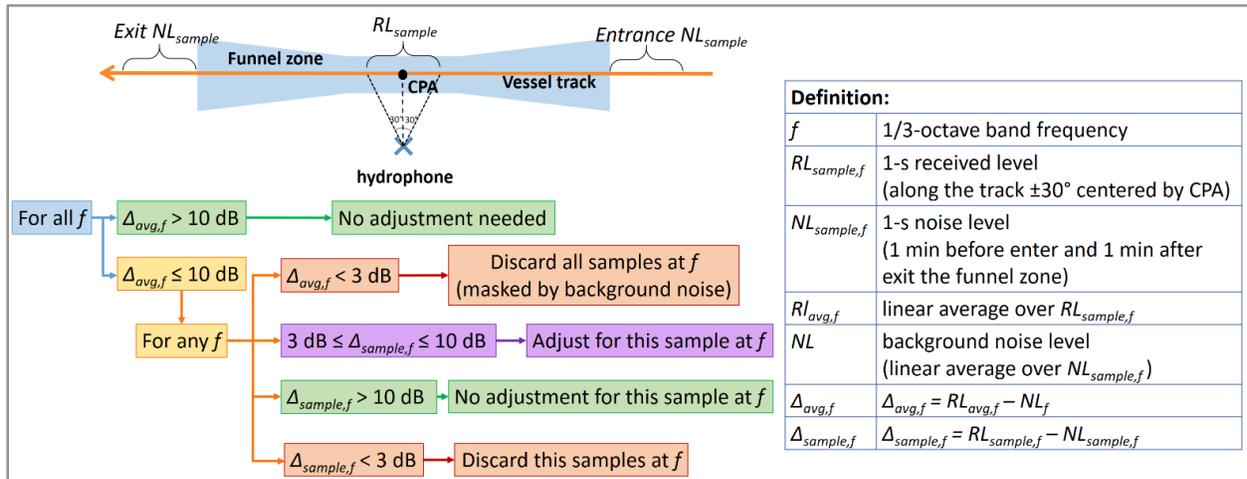


Figure E-2. Background noise comparison and adjustment process as part of the first (automated) phase of quality control.

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

Appendix F. Summary of Vessel Source Level Measurements

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

Table F-1. Number of accepted vessel source level measurements during Year 2 (October 2019 to December 2020). The number of measurements are lower for the first month (October 2019) because data were acquired for approximately half of that month.

Vessel category	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	Jun 2020	Jul 2020	Aug 2020	Sep 2020	Oct 2020	Nov 2020	Dec 2020	Total
Bulker	96	202	213	208	194	214	195	209	217	208	174	218	243	251	209	3051
Container Ship	48	90	109	91	79	80	92	95	90	92	93	99	114	101	94	1367
Cruise	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Dredger	0	0	1	0	0	1	0	0	0	0	0	0	0	0	2	4
Ferry	0	0	0	0	0	7	8	0	0	0	0	0	0	0	4	19
Fishing Vessel	4	2	2	1	0	0	0	2	6	1	2	0	3	11	1	35
Government/Research	1	0	3	0	3	3	1	2	4	1	2	2	2	0	0	24
High Speed Ferry	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Naval Vessel	1	6	7	0	0	12	14	4	0	11	0	4	9	7	7	82
Other	2	5	3	4	3	1	5	1	4	4	5	2	3	5	8	55
Passenger (<100 m)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Recreational	1	0	0	0	0	0	0	0	1	2	2	1	1	0	0	8
Tanker	10	19	22	20	21	17	25	24	18	18	20	17	16	15	21	283
Tug	12	30	39	14	22	34	28	31	35	23	34	40	32	32	22	428
Vehicle Carrier	11	30	34	31	27	29	19	15	15	24	24	29	37	31	31	387

Table F-2. Acceptance rate (percent) of vessel source level measurements during Year 2 (October 2019 December 2020). Cells with “NA” indicate there were no accepted or rejected measurements for the corresponding month and vessel category.

Vessel category	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	Jun 2020	Jul 2020	Aug 2020	Sep 2020	Oct 2020	Nov 2020	Dec 2020	Average
Bulker	76	76	76	84	75	76	75	73	74	79	77	81	77	83	84	78
Container Ship	79	78	78	83	75	79	80	83	71	77	79	88	85	87	80	80
Cruise	71	50	NA	67												
Dredger	NA	NA	50	NA	0	100	NA	100	67							
Ferry	NA	NA	NA	NA	0	47	67	0	NA	NA	NA	NA	NA	NA	100	58
Fishing Vessel	67	33	100	14	NA	0	0	40	75	50	100	NA	75	79	25	56
Government/Research	25	0	60	NA	60	33	100	40	57	33	50	33	14	0	0	35
High Speed Ferry	100	NA	0	NA	NA	NA	50									
Naval Vessel	25	20	18	NA	0	23	19	11	NA	34	NA	100	31	29	33	24
Other	100	45	60	80	60	14	83	100	100	100	83	33	60	100	100	69
Passenger (<100 m)	0	NA	100	NA	50											
Recreational	33	NA	50	50	100	50	50	NA	0	50						
Tanker	63	63	51	61	49	49	69	57	56	67	54	61	64	58	54	58
Tug	43	54	47	39	35	47	45	44	53	61	53	67	60	65	46	50
Vehicle Carrier	79	77	74	86	73	76	86	79	83	77	92	83	93	82	89	82