

Salish Sea Ambient Noise Study: Best Practices (2021)

This work was sponsored and financially supported by the Vancouver Fraser Port Authority. Transport Canada provided additional financial support.

For bibliographic purposes, this document should be cited as follows:

Eickmeier, J., Tollit, D., Trounce, K., Warner, G., Wood, J., MacGillivray, A. and Zizheng Li (2021) Salish Sea Ambient Noise Study: Best Practices (2021). Vancouver, British Columbia, Vancouver Fraser Port Authority, Enhancing Cetacean Habitat and Observation (ECHO) Program.

Authors: Justin Eickmeier¹, Dominic Tollit², Krista Trounce³, Graham Warner⁴, Jason Wood⁵, Alex MacGillivray⁶ and Zizheng Li⁷

1) Justin M. Eickmeier is a Consulting Scientist at SLR Consulting (Canada) Ltd., Vancouver, British Columbia, V6J 1V4 (jeickmeier@slrconsulting.com)

2) Dominic J. Tollit is the Principal Scientist at SMRU Consulting North America, Vancouver, British Columbia, V6B 1A1 (djt@smruconsulting.com)

3) Krista B. Trounce is the Research Manager for the ECHO Program, Vancouver Fraser Port Authority, Vancouver, British Columbia, V6C 3T4 (krista.trounce@portvancouver.com)

4) Graham Warner is a Project Scientist for JASCO Applied Sciences (Canada) Ltd.

5) Jason Wood is Operations Manager & Senior Research Scientist at SMRU Consulting North America

6) Alex MacGillivray is a Senior Scientist for JASCO Applied Sciences (Canada) Ltd.

7) Zizheng Li is a Project Scientist for JASCO Applied Sciences (Canada) Ltd.

Table of Contents

| | |
|--|----|
| Abstract | 2 |
| I. Introduction | 3 |
| II. Ambient Noise..... | 4 |
| III. Noise Monitoring in the Salish Sea | 6 |
| IV. Ambient Noise Evaluation Project (Best Practices) | 10 |
| A. Hydrophone systems | 12 |
| 1) Hydrophone systems - Summary of findings | 12 |
| Calibrations:..... | 12 |
| Sensitivity: | 12 |
| System noise:..... | 13 |
| Flow-noise: | 14 |
| 2) Hydrophone systems – Discussion and contemporary studies | 15 |
| 3) Hydrophone systems – key recommendations | 17 |
| Location:..... | 17 |
| Equipment: | 17 |
| Calibration: | 18 |
| System monitoring:..... | 18 |
| B. Vessel Traffic | 19 |
| 1) Vessel Traffic - Summary of findings | 19 |
| 2) Vessel traffic - Discussion and contemporary studies..... | 22 |
| 3) Vessel traffic - key recommendations | 24 |
| Large vessel traffic | 24 |
| C. Environmental Factors..... | 25 |
| 1) Environmental Factors – summary of findings | 25 |
| Wind and rain: | 25 |
| Tidal currents:..... | 26 |
| Sound speed profile: | 27 |
| Biologicals:..... | 29 |
| 2) Environmental factors - discussion and contemporary studies..... | 29 |
| 3) Environmental factors - key recommendations | 31 |
| D. Data Analysis and Reporting Metrics..... | 32 |
| 1) Data Analysis and Reporting Metrics – summary of findings | 32 |
| 2) Data Analysis and Reporting Metrics- discussion and contemporary studies..... | 34 |
| 3) Data analysis and reporting - key recommendations..... | 36 |
| V. Conclusion..... | 37 |
| Acknowledgments | 40 |
| References | 41 |

ABSTRACT

All monitoring locations and hydrophone systems have unique features that affect the ability to monitor ambient noise levels accurately. As anthropogenic underwater noise effects on marine species becomes increasingly important globally, it is imperative to understand how best to consistently measure, analyze, and account for factors contributing to the soundscape. The Enhancing Cetacean Habitat and Observation Program, led by the Vancouver Fraser Port Authority, seeks to mitigate shipping noise effects on at-risk whales, particularly endangered Southern Resident Killer Whales. Utilizing two years of data from three different, cabled inshore hydrophone stations in the Salish Sea, this high-level review aims to help understand and address key environmental and anthropogenic factors that contribute to ambient noise. Contributions from: the hydrophone system and ancillary equipment; rain, wind and tidal currents; factors affecting sound propagation; biological presence; and vessel traffic are considered in this study, and “best practice” recommendations for undertaking standardized long-term noise assessment are provided. Key findings highlight that early and frequent quality assessment protocols are imperative, weather and tidal information should be collected proximate to the hydrophone, vessel traffic was the dominating influence at all locations across all measured frequencies, and validated noise models should augment empirical data collection. Monthly variability in sound pressure levels was 2-6 dB, highlighting the analytical challenges in determining “existing” conditions and detecting trends or testing mitigation strategies. Accounting for the key factors contributing to the soundscape is considered critical in these evaluations.

Index Terms Acoustic signal processing, Best practices, Environmental factors, Oceanography, Remote monitoring, Underwater acoustics, and Underwater technology.

I. INTRODUCTION

The Vancouver Fraser Port Authority's (the port authority's) Enhancing Cetacean Habitat and Observation (ECHO) Program is a port authority-led collaborative program aimed at better understanding and managing the cumulative effects of shipping activities on at-risk whales throughout the southern coast of British Columbia. The ECHO Program is guided by the advice and input of a volunteer advisory working group and associated technical committees, with representatives from Canadian and American government agencies, the marine transportation industry, Indigenous communities, conservation and environmental groups, naval architects, engineers, and scientists.

One of the priorities of the ECHO Program is to develop mitigation measures leading to quantifiable reductions in underwater noise (UWN) caused by marine shipping, which the Department of Fisheries and Oceans Canada (DFO) Recovery Strategy identifies as one of the key threats to the recovery of the Southern Resident Killer Whales (SRKW). Therefore, quantifying the potential noise benefits of different mitigation strategies, developing an understanding of existing ambient noise conditions, and what factors most affect ambient noise is crucial.

In 2015, under the guidance of the ECHO Program's Acoustic Technical Committee (ATC), the program initiated an ambient noise monitoring project in the Salish Sea. An inland sea of the Pacific Ocean, the Salish Sea is located in British Columbia, Canada and Washington State, USA. It includes the Strait of Georgia, Strait of Juan de Fuca and a network of connecting channels. The primary purpose was to consistently measure ambient underwater acoustic levels, over two years, at three representative locations to:

- Establish existing underwater ambient noise levels regionally at key reference sites.
- Ground truth and better calibrate regional-level acoustic models.
- Establish trends in underwater noise levels regionally and temporally to facilitate on-going and adaptive underwater noise management in the future.
- Investigate the effectiveness of mitigation measures implemented by the ECHO Program or others.

This document summarizes the findings of the “Ambient Noise Evaluation Project,” [1] which evaluated two years of ambient noise level data collected from the three reference sites using standardized reporting protocols developed by the ATC. It provides guidance and recommendations on collecting and analyzing ambient noise data in the Salish Sea.

II. AMBIENT NOISE

The ECHO program focuses on assessing mitigation of underwater noise caused by marine shipping, a known threat to the recovery of endangered SRKW. To measure and understand how effective any noise reduction mitigation measure might be, requires a full understanding of variability and the accuracy of empirical measurements, and the factors that contribute or confound those measurements.

In 1962, Wenz published an early study on ambient noise, identifying three primary sources: the effects of surf, rain, hail, tides (or water motion), anthropogenic sources such as ships, and biological sources (crustaceans, fish, and marine mammals). Wenz suggested that future studies of ambient noise should consider temporal (hourly, daily, and seasonal) and spatial (directional) measurements [2]. Talham studied the directional distribution of ambient noise and found the noise field to be anisotropic but indicated no existing theory accounted for energy from a single source arriving at the same terminal location over multiple paths [3]. Urlick classified ambient noise under two categories, based on directional properties. Type I noise (low-frequency) arrived at all hydrophones on a vertical array with high coherence and no time delay. Anthropogenic noise from distance vessels is the primary source of this noise. Type II noise originated at the sea surface and was the dominant high-frequency noise source when wind speeds are high [4].

In 1970, Perrone determined ambient noise levels to be a function of water depth, frequency, and wind speed in the Northwest Atlantic. Calibration of the hydrophone and data acquisition system was an integral component of this study [5]. By 1981, Wagstaff had determined the study of ambient noise to be a complex

phenomenon requiring both the interpretation of measurements and an understanding of acoustic propagation theory [6].

In the 1990s, the monitoring and modeling of ambient noise were studied (concerning a three-dimensional ocean environment), and consideration in the design and placement of hydrophones for in situ measurements improved acoustic propagation modeling [7]. Existing concepts on ambient noise's directionality expanded to include range-dependent environments and focused on the attenuation effects of upslope and downslope propagation [8].

In 2009, the study of ambient noise in the ocean was advanced significantly by Hildebrand through an extensive investigation into anthropogenic and natural noise sources. Frequency bands were used to classify noise sources: low (10 to 500 Hz), mid (500 Hz to 25 kHz), and high (above 25 kHz) [9]. Anthropogenic sources such as commercial vessel traffic or seismic surveys dominated the low-frequency noise band. Oceanographic and meteorological processes such as breaking waves, sea spray, bubble formation/collapse, and rainfall contributed to the mid-frequency band. Small vessels also contributed to ambient noise in the mid-frequency band. Hildebrand identified small vessels as having peak energy at 5 kHz when operated at speeds between 10 to 20 knots. At high frequencies, propagation loss confines all noise sources to an area close to the receiver. Hildebrand identified four critical environmental factors that influence acoustic propagation and the measurement of ambient noise levels: I) measurement of the sound speed profile, II) attenuation properties of seawater, III) local bathymetry and IV) the properties of bottom sediment layers [9].

The above studies are standard references for contemporary investigations (2010-2020) on ambient noise. Contributions from Merchant et al., (2012), Dekeling et al., (2014) and MacGillivray et al., (2018) [10-12] (amongst other studies discussed in this document) reported overall ambient noise levels and individual contributions from anthropogenic, biological, and environmental sources. These studies and guides set the groundwork for this best practices document.

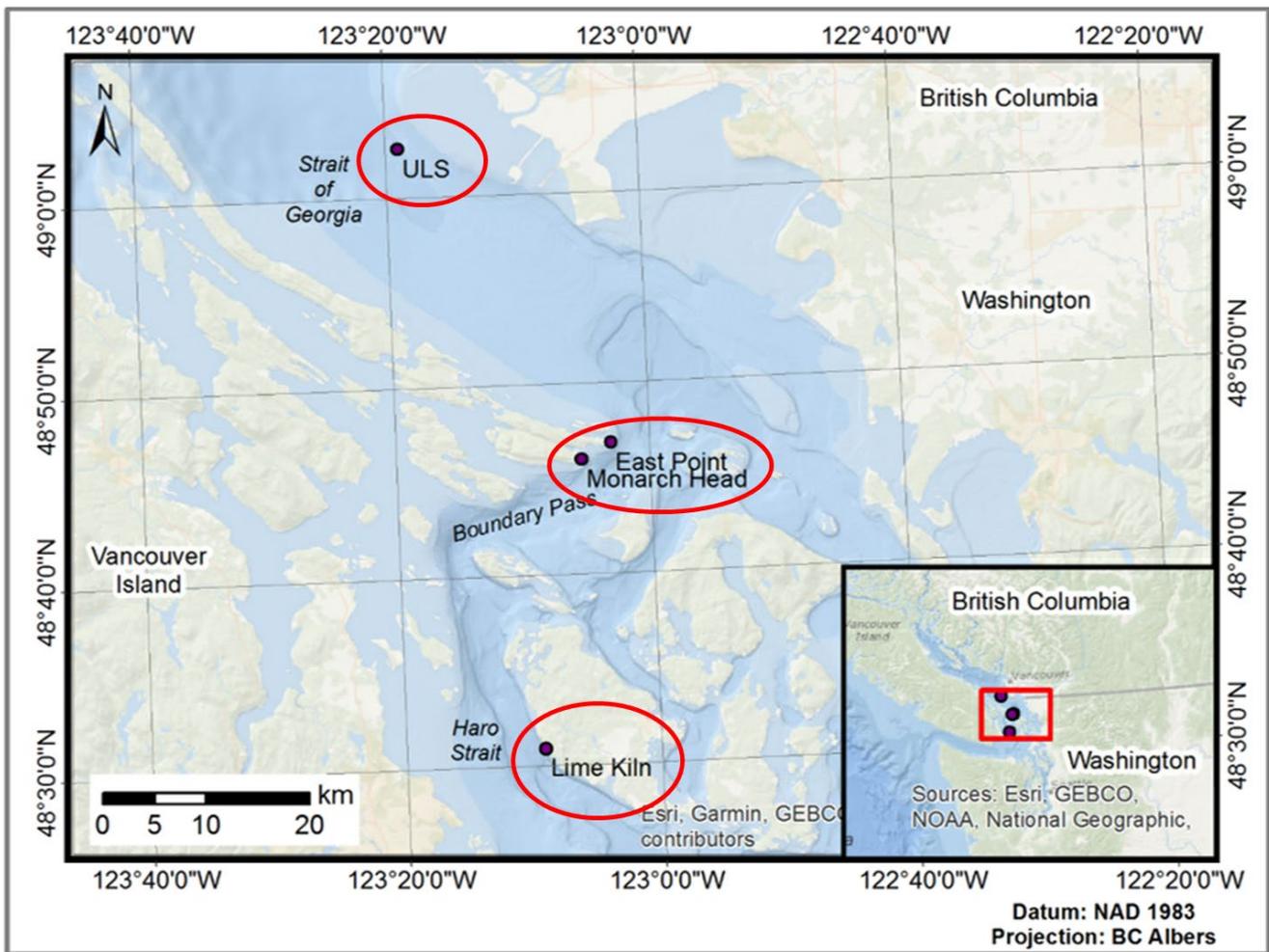


Figure 1: Ambient noise monitoring stations in the Salish Sea (2016-2017).

