Marine Mammal Behavioral Response to Tidal Turbine Sound

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Executive Summary

The sound emitted by tidal turbines overlaps with the generalized hearing ranges for marine mammals and may, consequently, affect marine mammal behavior. Because of the strong environmental protections for marine mammals, these effects are of interest to resource agencies and project developers. The primary goal of this project is to improve the understanding of how sound emitted by tidal turbines may affect marine mammal behavior, with the intent that such understanding may allow this environmental risk to be "retired" for initial demonstrations and arrays. A secondary project goal is to evaluate the efficacy of marine mammal observations from a shore-based vantage point as a method to detect change as a consequence of marine energy stressors.

Three, two-week trials were conducted across spring, summer and autumn of 2017 during which vantage-point observations of marine mammals were made from land. We refer to these two-week periods as 'trials' as they represent different periods of field data collection. These observations consisted of scan samples every 10 minutes with a set of binoculars and a DSLR camera. When pinnipeds were sighted, still images were taken. When harbor porpoise were sighted, focal follows using video were initiated. These data were later analyzed to estimate the location of animals sighted using photogrammetric techniques. For approximately half of each trial period, a boat was moored in the study area from which an underwater projector was used to play back tidal turbine sounds at a broadband source level of 158 dB re µPa @ 1m. The other half of each trial period had no playbacks and was used as a control period[1]. During the control and playback periods, ancillary data were collected in the study area near the sea floor (ambient noise, tidal velocity, and porpoise clicks) while weather and vessel tracks were recorded near the vantage-point station.

Harbor seals did not show a significant response to the simulated turbine noise, nor did harbor porpoise change their closest point of approach or change the direction/deviation of the paths during periods when the playback was occurring. While porpoise sightings and porpoise acoustic detections were significantly reduced during playback periods in the first two trials, the number of detections during the playback periods increased during the third trial. Similarly, the calculated distance from porpoises to the playback location suggests that harbor porpoises avoided an area around the playback location of approximately 300 m during Trial 1, which decreased to approximately