III. NOISE MONITORING IN THE SALISH SEA

The ECHO Program ambient noise evaluation project included collecting two years of ambient noise data from key reference locations within the Salish Sea. Three existing cabled hydrophone sites were selected to represent three sub-areas of the Salish Sea in proximity to the commercial shipping lanes (Fig. 1). Based on the Acoustic Technical Committee’s advice, two years of data was recommended as the minimum timeframe to evaluate existing ambient noise conditions and describe any clear trends. Calibrated hydrophones in Haro Strait (Lime Kiln) and Boundary Pass (East Point and subsequently nearby at Monarch Head) were deployed in shallow water (23-30 m depth) in critical SRKW habitat, between one and five kilometers from the

shipping lanes, noting the ATC considered a depth of less than 20 m to be sub-optimal for monitoring low-frequency ambient noise bands. The hydrophone in the Strait of Georgia, termed underwater listening station (ULS), was deployed in deeper water (173 m) and precisely positioned between the northbound and southbound shipping lanes to accurately measure source levels of transiting Automated Identification System (AIS) equipped vessels while also collecting ambient noise data.

Acoustic data from these three sites were collected for approximately two years (2016-2017), noting a relatively small location change (East Point to Monarch Head) at Boundary Pass in year two. The East Point hydrophone was operational from January 2016 until March 2017. The Monarch Head hydrophone was operational during all of 2017 [1]. Each location has a unique soundscape based on local bathymetry, environmental characteristics, anthropogenic contributions, and source-receiver geometry. Furthermore, the data acquisition hardware for each hydrophone system varied between sites. In 2015, Dakin and Heise provided a pertinent regional review of hydrophone system installation decisions for various scenarios, including choice of location, depth and hydrophone system specifications, and recommendations for post-processing techniques [13].

The review of underwater noise monitoring guidance documents [10,11,14] subsequently led the ECHO Program's ATC to develop an initial standardized sampling, analysis, and reporting scheme for long-term ambient noise measurements. The results of that work, summarized in Table 1, governed the data collection and standardized analysis protocols. It is important that the precise definition of the frequency bands used in the ECHO study be specified, as different conventions can be encountered in the literature. All frequency bands used by the Program are distributed on a logarithmic scale and are based on powers of ten around a reference frequency of 1000 Hz. The lower and upper frequency limits of the decade bands are:

$$\text{(Eq. 1)} \quad f_{lower} = 1000 \text{ Hz} \cdot 10^n$$

$$\text{(Eq.2)} \quad f_{upper} = 1000 \text{ Hz} \cdot 10^{(n+1)}, \quad n = -2, -1, 0, \dots$$

where the lower frequency limit of the first decade band starts at 10 Hz and the upper frequency limit of the highest decade band is truncated at the maximum sampling frequency.

For a finer resolution, the center frequencies of nominal 1/3-octave bands (which are, by convention, one-tenth decade bands) are constructed by multiplying the reference frequency by $10^{(n/10)}$, with $n = -20$ corresponding to a center frequency of 10 Hz. The lower and upper frequency limits for any of these bands goes from:

$$(Eq.3) \quad f_{lower} = 1000 \text{ Hz} \cdot 10^{\frac{(n-0.5)}{10}}, \text{ to}$$

$$(Eq.4) \quad f_{upper} = 1000 \text{ Hz} \cdot 10^{\frac{(n+0.5)}{10}}, \quad n \geq -20$$

For example, for the center frequency of 100 Hz ($n = -10$) the band limits are 89.125 Hz and 112.20 Hz. Although the more formal qualifier for these bands is decidecade as per the ISO 18405 standard [15], the combined bandwidth of three contiguous decidecade bands is approximately one octave, and for this reason some standards still refer to them as “1/3-octave” bands [16]. This traditional terminology is used in the ECHO analyses.

TABLE I

ECHO PROGRAM ANALYSIS AND REPORTING SCHEME (2017)

| Factor | Proposed | Rationale |
|-------------------------------|---|--|
| Temporal sampling | 2 years of reference measurements, analysis, and review. | Considered the minimum period to collect reference ambient noise data. |
| Data sampling blocks | Lunar month, with analysis of weekly and daily rhythms. | “Standardize” platform flow noise across comparative periods, given the difficulties in removing platform flow-noise due to tidal current effects. |
| Fundamental reporting metrics | Power Spectral Density (PSD): (dB re 1 $\mu\text{Pa}^2/\text{Hz}$) Sound Pressure Levels (SPL): (dB re 1 μPa) | PSD and SPL are both standard ambient noise reporting metrics. |
| Bandwidth | 10 Hz–100 kHz | This frequency bandwidth range captures acoustic energy from vessels, as well as SRKW communication and echolocation bands. |
| PSD reporting protocols | Percentile exceedance PSD plots (1-minute average) Annotated PSD spectrogram plots (1-hour average) | Percentile PSD plots are useful for comparison across regional sites and interpreting noise sources and system noise. Long-term spectral averages or spectrograms allow the interpretation of temporal noise cycles (diurnal and tidal) and identification of dominant acoustic sources (natural and anthropogenic). |
| SPL reporting protocols | SPL reporting in broadband, decade band, and 1/3-octave bands (re 1 μPa , 1-minute average) with consideration to SRKW specific communication and echolocation frequency bands. SPL, in the form of exceedance percentiles, | To provide summary noise data using metrics suitable for universal comparison and in frequency bands relevant to SRKW. At the time of the 2017 study, no universal reporting metrics were identifiable in peer-reviewed publications or international guides. Given the evolving nature of this field of study, a range |

| | | |
|-------------------------------------|---|--|
| | including median (L_{50}), min., max., quartiles (L_{25} and L_{75}), and using the arithmetic mean (L_{eq}) of the squared sound pressure. | of metrics were considered. |
| System performance and data quality | Full calibration (at the start of each study) and regular in situ system checks, consisting of high dynamic range and sensitivity gain checks. | Maintain high-quality data collection. |
| Auxiliary data needs | Environmental auxiliary data includes: weather, current speed, and sound propagation conditions. For anthropogenic sources, vessel movement patterns. | Key local influencing factors. |

IV. AMBIENT NOISE EVALUATION PROJECT (BEST PRACTICES)

In 2018, the ECHO Program’s ATC met to review the processed dataset from the 2016-2017 ambient noise monitoring project and plan a study to identify key factors that require further investigation when evaluating ambient noise trends and applied mitigation efforts. The ECHO Program subsequently initiated the ambient noise evaluation project to seek answers to the following questions:

1. What were the temporal variabilities and trends in ambient noise (across both broadband and finer-scale frequency bands) for each site, and did these hold for all three sites?
2. What key factors and trends (if any) affected ambient noise differences and variability at each site?
3. What are the critical requirements for future monitoring of ambient noise (i.e., including system performance, resolution, and methods for data analysis) to best understand the contribution of commercial vessel traffic to ambient noise levels?

The generalized approach began with defining factors that influence ambient noise levels in these complex and heavily trafficked inshore waters. The following factors were deemed to require additional study to determine how they contribute to underwater ambient noise levels at each site:

- Hydrophone systems and data quality (system noise, sensitivity range, and calibration)
- Vessel traffic
- Weather and tidal conditions
- Sound speed profile (SSP) and associated variability in acoustic propagation
- Biological (animal) presence

Dekeling et al. recommended consideration of sea state, wave height, water and air temperature, proximity to marine nature reserves, wrecks, and military sites as well as other nearby permanent anthropogenic noise sources (e.g., gas pipeline, wind farm, fish farm) for evaluation of ambient noise [11]. These factors (except for water temperature used in the calculation of sound speed) were not evaluated in the ECHO Program study, noting that evaluation of wind speed was conducted as a suitable proxy metric for sea state and wave height.

Given the ECHO Program's focus on SRKWs (considered a high-frequency odontocete) [17] it was essential to distinguish how these factors affect different frequency bands; therefore, a decade band analytical approach was taken. In the low-frequency band (10-100 Hz, 1 decade), vessel noise dominates the soundscape. In higher frequency decade bands (0.1-1 kHz, 1-10 kHz, and 10-100 kHz), killer whale vocalizations occur and hearing abilities peak.

For each of the influencing factors identified for this region, the following sections describe the factor, a high-level summary of findings from the ECHO Program's ambient noise evaluation project, a discussion of how other studies have considered this factor, and recommendations or best practices for measurement and evaluation in the Salish Sea based on findings from the ECHO Program, and key guidance formulated from other studies.

A. *Hydrophone systems*

1) *Hydrophone systems - Summary of findings*

A hydrophone system's performance relates to how a data acquisition system affects measured levels of underwater ambient noise: including consideration of system noise, hydrophone sensitivity, frequency range, and calibration. In the ambient noise evaluation project, aural and visual methods allowed system noise assessment after hydrophone calibration. All three sites are cabled systems, run independently and consequently utilized different hydrophones and systems. System noise was unique to each recording system; however, contamination of data from narrow-band tones and electrical power supplies was identifiable at all study sites. Some system noises varied with time, but others were consistent. All sites had low-pass anti-aliasing filters, which affected the detection of quiet sounds at high frequencies. At East Point, a site that relied on solar power, system noise was substantial and frequently present in all decade bands (Fig.2). Using such heavily "contaminated" data to establish existing conditions is not recommended without careful consideration of additional filtering needs. Forced redactions due to naval activity occurred in some months at the ULS, resulting in loss of data in the lower frequency decade bands.

Calibrations:

All three sites used high quality calibrated hydrophones, but calibration methods varied. The pistonphone calibrations made at Lime Kiln found no loss of sensitivity at 250 Hz, whereas, at Monarch Head, a high-frequency calibration error biased the 10–64 kHz decade band levels.

Sensitivity:

The sensitivity of hydrophones at all sites met ECHO Program requirements and ranged between -165 and -171 dB re 1 V/ μ Pa, well within recommended sensitivity levels for this type of monitoring [11].

System noise:

A review of PSD exceedances identified several system noise issues. The effects of these varied across sites and were more substantial during quiet periods (e.g., nighttime, no vessels present, slack tide, low wind), including; electrical noise spikes at both low and high frequencies, unwanted noise from GPS, and an acoustic Doppler current profiler (ADCP). East Point (Fig. 2) had a significant power supply spike at 60 Hz with harmonics extending to 3800 Hz. Autonomous deployments may reduce certain aspects of system noise generally associated with cabled external power supplies.

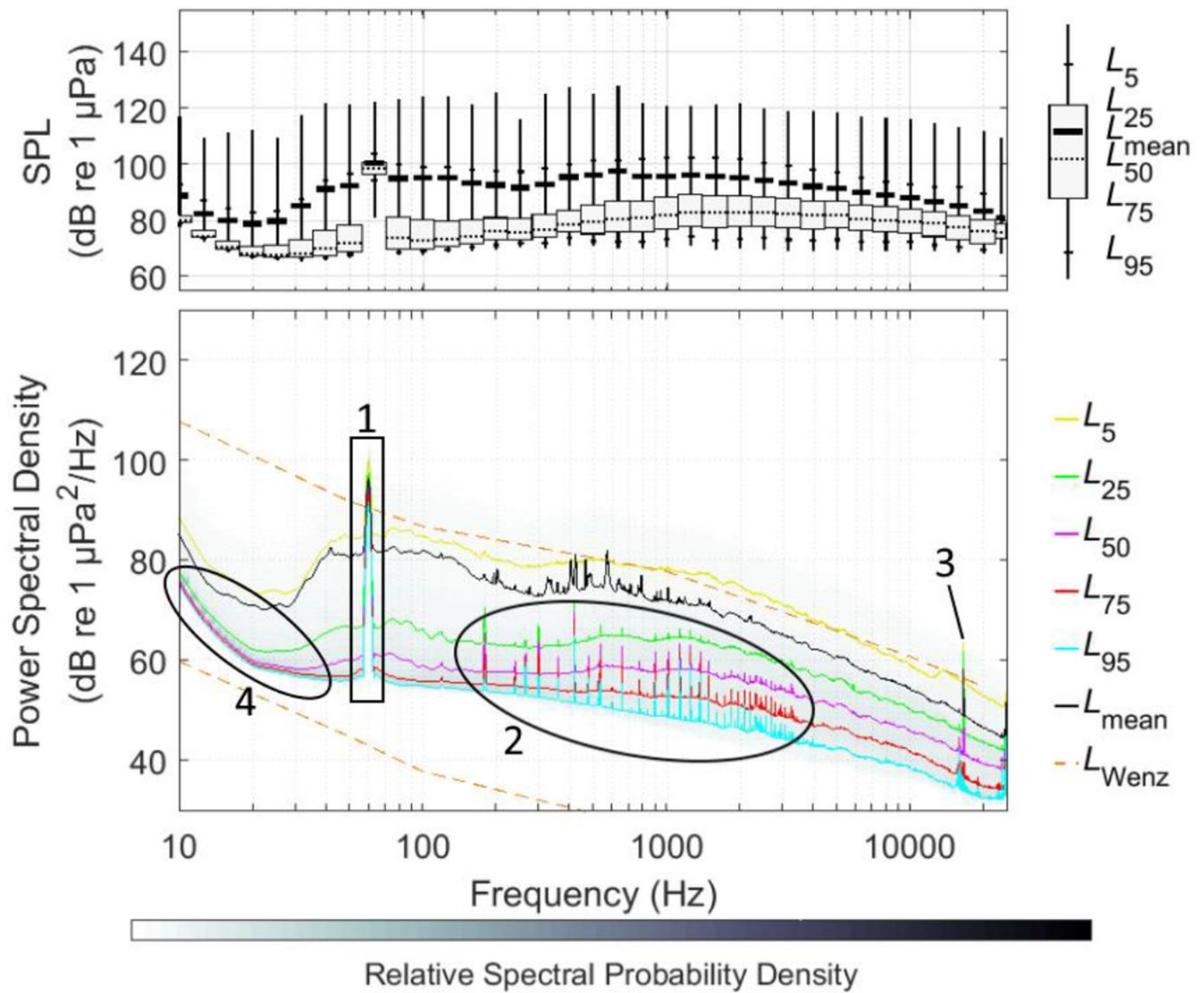


Figure 2: Example of notable data quality issues identified using 1/3-octave bands and power spectral density levels recorded from 22 Jan 2016 to 21 Feb 2016 (East Point) with four annotated system noise features identified. Annotation 1 shows the 60 Hz power supply tone. Annotation 2 shows harmonics from the power supply tone. Annotation 3 shows tones from a solar panel feeding the power grid. Annotation 4 shows the low-frequency noise floor [1].

Flow-noise:

Currents in the study area are predominantly tidally driven, with typical peak flow speeds ranging between 0.5-1.0 m/s at ebb and flood. Tidal currents can produce substantial flow noise on the hydrophone and mooring components, with effects documented at 10–100 Hz levels during high-current periods. At such

times, this noise limited a recorder's ability to measure low levels of low-frequency sounds. Site comparisons were not possible due to the lack of local current data at Lime Kiln and East Point.

2) *Hydrophone systems – Discussion and contemporary studies*

In 2016, Merchant et al. suggested that consistency in the monitoring instrumentation, sensor placement, and continuity of the time series have a strong influence on the statistical power of passive monitoring programs and that shallower bathymetry results in comparatively poor acoustic propagation, attenuating the contribution of shipping noise [18]. ACCOBAMS (The Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area) suggested that long-term hydrophone stations should be placed in high and low traffic areas and near oceanographic stations. In addition, a recent sonar survey of local bathymetry is recommended for hydrophone deployment and subsequent analysis (with emphasis on hydrophone deployment sites in deep water with low current speeds) [19].

In 2014, Robinson et al. wrote a “Good Practice Guide for Underwater Noise Measurement” on behalf of Marine Scotland. This guide provided direction on noise measurements and identified commonly used metrics for describing underwater noise, including definitions and units. The recommendations included reporting metrics and guidance on hydrophone selection, data acquisition systems, and calibration procedures. For shallow water deployments, the measuring hydrophone ideally resides in the lower half of the water column, between half and three-quarters of the total depth (measured from the sea surface). In very shallow water, the variation in tidal depth may significantly affect sound propagation [14].

Dekeling et al. recommended that calibration should include the full frequency range of interest for the specific application at hand, noting that it is possible to calibrate a hydrophone and recording system with an overall uncertainty of less than 1 dB [11].

Dakin and Heise suggested that hydrophone calibrations take place at least once every two years. Calibration facilities provide a higher degree of accuracy (± 0.5 to ± 2 dB) than in situ calibrations (± 3 to \pm

6 dB) but are more labor and time-intensive. It is tempting to set the system gain high to detect distant or low amplitude sounds on recording systems with adjustable gain. However, this also amplifies the system's self-noise and can cause louder sounds to saturate the hydrophone, and the combination reduces the dynamic range of the system. System noise can be associated with the pre-amplifiers, filters, and power supplies in the data acquisition system. Also, cables, moorings, and anchoring systems may add to the noise of a hydrophone installation. The use of a shroud, installed over the hydrophone element, is recommended, and decoupling the hydrophone from the mooring using a shock cord can also help to dampen noise, including fauna noise on the mooring, such as crabs and fish [13]. Kinda et al. also highlighted flow noise as an issue for autonomous moorings and suggested flow noise effects might be minimized by reporting (low-frequency) results only for periods of low current flow [20].

The Joint Monitoring Programme for Ambient Noise in the North Sea (JOMOPANS) issued a 2018 report on “Standard procedure for equipment performance, calibration, and deployment”. The report also recommended calibration for any hydrophone and recording system deployed for the study of ambient noise. Ideally, hydrophone calibrations should occur in the same mounting configuration and temperature/depth, which the hydrophone is likely to experience in the field. Prior to deployment and following the recovery, field calibrations are essential to ensure no significant changes in the hydrophone response occur throughout the deployment. The recommended frequency range for calibrations should, at a minimum, cover the frequencies of interest between 10 Hz and 20 kHz [21].

Flow noise contamination can reduce the correlation between broadband shipping noise and the frequency bands used as anthropogenic noise indicators, making these indicators less effective. Since flow noise increases with decreasing frequency, lower frequency bands are more affected, particularly the 63 Hz band used for the European Commission Marine Strategy Framework Directive [18].

In 2015, the Baltic Sea Information on the Acoustic Soundscape (BIAS) report stated that system-noise is a key consideration when measuring low amplitude signals. Expression of self-noise as a spectrum level, either in $\mu\text{V}/\text{Hz}$ at the amplifier input or back-calculated as $\mu\text{Pa}/\text{Hz}$ at the hydrophone, should be at least 6

dB below the lowest noise level of interest [22]. To minimize random and systematic uncertainties, quality controls were implemented throughout the processing steps by testing the signal processing software and performing inter-organization comparisons (ring tests) of the signal processing methodologies.

3) *Hydrophone systems – key recommendations*

Based on the learnings of the ECHO Program ambient noise evaluation project and a review of other relevant studies, the following points represent best practices for hydrophone systems and data quality:

Location:

Hydrophone sampling should be conducted at the same location and depth, year-over-year, to confidently establish long-term trends. Consistency is particularly crucial for near-shore hydrophones, which can be substantially affected by bathymetric features and shorelines blocking noise sources.

Equipment:

Where possible, the use of cabled systems for long term monitoring is advantageous. This allows for continuous data collection (no duty cycle required) at wide bandwidth and on-going system performance checks. A minimum water depth of 20 - 30 m is recommended for any installation.

If possible, utilize identical systems at all monitoring locations if looking to characterize a regional soundscape. If this is not possible, select systems with similar performance (sampling rate, bit-rate, and anti-aliasing filters). Installation of shrouds to help reduce biofouling (in addition to reducing flow noise) and a ready supply of system components to ensure timely replacement (if a failure occurs) is pragmatic.

Calibration:

Characterization of a hydrophone and recording system's response curve should ideally be within ± 1 dB over the full frequency range of interest (e.g., 10 Hz to 100 kHz). End-to-end system calibrations should be spot-checked, at minimum, annually (using a pistonphone or other controlled sound source) to ensure no long-term variations in the recording system's sensitivity. Where possible, different recorders should be co-located during calibration, allowing for comparison of ambient noise measurements and characterization of system noise.

System monitoring:

Before deployment, measurement of the hydrophone's noise floor (1-minute PSD spectrum) in a quiet laboratory setting is preferable. After deployment, the noise floor (1-minute PSD spectrum) of the hydrophone and recording system should be measured monthly during a quiet period. Interfering noise sources should be identified in situ, if possible.

Undertake regular aural checks on data quality (unusual noises, reduced performance). Catalogue and ideally fix any underlying data quality issues (Fig. 2). Identifying residual data quality issues is preferable in early data post-processing (to allow filtering or analytical remedies).

Monthly reviews of measured 1-minute 1/3-octave band noise levels are suitable for monitoring changes in system noise characteristics. Any significant changes in system noise characteristics require investigation, as they may indicate impending system failure (e.g., increased low-frequency noise may be associated with water ingress into hydrophone electronics).

Consistently record all system specifications and all modifications (e.g., gain settings, maintenance operations, calibration events) that occur between deployments.

B. *Vessel Traffic*

1) *Vessel Traffic - Summary of findings*

Vessel movement patterns at all three ECHO Program reference sites made use of AIS data. Additional small boat (non-AIS) information was collected from photographic evidence at East Point and by an acoustic detector at Lime Kiln.

Vessels were the dominating factor affecting ambient noise levels at all three sites and across all frequencies considered. Large AIS vessel presence dominated noise levels between 10-100 Hz and was also a significant contributing factor at higher frequencies. This mirrors published sources in the Salish Sea [23], especially for sites close to the shipping lane [18]. Fig. 3 (below) shows a density plot of vessel traffic hours versus distance from the hydrophone at each study site. In Haro Strait, the peaks at 2.5 and 4.5 km from the Lime Kiln hydrophone correspond to the inbound and outbound international shipping lanes, respectively. The peak in the Boundary Pass density plot, 2 km from the East Point / Monarch Head hydrophones, was due to vessel traffic in both the inbound and outbound shipping lanes. A spike in the density plot around 6.25 km from the ULS in the Strait of Georgia was primarily due to tug traffic entering and exiting the Fraser River [1].

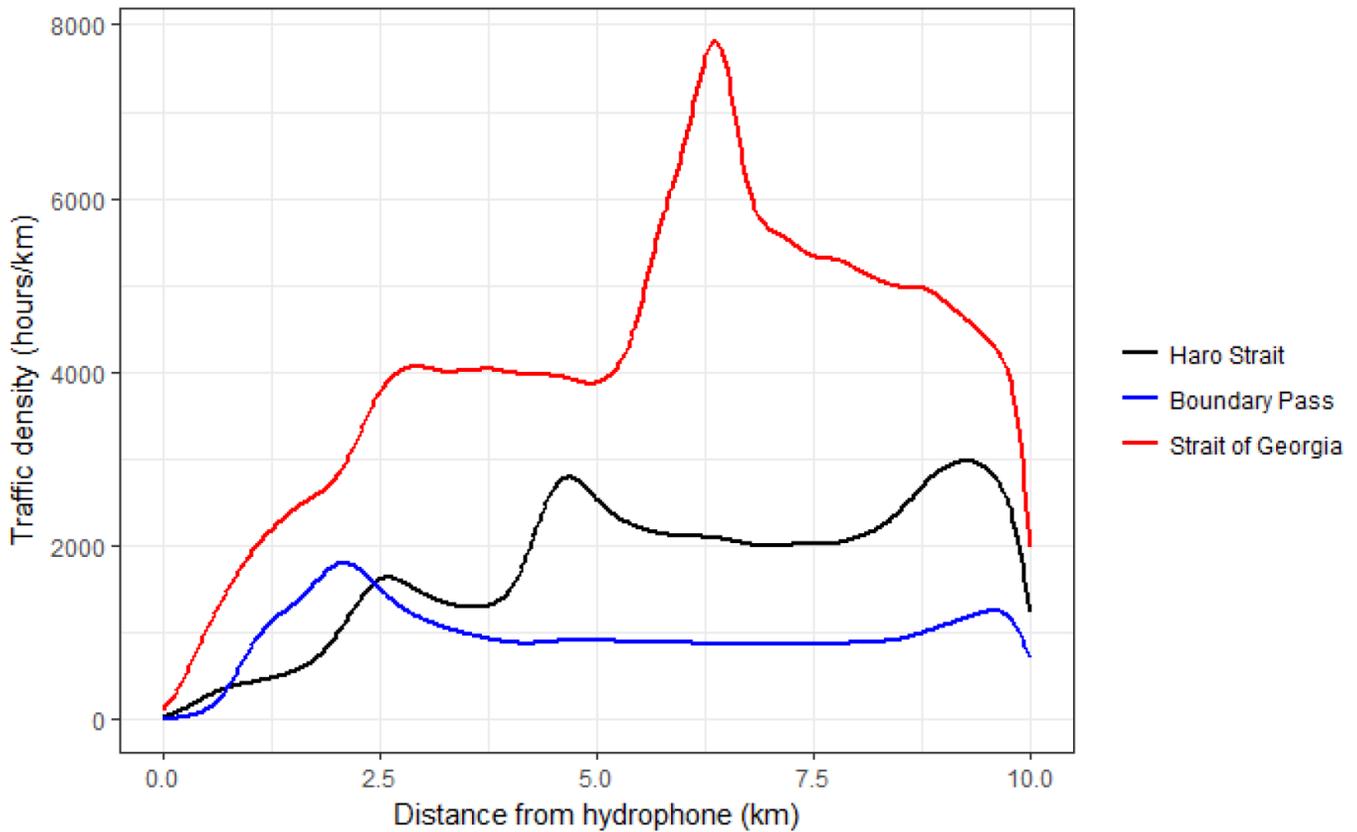


Figure 3: Density plot of vessel traffic hours versus distance from the hydrophone at each site [1].

When reviewing sound pressure level (SPL) statistics, the arithmetic mean (L_{eq}) values were below the L_5 values but well above (>10 dB) the L_{50} (median SPL) at all sites, which indicated that short-term, high-amplitude noise sources were present (such as large vessels). The ULS, adjacent to the shipping lane, had the highest monthly mean ambient noise sound pressure levels ($L_{eq} = 119.8$ dB re $1\mu\text{Pa}$). Lime Kiln, the site furthest from the shipping lanes, had the highest monthly median ambient noise levels ($L_{50} = 108.4$ dB re $1\mu\text{Pa}$), and experienced regular, close proximity transits of small boats [1].

Fig. 4 (below) shows the influence of traffic volume from large commercial vessels at Lime Kiln. Low, medium, and high-volume traffic days were determined from daily large commercial vessel traffic hours in the 0-25th, 25th-75th, and 75th-100th percentiles, respectively. At Lime Kiln, hourly sound levels increased

with vessel traffic in the first three-decade bands (especially in January), but increases in the fourth decade band (10-100 kHz) were either smaller (July) or negligible (January).

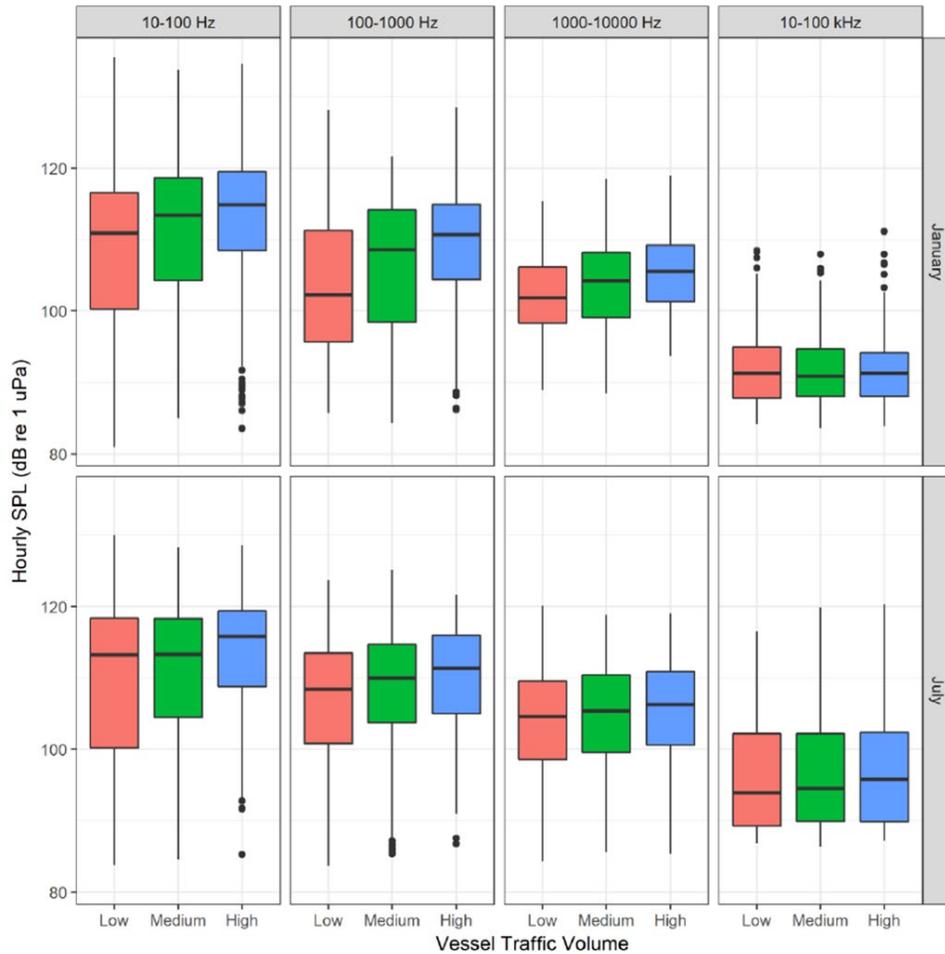


Figure 4: Box-and-whisker plots of hourly decade-band sound levels (Lime Kiln) versus large commercial traffic volume in January (top) and July (bottom) 2017 [1]. A box-and-whisker plots illustrates the center, spread, and overall range of data from a visual 5-number summary. The top and bottom of the box are the upper and lower quartiles (25th and 75th percentiles), while the horizontal line is the median (50th percentile). Whiskers (vertical lines) indicate the lower extreme and upper extreme values within 1.5 x the interquartile range. Black dots indicate outliers.

Small (non-AIS) vessels in close proximity to the hydrophone can dominate the soundscape, as found at Lime Kiln (Fig. 5). Overall, at this site small vessels were found to dominate some higher frequencies. Fig.

5 compares SPL cumulative distribution functions when no vessels were detected, when large vessels were acoustically detected, when large vessels were detected by AIS, and when small vessels were acoustically detected. The large vessel acoustic detector was in good agreement with AIS detections above an SPL of 115 dB re 1 μ Pa. Divergence at lower levels is driven by false negatives (missed detections of distant vessels).

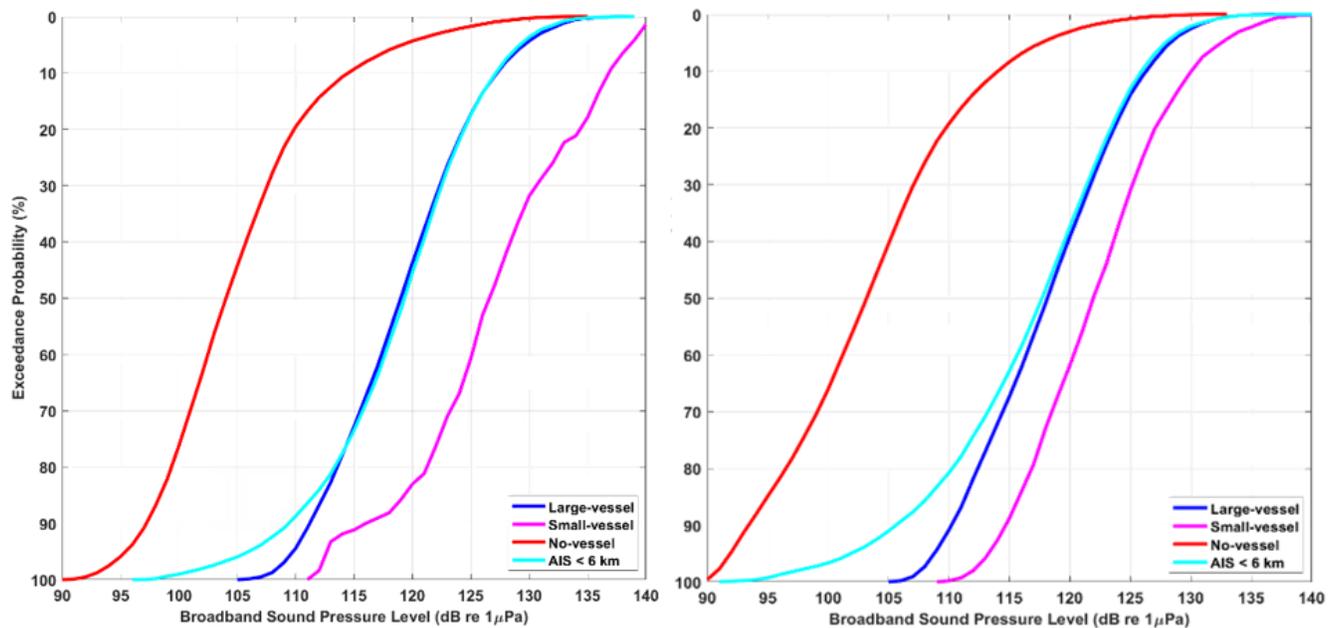


Figure 5: SPL cumulative distribution functions (Lime Kiln) with broadband (10 Hz to 100 kHz) 1-minute cumulative exceedance probability plots for January (left) and July (right) 2017, during periods with acoustic detections of large vessels (dark blue), small vessels (pink), and no-vessels (red). SPLs for times when there were AIS transmissions within 6 km of the hydrophone are shown in cyan [1].

2) Vessel traffic - Discussion and contemporary studies

Studies focused on vessel noise typically only report ambient noise levels at lower frequencies where large vessels are known to be significant contributors [9]. Vessel noise effects have thus often focused on baleen whales that are considered a low-frequency hearing group. However, more recent regional studies have highlighted elevated median background levels associated with vessel presence at low frequencies

(20-30 dB from 100 to 1,000 Hz) and higher frequencies (5-13 dB from 10,000 to 96,000 Hz). Thus, noise received from commercial vessels at ranges less than 3 km extends to mid-frequencies used by odontocetes, such as killer whales, for communication and echolocation [24]. Typically, noise from small boats peaks at higher frequencies than larger ocean-going commercial vessels. Managing underwater noise, as part of the European Union's "Marine Strategy Framework Directive" (MSFD), has resulted in a focus on measuring annual mean (L_{eq}) continuous noise (such as that emitted by large commercial vessels) levels in just two 1/3-octave bands centered at 63 and 125 Hz.

Several subsequent publications and reports have extended reporting frequencies, especially to higher frequencies (e.g., 2 kHz), mainly to take better account of the frequencies in which key large cetaceans vocalize, as well as suggesting alternative or additional reporting metrics [10, 18, 19]. Consequently, in addition to annual mean estimates, reports of cumulative distribution functions (CDF, Fig. 5) of SPL are recommended by many of the more recent European reports and papers reviewed (see further discussion in Data Analysis and Reporting Metrics section). This CDF approach permits the concurrent visualization of multiple SPL dB exceedance metrics. In a recent SRKW noise effect study in the Salish Sea [25], a CDF approach was used to generate monthly cumulative noise distribution maps. Merchant *et al.* undertook a systematic review of different noise metrics and concluded that L_{10} or L_5 is the most appropriate for tracking anthropogenic noise levels in the marine environment, as these high dB exceedance metrics are most sensitive to intermittent high noise levels typically caused by vessel transits [18].

All reviewed contemporary ambient noise studies highlighted the need to access AIS information on shipping movements as AIS data provide information on vessel density and proximity to monitoring locations, as well as vessel speed and class [18, 25]. Such factors are considered necessary in understanding trends in ambient noise levels. Only a small fraction of private pleasure crafts, fishing vessels, and ecotourism boats are equipped with AIS transponders, yielding an underestimation of these vessels' actual contribution to noise levels. In some inner coastal waters, noise from motorized recreational (non-AIS) vessels can elevate 1/3-octave band noise centered at 0.125, 2, and 16 kHz by 47–51 dB [26] and dominate

the soundscape. In areas of known high density non-AIS recreational traffic, understanding these vessel's contributions are essential when interpreting ambient noise levels and generating cumulative noise models. Multiple studies also recommend considering auxiliary environmental data when assessing the influence of vessel noise on ambient noise levels (see Environmental Factors section below).

3) Vessel traffic - key recommendations

Based on the learnings of the ECHO Program ambient noise evaluation project and a review of other relevant studies, the following points represent best practices for collecting and analyzing AIS and non-AIS vessel movements:

Large vessel traffic

Continuous traffic monitoring using a land-based AIS receiver located near the hydrophone is preferable. Periods with AIS receiver outages require identification and AIS data quality checks (e.g., vessel type) to help ensure data consistency. Additional factors such as vessel proximity to the hydrophone, vessel type/size, and vessel speed are necessary for detailed analyses.

Transits of non-AIS vessel traffic should be monitored at the hydrophone location, using a combination of acoustic and non-acoustic methods to increase the detection rate. Results from this study suggest that a combination of camera and hydrophone-based detections may be an effective method. Alternative monitoring methods, such as radar, may also be useful for monitoring non-AIS vessels.

Utilizing vessel source levels [27], combined with AIS and other tracking data to model the noise field of both AIS and non-AIS vessels, is also recommended for a fulsome evaluation of ambient noise contributions across larger areas, as well as to explore mitigation efficacy [28].

C. Environmental Factors

1) Environmental Factors – summary of findings

Environmental factors that influence ambient noise belong to three broad categories: weather and tides, sound speed profile variability, and the presence of biological noise sources.

Wind creates breaking waves and can elevate ambient noise levels during quiet periods when vessel noise is negligible. It also increases high-frequency transmission loss due to rough sea surface-induced scattering and weakened coherent reflections. The sound of rainfall may be detected at the hydrophone, particularly for shallow installations.

Variation in the refractive properties of the SSP influences the path of acoustic propagation. Refraction occurs due to changes in sound speed, which is a function of temperature, pressure, and salinity. Sea-surface roughness, bathymetry, and seabed composition (e.g., sand, silt, and clay) also affect sound propagation. These characteristics of the water column, surface, and seafloor are critical inputs for accurate modeling and developing a robust understanding of acoustic propagation at a particular monitoring site.

Biological presence relates to underwater sounds generated by marine fauna, such as marine mammal vocalizations and echolocation clicks, that affect ambient noise.

In combination with a predictive ocean current model and local current measurements (where available), local weather station data allows evaluation of how wind, rain, and tidal currents may have affected ambient noise data.

Wind and rain:

Seasonal changes in wind-induced ambient noise (>100 Hz) were identifiable at Lime Kiln and East Point for winter conditions but not during summer conditions. Rainfall events in this study made negligible contributions to ambient noise levels at each site. Ideally, to better understand the acoustic impact of rainfall, data should be collected close to the hydrophone location and on a fine (e.g., 1-minute) timescale.

Tidal currents:

At the ULS, ADCP measurements allowed for better characterization of flow noise from tidal currents (Fig. 6); however, the high-frequency chirps of the ADCP also contaminated the acoustic recordings. With current data from a predictive tidal model, correlations were less distinct at Lime Kiln and East Point/Monarch Head. Low-frequency system noise at East Pont also limited the ability to interpret tidal effects. Mechanical or electromagnetic current meters located proximate to the hydrophone deployment may be preferable for future ambient monitoring.

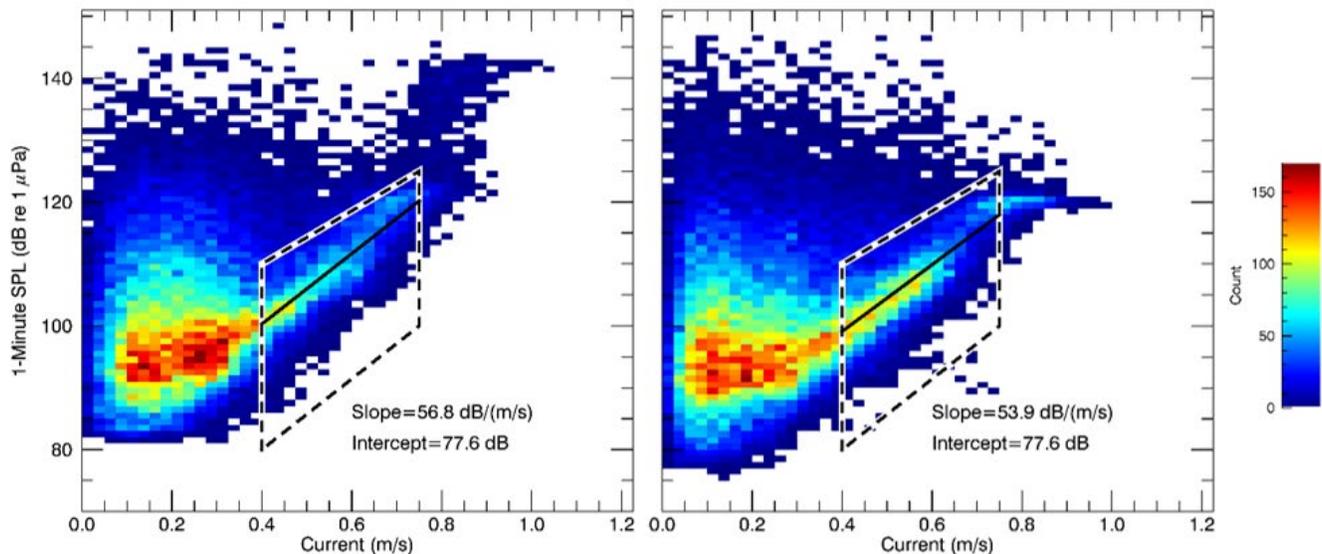


Figure 6: ULS correlation analysis to assess current speed effects on noise levels. Sound pressure levels (SPL; 1-minute average) in the 10–100 Hz decade band as a function of water current speed were compared for January (left) and July 2017 (right). Linear regressions (solid black lines) were fit to the data within the dashed line, indicating a positive correlation effect above 0.4 m/s [1].

Sound speed profile:

SSP measurements in the Salish Sea showed more seasonal variations at the ULS than either Lime Kiln or East Point; however, greater temporal and spatial coverage of SSP measurements at that location may have played a factor (Fig.7).

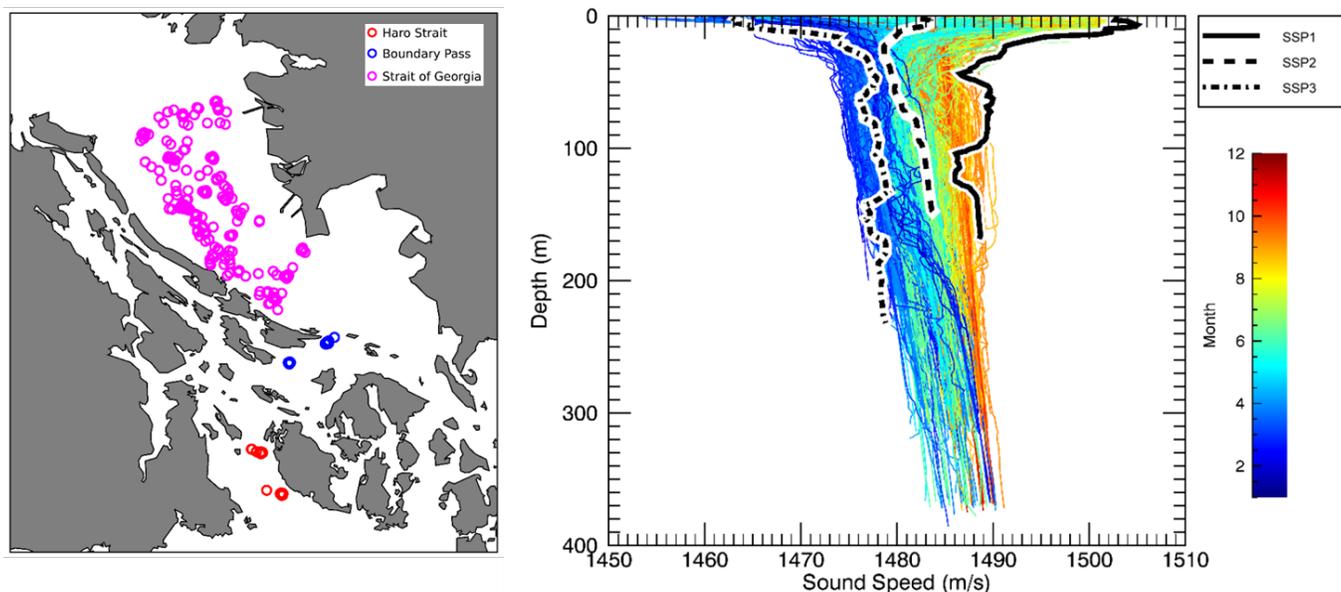


Figure 7: Map (left) showing sound speed profile (SSP) measurements locations in the Salish Sea (circles) [29]. Sound speed profiles measured in the Strait of Georgia (right). SSP profiles 1, 2, and 3 (summer, fall/spring, and winter) represent the observed range of SSP variability at this site. The sound channels at ~50 and 120 m will not have a large effect on transmission loss between shallow noise sources (e.g., ships and waves) and the hydrophone at 170 m depth [1].

SSP measurements were used with wind speed measurements and seabed properties to model acoustic propagation at each site (Fig. 8). Propagation modelling, used JASCO's Marine Operations Noise Model (MONM) that incorporates the following site-specific environmental properties: I) a bathymetric grid of the modeled area II) underwater sound speed as a function of depth, and III) a geo-acoustic profile based on the seafloor's overall stratified composition. MONM computes acoustic fields in three dimensions by modeling

transmission loss within two dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source [1].

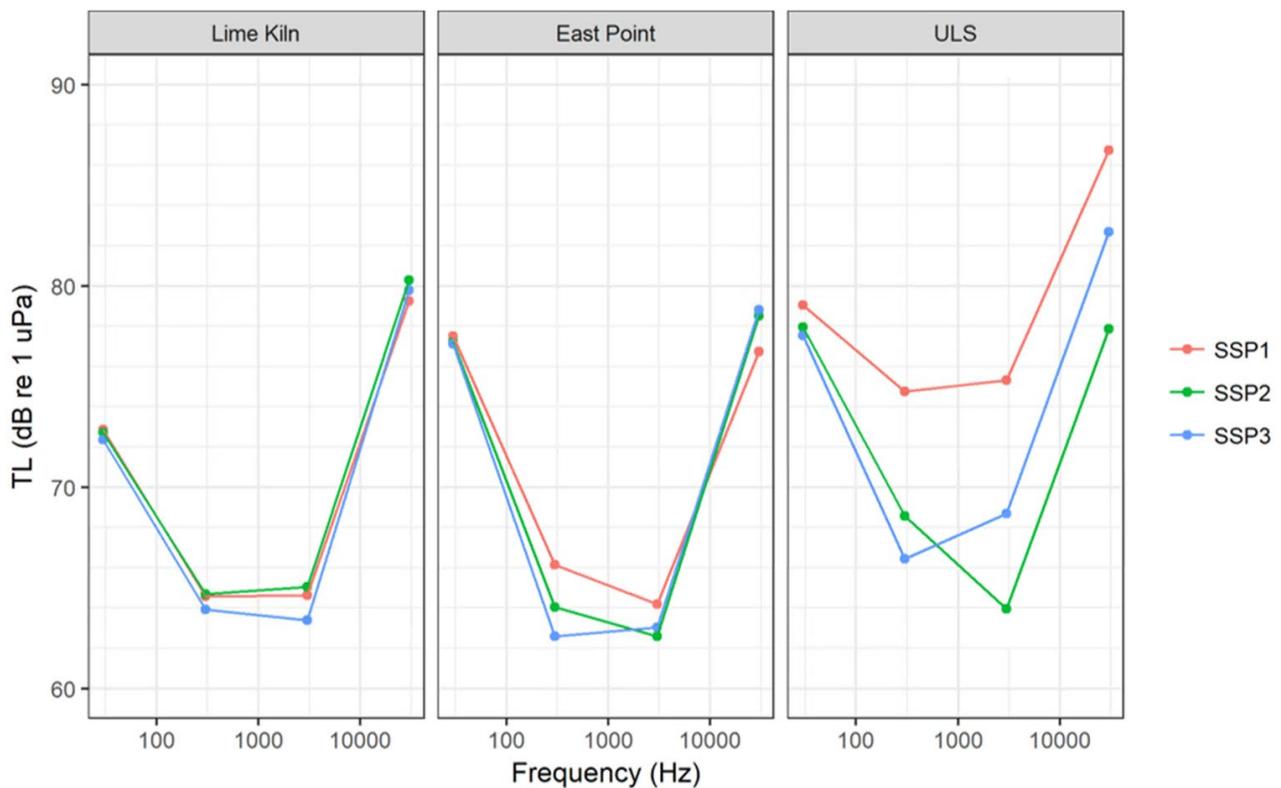


Figure 8: Average transmission loss (TL) for Lime Kiln (left), East Point (middle), and ULS (right) for a near-surface source between 2 and 4 km range along a radial between the international shipping lanes and the hydrophone. Line colors represent the seasonality of sound speed profiles (SSPs), used for modelling (red: summer, green: fall or spring and blue: winter). Measured seasonal profiles were unique to each site [1].

Sound propagation modeling showed that propagation loss was lowest for the mid frequencies, 300 and 3000 Hz and higher during summer (downwards-refracting) conditions. Despite this, ambient noise levels were higher in summer at all three reference sites, indicating traffic volumes (higher in summer) played a more important role than the seasonal effects of SSP.

Biologicals:

The effect of biological presence was analyzed by comparing sound levels at times with and without (immediately before and after) acoustic detections of marine mammals. Sounds from biological sources are automatically detected using PAMGuard software and subject to verification by a human analyst. This evaluation focused on Lime Kiln where there were sufficient periods of confirmed SRKW vocalizations to conduct an assessment. Biological presence from SRKW increased sound levels in the 1-10 kHz and 10–100 kHz frequency range by approximately 3 and 7 dB, respectively (Fig. 9).

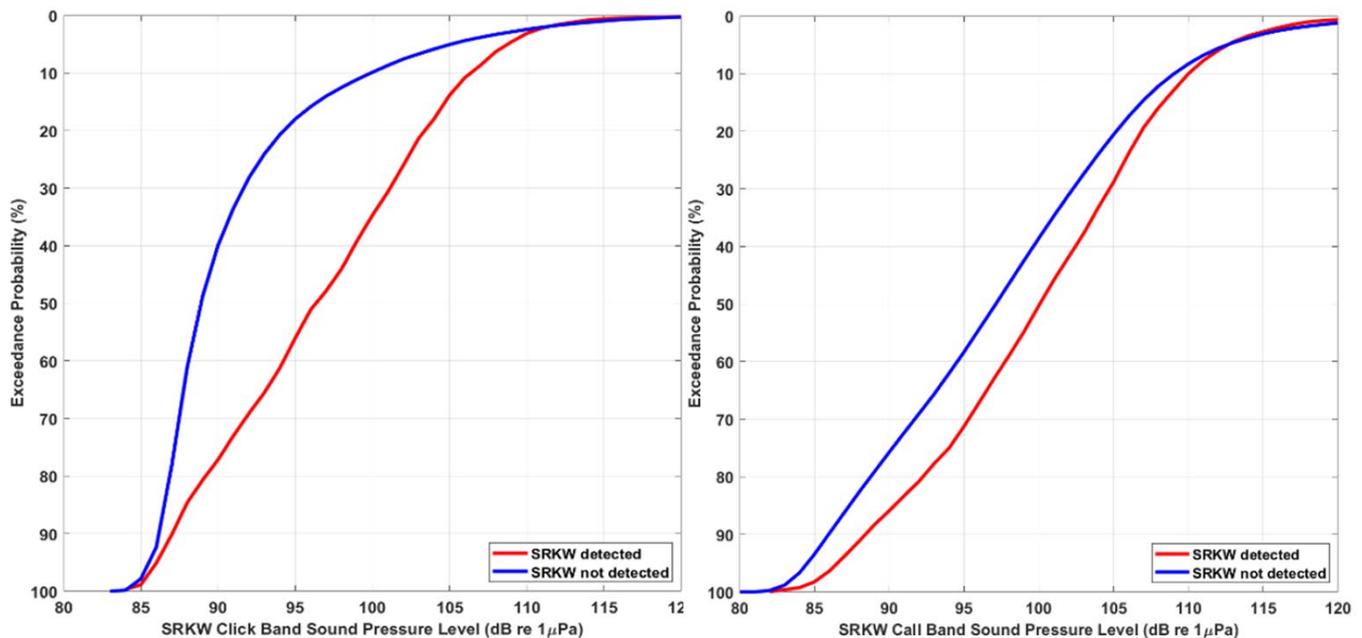


Figure 9: Lime Kiln: One-minute cumulative exceedance probability plots for periods with and without Southern Resident Killer Whale (SRKW) detections for “vocalization” decade band SPL (1-10 kHz) (left) and SRKW “click” decade band SPL (10-100 kHz) [1].

2) Environmental factors - discussion and contemporary studies

A “soundscape” is formally defined by ISO [30] as the “characterization of ambient sound in terms of its spatial, temporal and frequency attributes, and the types of sources contributing to the sound field”. In 2018, Ainslie described the Atlantic Deepwater Ecosystem Observatory Network (ADEON) project’s focus on establishing an acoustical/environmental observation network to support baseline measurements and predictive modeling of the soundscape. This report adds that the ISO definition for soundscape does not include many “region-specific” sources: system noise, noise from turbulent flow (flow-noise) or surface gravity waves, nor emissions from vessels or biologicals. The ADEON study includes these sources to facilitate compatibility between inter-study soundscapes and those studied by other researchers and institutions [30]. ADEON also focused on biological sources and commercial vessel detection. The regional detection of biological sources ranged from Fin whales to dolphins.

Garrett et al. assessed ambient noise with an environmental focus on seasons, wind, and wave height in Falmouth Bay, UK. The study found that improved propagation conditions in winter may be contributing to the observed louder average sound levels during this season. Increasing wave height significantly affects the 63 & 125 Hz 1/3-octave band levels likely contributing to increased noise levels with increasing wave height in winter. A site-specific environmental evaluation accounts for these natural contributions to local sound levels [31].

Dekeling et al. stated that it is beneficial to record any relevant auxiliary data and correlate it with the measured noise levels during analysis. If auxiliary data must be measured locally, this may require the deployment of additional equipment. Relevant auxiliary data may include sea-state, wind speed (and associated measurement height), rate of rainfall and other precipitation (including snow), water depth and tidal variations across that depth range, water/air temperature, hydrophone depth in the water column, GPS locations of hydrophones and recording systems, seabed properties, profiles of conductivity, and hydrostatic pressure as a function of depth [11].

3) Environmental factors - key recommendations

The monitoring of wind and rain data should occur near the hydrophone location. Wind speed, wind direction, and precipitation should be recorded on a 1-minute basis, if possible. Wind data is ideally measured at a standard elevation (a mast 10 m above sea level is recommended).

A current meter (mechanical, electromagnetic, or acoustical) preferably records water currents' speed and direction near the hydrophone. In combination with 1-minute SPL data, a linear correlation defines the relationship between current speed and flow-induced noise (Fig. 6). Acoustical meters require sufficient separation from the hydrophone to minimize noise contamination. The amount of noise contamination depends on the current meter (e.g., frequency, power, and beam pattern), recorder (e.g., sample rate and frequency response), and transmission loss. Determining an appropriate separation distance to minimize acoustic contamination may require acoustic modelling and test measurements. Electromagnetic meters require periodic maintenance to clean biofouling. Consideration of fairings, shrouds, and other noise reduction methods for moorings is recommended.

Sampling of temperature and salinity profiles should, at minimum, be seasonal (ideally monthly) and near the hydrophone. Recent storm events and freshwater outflow from major river systems affect previously measured profiles, so their influence requires consideration. Transmission loss modelling should use seasonal SSPs to better quantify location-specific and seasonal variability in underwater sound propagation.

For assessing the influence of biologicals (marine mammals and fish), automatic acoustic detectors, with a portion manually validated, should be run on the data. Comparing “quiet times” with and without marine mammal detections is optimal to evaluate biological sources' potential contribution. Aural review of acoustic data during quality assurance protocols will help identify other critical biological contributors.

D. *Data Analysis and Reporting Metrics*

1) *Data Analysis and Reporting Metrics – summary of findings*

Underwater SPL varied across months and considerably between sites. Lunar month reporting was originally specified by the ECHO Program ATC to reduce flow noise variability caused by changing tidal cycles within a standard month; however, this approach resulted in a temporal mismatch when comparing across years and added to the complexity in defining each analytical period. Data were analyzed consistently, at high resolution, at each site as per ECHO Program guidelines (Table 1). A wide range of SPL cumulative distribution function exceedance percentiles metrics were reported: median (L_{50}), mean (L_{eq}), quartiles (L_{25} and L_{75}), min. and max., as well as L_{95} and L_5 . This multi-faceted approach was adopted until universal standards for reporting metrics are agreed.

An evaluation of various unwanted noise sources (e.g., flow noise, ADCP, electrical noise) is recommended; however, these sources were not extracted or otherwise accounted for in the data analysis, except for identifying associated uncertainties in the frequency bands they occurred.

Accounting for military-based redactions occurred wherever possible (redactions filter out sound levels below 4 kHz). Sound level statistics, automatically generated, included redaction periods, yielding an artificial reduction in monthly average sound levels in the 10–100 Hz, 100–1000 Hz, and 1000–10000 Hz bands. Subsequent removal of redacted periods and recalculation of statistics is recommended. The observed variability (Fig. 10) in site-to-site and intra-site broadband median (L_{50}) SPL (2–6 dB) highlighted the analytical challenges in determining “existing” conditions, detecting future trends, and assessing efficacy of short-term mitigation measures.

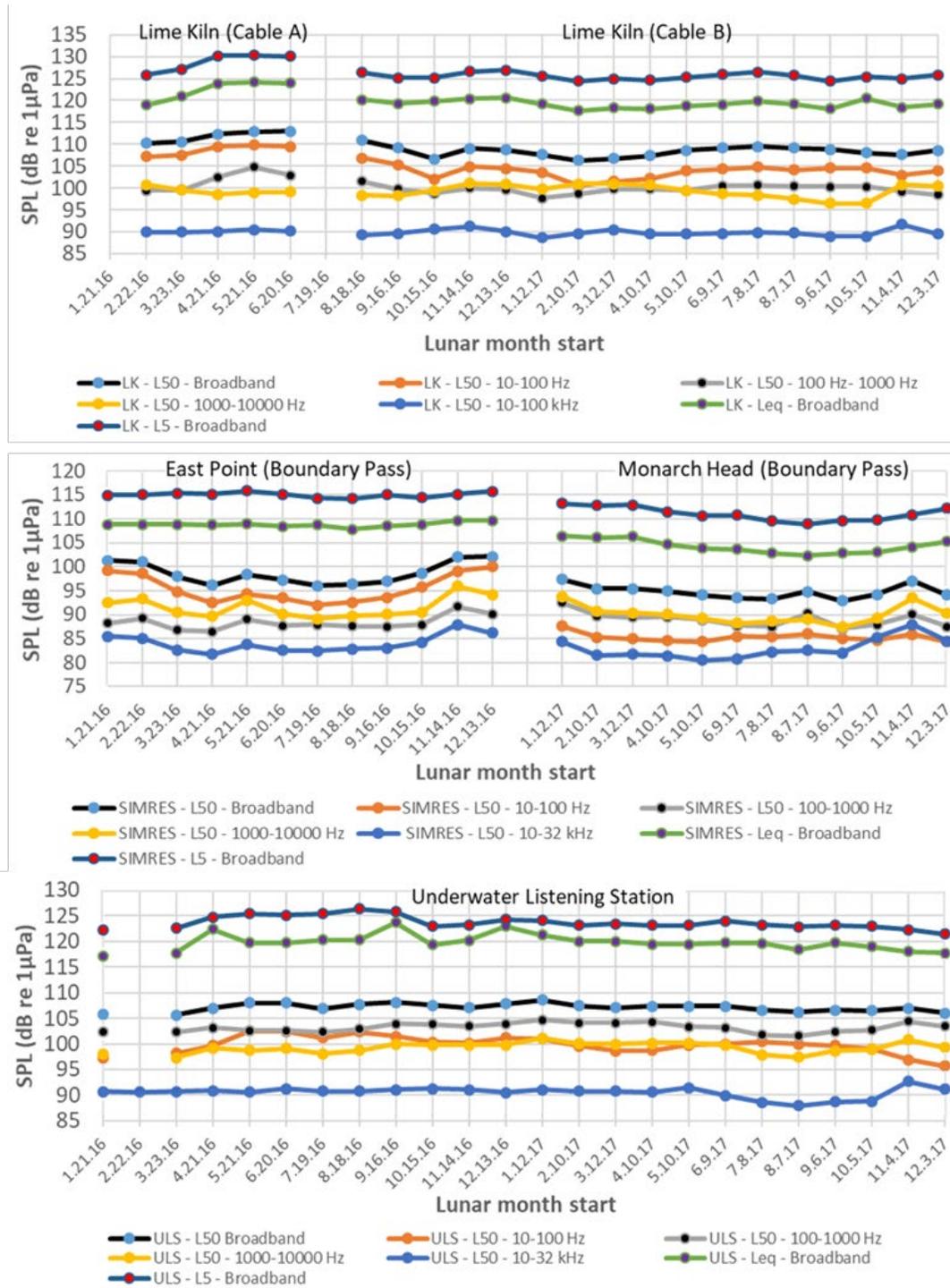


Figure 10: Ambient noise levels for Lime Kiln (top), East Point/Monarch Head (middle) and the Strait of Georgia ULS (bottom) using L₅₀, L₅ and L_{eq} (decadal and broadband) sound pressure level (SPL, 1-minute average) by lunar month during the study period [1].

Broadband sound levels at Lime Kiln from February to June were approximately 5 dB higher in 2016 than in 2017. These levels were dominated by the 10-100 Hz band. In July 2016, the Lime Kiln hydrophone was upgraded with a new cable. This change in system set-up is believed to have resulted in subsequently lower recorded sound levels (as no other important factors were changed over the monitoring study period).

2) *Data Analysis and Reporting Metrics- discussion and contemporary studies*

Heaney et al. issued “The ADEON Data Processing Specification” to study ambient noise in 2017. The ADEON project's objectives are similar to both the ECHO Program ambient noise monitoring project and JOMOPANS. ADEON seeks to develop standardized measurement and processing methods and visualization metrics for comparing ADEON acoustic data and observations with results from other monitoring networks [32]. Critical to these objectives are the following deductions:

- No single measurement system is sufficient for describing any of the ocean state variables.
- A multi-platform, multi-variable approach integrated with modelling is required.
- Ideally, collect measurements from stationary instruments, autonomous systems, and mobile platforms.
- Each station has a unique soundscape based on local bathymetry, environmental conditions, and source/receiver geometry.

Dekeling et al. provided comprehensive advice to the European Commission in 2014, which is followed by many regional practitioners. The recommended metrics for reporting ambient noise levels are in 1/3-octave bands for 63 and 125 Hz. Average noise levels (root mean square (RMS) re 1 μ Pa) in these octave bands are measured over a year, either through observation stations or combined with predictive noise models where appropriate. The report concludes that the combined use of measurements and models is the

best way to ascertain ambient noise levels and trends (however, modeling efforts should be balanced by in situ measurements). Dekeling et al. recommends retaining the complete noise distributions (received levels within each 1 Hz bin for each minute, across a frequency bandwidth of 10 Hz to 20 kHz) in the form of sound pressure levels as a function of time [11].

The OSPAR (Oslo/Paris convention for the Protection of the Marine Environment of the North-East Atlantic) Commission's 2015 report "Monitoring Strategy for Ambient Underwater Noise" offered a methodology for monitoring underwater ambient noise, using sound maps generated from a combination of models and measurements [33].

The JOMOPANS project focuses on EU MSFD reporting, as detailed in Dekeling et al. [11]. JOMOPANS states that underwater sound shows high variability in both time and space, and therefore monitoring based solely on in situ measurements would be impractical. The JOMOPANS project derived shipping and wind noise maps from numerical modeling to overcome this problem. Statistical modeling techniques were applied to quantify uncertainties in model output.

Merchant et al. produced an acoustic metric specification report of the EU INTERREG Joint Monitoring Programme for JOMOPANS in 2018. The report sets out the context and rationale for the acoustic metric specification. The first criterion for the metrics is ecological relevance, such that the metrics used to measure and model underwater sound reflect how marine species are affected by sound. Secondly, the metrics must be realistic in terms of the practical constraints on monitoring, both for field measurements and modeling. Temporal units were percentiles of the SPL distribution, based on individual SPL measurements of 1 second (snapshot duration), and computed over one month [34].

In one UK anthropogenic noise monitoring study by Merchant et al., four summary metrics of noise level were computed: the mode, median, 90th percentile, and arithmetic mean (termed RMS) level. The RMS level was not considered a robust metric and was highly sensitive to outliers in the noise level distribution since it represents the mean computed before noise levels are log-transformed to decibels [18].

Nevertheless, this is currently the metric recommended for use as an environmental indicator under the EU

MSFD. A comparison of acoustic metrics found that the RMS level was highly skewed by outliers, exceeding the 97th percentile at some frequencies. Environmental indicators of anthropogenic noise should instead use percentiles to ensure statistical robustness. This report demonstrated that the choice of summary metric can affect the statistical power to detect trends in the time series and that in choosing a metric, consideration of the management objective is recommended. The magnitude of change in noise level, in general, would be expected to be more significant for the 90th percentile and the RMS level than for the mode or the median since these metrics are more sensitive to changes in the right tail of the probability distribution (higher noise levels), which are associated with anthropogenic noise sources such as shipping. Ideally, environmental indicators of anthropogenic noise should instead use percentiles to ensure statistical robustness, noting that they are easy to interpret and directly related to the temporal distribution of noise levels, making them appropriate for assessing the risk of acoustic masking. The report recommends that the 90th percentile (L_{10} exceedance level) or the L_5 is appropriate for tracking anthropogenic noise levels in the marine environment.

3) *Data analysis and reporting - key recommendations*

The following recommendations on data analysis and metrics stem from the findings of the ECHO Program ambient noise evaluation project and a review of other relevant studies:

- Spectrum levels (1-minute PSD) reporting in monthly spectrograms and exceedance plots. The selection of lunar months for reporting to account for tides poses significant challenges for year-by-year comparison and evaluation of trends and is not preferable going forward.
- Calculation of sound pressure levels (broadband, decade-band, and 1/3-octave band) on a 1-minute basis, statistics reporting by month is pragmatic, with diurnal and weekly plots.
- The designation of SPL in the form of exceedance percentiles, including median (L_{50}), quartiles (L_{25} and L_{75}), L_5 , and L_{95} , and using the arithmetic mean (L_{eq}) of the squared sound pressure.

- Exclusion of redactions and other outages from reported sound level statistics is appropriate. Where notable, removal of electrical spikes from the PSD data before SPL processing is recommended.
- At locations where tidal currents incite flow noise, assessment and development of data filtering methods for high current periods are ideal for assessing vessel-related noise effects.

V. CONCLUSION

The long-term systematic collection and analysis of high quality, wide bandwidth ambient noise data is extremely challenging and requires high standards, feedback loops, and frequent inspection routines to control and harmonize procedures and undertake quality assessments. The influence of key factors affecting ambient noise are discussed in this document; however, these factors varied between sites, across frequency bands, and showed seasonal variability within each site. A summary of the recommendations discussed in this study follows in Table 2.

Table 2. Summary recommendations for key factors influencing underwater ambient noise monitoring programs

| Factor | Recommendation |
|------------------------|---|
| Equipment | Consistent equipment across all sites is preferable when deploying multiple hydrophone systems. If deploying different systems, consistency in system performance (e.g., bit-rate, bandwidth, sensitivity) is important. |
| Acoustic data analysis | Spectrum levels (1-minute PSD) reporting is recommended in the form of monthly spectrograms and exceedance plots. SPL calculations (broadband, decade-band, and 1/3-octave band) are recommended on a 1-minute basis with statistics analysis reported by month, with weekly and diurnal plots. Description of SPL is recommended in the form of exceedance percentiles including median (L_{50}), quartiles (L_{25} and L_{75}), L_5 , and L_{95} and using the arithmetic mean (L_{eq}) of the squared sound pressure. |

| | |
|-------------------------------|---|
| Temporal and spatial sampling | Continuous sampling is advisable whenever possible; however, power and storage limits may require duty-cycling. The maintenance of consistent hydrophone depth, and deployment location over multiple deployments and a minimum hydrophone depth of 20 m (ideally > 30 m) is recommended. |
| Calibration | Characterize system response over the full frequency range of interest before and after deployment. Annual in situ calibrations are recommended for extended deployments. |
| System Noise | Early (if possible) reviews of PSD plots and 1/3-octave levels assess noise and the noise floor. Undertake regular aural checks on data quality (unusual noises, reduced performance). Catalogue and ideally fix any underlying data quality issues. |
| Water currents, wind & rain | Continuous environmental measurements (1-min resolution, proximate to the hydrophone location) are recommended. Post-processing may require filtering of measurements made during periods of high current flow or wind speed. |
| Sound speed profile (SSP) | At a minimum, seasonal SSP measurements near the hydrophone are recommended, primarily to compare reference or control periods to periods with mitigation. Transmission loss modeling using seasonal SSPs better quantify location-specific and seasonal variability in underwater sound propagation. |
| Vessel traffic | Continuous monitoring of vessel traffic using a combination of AIS, photographic (as well as Radar and LIDAR), and acoustic detectors allows for consideration of acoustic impacts from both commercial vessels and smaller (non-AIS equipped) boats. Methods that take account of variability in vessel presence are recommended when comparing ambient noise over time. |
| Biological presence | Preferentially, monitoring for biological presence is continuous and involves automated acoustic detectors with a subset of manual validations for quality control. |
| Soundscape | Definition of the soundscape at each individual study site is recommended. Source, bathymetry, and propagation characteristics (amongst others) that define a soundscape vary between different regional and global sites, complicating direct comparison between datasets. |
| Noise modeling | Computational modeling and in-situ measurements of ambient noise are complementary and recommended. Modeling can help determine ideal sites for hydrophone deployments, and in situ measurements are advantageous for model verification. Models allow assessment of mitigation actions at |

| | |
|--|--|
| | a regional scale while controlling for confounding factors and avoiding unwanted noise sources. Ideally, models should be ground-truthed following the collection of empirical data. |
|--|--|

To understand the causes of variability in underwater noise levels requires a full (and on-going) assessment of the hydrophone data acquisition system's performance (e.g., regular calibration) and data quality (e.g., reviewing data early and assessing unwanted noise sources), collection of a wide range of anthropogenic and environmental factors local to the hydrophone, and multi-variate analyses and reporting.

Evaluation of unwanted noise sources and potential data redactions or losses before data analysis is advantageous. This study recommends calculation of sound pressure levels (broadband, decade-band, and 1/3-octave band) on a 1-minute basis and statistics reported by month, with weekly and diurnal plots, in the form of exceedance percentiles including median (L_{50}), quartiles (L_{25} and L_{75}), L_5 and L_{95} , as well as the arithmetic mean (L_{eq}). Multiple metric reporting can improve interpretation and allow for better site-to-site comparison.

To reduce unwanted variability for regional noise monitoring it is recommended that the same system (or systems with similar performance) be utilized at each site, if possible. The choice of deployment location depends on study objectives, but it is crucial to understand that there is a unique soundscape for each unique site. Shallow water sites are far more accessible and cost-effective but have potential limitations regarding low-frequency signal transmission. SSP conditions may more strongly influence propagation at deeper sites and assessment of these factors are recommended.

A variety of different approaches may be necessary to address study-specific program objectives. For example, fine-scale analyses of mitigation measures, such as slowdowns [35] and lateral displacement shifts [36], should consider confounding covariates. Validation of noise modeling to review predicted changes in ambient SPL as a consequence of mitigation actions is advantageous. Noise models allow one to

assess the effects of mitigation actions on a regional scale while controlling for confounding factors and are not affected by unintentional noise sources [28]. Ideally, models are ground-truthed following the collection of empirical data [27].

When considering the evaluation of a mitigation effort, selecting a control period is crucial because some of the influencing factors noted in this document, such as sound speed profile, can change on monthly (or shorter) timescales, and some factors, such as system noise and biological presence, can be unpredictable. Ideally, select existing or control period noise levels from times just before or just after a noise mitigation action or from the same time during a previous year.

As organizations seek to understand trends in underwater noise, test mitigation strategies and evaluate potential limits on underwater noise, evaluating and accounting for the key factors contributing to the soundscape is considered critical.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the ECHO Program's Acoustic Technical Committee who provided expert technical advice on the formulation of the original ambient noise monitoring project, and the subsequent evaluation of ambient noise study and best practices document. Special thanks go to project partners The Whale Museum of Friday Harbor, Washington; Saturna Island Marine Research and Education Society (SIMRES), British Columbia; and Ocean Networks Canada, British Columbia for the shared use of hydrophone data, and Dr. Tom Dakin for his knowledge and commitment to supporting these, and other, organizations in the region. Other contributors to the study include Sandra Frey and Lauren McWhinnie of Coastal and Ocean Resource Analysis Laboratory and Karen Scanlon and Roberto Racca of Jasco Applied Sciences.

REFERENCES

- [1] G. A. Warner, J. D. Wood, S. Frey, A. O. MacGillivray, D. J. Tollit, Z. Li, and L. McWhinnie, “Salish Sea Ambient Noise Evaluation 2016–2017: Enhancing Cetacean Habitat and Observation Program,” Version 2. Technical report by JASCO Applied Sciences, SMRU Consulting, and Coastal and Ocean Resource Analysis Laboratory for Vancouver Fraser Port Authority, 2019.
<https://www.portvancouver.com/wp-content/uploads/2020/05/2020-05-19-ECHO-Program-Salish-Sea-Ambient-Noise-Evaluation.pdf>
- [2] G. M. Wenz, “Acoustic Ambient Noise in the Ocean: Spectra and Sources,” *J. Acoust. Soc. Am.*, vol. 34, pp. 1936-1956, 1963. <https://doi.org/10.1121/1.1909155>.
- [3] R. J. Talham, “Ambient-Sea-Noise Model,” *J. Acoust. Soc. Am.*, vol. 36, pp. 1541-1544, 1964.
<https://doi.org/10.1121/1.1919240>.
- [4] R. J. Urick, “Correlative properties of ambient noise at Bermuda,” *J. Acoust. Soc. Am.*, vol. 40, pp. 1108, 1966. <https://doi.org/10.1121/1.1910195>.
- [5] A. J. Perrone, “Ambient-noise-spectrum levels as a function of water depth,” *J. Acoust. Soc. Am.*, vol. 48, pp. 362-370, 1970. <https://doi.org/10.1121/1.1912137>.
- [6] R. A. Wagstaff, “Low-frequency ambient noise in the deep sound channel—The missing component,” *J. Acoust. Soc. Am.*, vol. 69, pp. 1009-1014, 1981. <https://doi.org/10.1121/1.385680>.

- [7] J. S. Perkins, W. A. Kuperman, F. Ingenito, L. T. Fialkowski, and J. Glattetre, “Modeling ambient noise in three-dimensional ocean environments,” *J. Acoust. Soc. Am.*, vol. 93, pp. 739, 1993.
<https://doi.org/10.1121/1.405437>.
- [8] C. H. Harrison, “Noise directionality for surface sources in range dependent environments,” *J. Acoust. Soc. Am.*, vol. 102, pp. 2655, 1997. <https://doi.org/10.1121/1.420319>
- [9] J. A. Hildebrand, “Anthropogenic and natural sources of ambient noise in the ocean,” *Mar. Ecol. Prog. Ser.*, vol. 395, pp. 5-20, 2009. <https://doi.org/10.3354/meps08353>.
- [10] N. D. Merchant, P. Blondel, T. Dakin, and J. Dorocicz, “Averaging underwater noise level for environmental assessment of shipping,” *J. Acoust. Soc. Am.*, vol. 132, pp. EL343-EL349, 2012.
<https://doi.org/10.1121/1.4754429>.
- [11] R. P. A. Dekeling, M. L. Tasker, M. A. Ainslie, M. Andersson, M. André, M. Castellote, J. F. Borsani, J. Dalen, T. Folegot, R. Leaper, A. Liebschner, J. Pajala, S. P. Robinson, P. Sigray, G. Sutton, F. Thomsen, A. J. van der Graaf, S. Werner, D. Wittekind, and J.V. Young, “Monitoring guidance for underwater noise in the European seas—monitoring guidance specifications,” Report number: JRC Scientific and Policy Report EUR 26555 EN Affiliation: Publications Office of the European Union, Luxembourg, 2014.
<https://doi.org/10.2788/27158>.
- [12] A. O. MacGillivray and Z. Li, “Reductions in underwater radiated noise from shipping during the 2017 Haro Strait vessel slowdown trial,” *J. Acoust. Soc. Am.*, vol. 144, pp. 1731, 2018.
<https://doi.org/10.1121/1.5067678>.

[13] T. Dakin, K. Heise, “Guidelines for Installing Cabled Hydrophones for Monitoring Marine Mammals, Vessels and Other Sources of Underwater Noise,” Technical report, Fisheries and Oceans Canada.

[14] S. P. Robinson, P. A. Lepper, R. A. Hazelwood, “Good Practice Guide for Underwater Noise Measurement,” Teddington, England, National Measurement Office, Marine Scotland, The Crown Estate, NPL Good Practice Guide No. 133, ISSN: 1368-6550, 2014. <https://www.npl.co.uk/special-pages/guides/gpg133underwater>

[15] ISO 18405:2017 Underwater acoustics - Terminology

[16] IEC 61260-1:2014, “Electroacoustics – Octave-Band and Fractional-Octave-Band Filters – Part 1: Specifications.”

[17] B. L. Southall, J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. P. Nowacek, and P. L. Tyack, “Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects,” *Aquat. Mamm.*, vol 45, pp. 125-232, 2019. <https://doi.org/10.1578/AM.45.2.2019.125>

[18] N. D. Merchant, K. L. Brookes, R. C. Faulkner, A. W. Bicknell, B. J. Godley, and M. J. Witt, “Underwater noise levels in UK waters”, *Sci. Rep.*, vol 6, article: 36942, 2016. <https://doi.org/10.1038/srep36942>.

[19] ACCOBAMS (2016) “A basin wide strategy for underwater noise monitoring in the Mediterranean,” https://www.accobams.org/new_accobams/wp-content/uploads/2017/05/MOP6.Doc27.pdf

- [20] G. Kinda, F. Le Courtois, and Y. Stéphan, “Ambient Noise Dynamics in a Heavy Shipping Area”, *Mar. Pollut. Bull.*, vol 124, pp. 535-564, 2017. <https://doi.org/10.1016/j.marpolbul.2017.07.031>.
- [21] N. Crawford, S. Robinson, and L. Wang, “Standard procedure for equipment performance, calibration and deployment,” Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS), 2018.
https://vb.northsearegion.eu/public/files/repository/20190325133343_Jomopans_STD_EquipmentPerformance_Calibration-Deployment.pdf
- [22] U. K. Verfuß, M. Andersson, T. Folegot, J. Laanearu, R. Matuschek, J. Pajala, P. Sigray, J. Tegowski and J. Tougaard, “BIAS Standards for noise measurements. Background information, Guidelines and Quality Assurance”, Amended version, 2015.
https://biasproject.files.wordpress.com/2016/04/bias_standards_v5_final.pdf
- [23] C. Bassett, B. Polagye, M. Holt, and J. Thomson, “A vessel noise budget for Admiralty Inlet, Puget Sound, Washington (USA),” *J. Acoust. Soc. Am.*, vol. 120, pp. 711-718, 2012.
<https://doi.org/10.1121/1.4763548>
- [24] S. Veirs, V. Veirs, and J. D. Wood, “Ship noise extends to frequencies used for echolocation by endangered killer whales,” *PeerJ*.4:e1657, 2016. <https://doi.org/10.7717/peerj.1657>
- [25] S. Cominelli, R. Devillers, H. Yurk, A. MacGillivray, L. McWhinnie, and R. Canessa, “Noise exposure from commercial shipping for the southern resident killer whale population”, *Mar. Pollut. Bull.*, vol 136, pp. 177-200, 2018. <https://doi.org/10.1016/j.marpolbul.2018.08.050>

[26] L. Hermanssen, L. Mikkelsen, J. Tougaard, K. Beedholm, M. Johnson, and P. T. Madsen, “Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscape”, *Sci. Rep.*, vol 9, article: 15477, 2019.

<https://doi.org/10.1038/s41598-019-51222-9>

[27] A. O. MacGillivray, Z. Li, D. E. Hannay, K. B. Trounce, and O. Robinson, “Slowing deep-sea commercial vessels reduces underwater radiated noise,” *J. Acoust. Soc. Am.*, vol. 146, pp. 340-351, 2019.

<https://doi.org/10.1121/1.5116140>

[28] J. Ruth, D. Tollit, J. Wood, A. MacGillivray, L. Zi, K. Trounce and O. Robinson, “Potential Benefits of Vessel Slowdowns on Endangered Southern Resident Killer Whales,” *Front. Mar. Sci.*, vol 26, 2016.

<https://doi.org/10.3389/fmars.2019.00344>

[29] Water Properties Group. 2019. Water properties. Fisheries and Oceans Canada, Institute of Ocean Sciences.

<https://www.waterproperties.ca/data/> (Accessed 16 Jan 2019)

[30] M. A. Ainslie, J. L. Miksis-Olds, B. Martin, K. Heaney, C. A. F. de Jong, A. M. von Benda-Beckmann, and A. P. Lyons, “ADEON Underwater Soundscape and Modeling Metadata Standard,” Version 1.0. Technical report by JASCO Applied Sciences for ADEON Prime Contract No. M16PC00003, 2018.

<https://adeon.unh.edu/sites/default/files/user-uploads/ADEON%20Soundscape%20Specification%20Deliverable%20v1.0%20FINAL%20Submission.pdf>

[31] J. K. Garrett, Ph. Blondel, B. J. Godley, S. K. Pikesley, M. J. Witt, and L. Johanning, “Long-term underwater sound measurements in the shipping noise indicator bands 63 Hz and 125 Hz from the port of Falmouth Bay, UK”, *Mar. Pollut. Bull.*, vol 110, pp. 438-448, 2019.

<https://doi.org/10.1016/j.marpolbul.2016.06.021>.

[32] K. Heaney, B. Martin, J. Miksis-Olds, T. Moore, and J. Warren, “ADEON Data Processing Specification,” Version 2.0 DRAFT. Technical report by OASIS for ADEON Prime Contract No. M16PC00003, 2017.

https://adeon.unh.edu/sites/default/files/user-uploads/DRAFT%20Data%20Processing_submissionV2.pdf

[33] R. C. Snoek, M. A. Ainslie, M. K. Prior, and E. Van Onselen, “Ambient noise monitoring strategy and joint monitoring programme for the North Sea Part I: monitoring strategy ambient noise,” OSPAR document EIHA 15/5/7 Add.1-E, 2015.

[34] N. D. Merchant, A. Farcas, and C. F. Powell, “Acoustic metric specification,” report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS), 2018.

https://vb.northsearegion.eu/public/files/repository/20180925143035_Jomopans_Acoustic_indicator_report.pdf

[35] Enhancing Cetacean Habitat and Observation (ECHO) Program, “2019 voluntary vessel slowdown trials in Haro Strait and Boundary Pass,” Vancouver, British Columbia, Vancouver Fraser Port Authority, July 2020.

<https://www.portvancouver.com/wp-content/uploads/2020/08/ECHO-Program-2019-voluntary-vessel-slowdown-in-Haro-Strait-and-Boundary-Pass-final-report.pdf>

[36] Enhancing Cetacean Habitat and Observation (ECHO) Program, “2020 voluntary inshore lateral displacement in the Strait of Juan de Fuca,” Vancouver, British Columbia, Vancouver Fraser Port Authority, March 2021.

<https://www.portvancouver.com/wp-content/uploads/2021/04/2021-03-28-Summary-report-2020-SJDF-lateral-displacement.pdf>



Justin Michael Eickmeier, Ph.D. is a Consulting Scientist for SLR Consulting (Canada) Ltd. in Vancouver, British Columbia and an Acoustic Technical Advisor for the Enhancing Cetacean Habitat and Observation Program. He received a BA Sc and MA Sc in Ocean Engineering from the Florida Institute of Technology in 2007 and 2009, respectively. Following doctoral studies at the University of Delaware, Justin received a Ph.D in Oceanography in 2016.



Dominic J. Tollit Ph.D.
Dominic received the B.Sc. (Hons) degree in Marine Biology from the University of Wales, Aberystwyth in 1986 and a Ph.D. degree in Zoology from the University of Aberdeen, Scotland, in 1996. He led a Stellar Sea Lion foraging program at the University of British Columbia between 2000-2008 and has over 35 publications. In 2009, he became Senior Scientist and VP of SMRU Consulting Canada, a not-for-profit marine mammal consultancy company headquartered at the University of St. Andrews, but Dominic remains based out of Vancouver, Canada.



Krista Bisang Trounce, P.Eng became the Research Manager for the Enhancing Cetacean Habitat and Observation Program in 2015, following nearly 20 years as an consulting engineer assessing the risk to human and ecological receptors from environmental contaminants. Krista received a BA Sc from the University of Waterloo in Civil Engineering – Water Resources in 1996, and is a licensed engineer in the province of British Columbia, Canada.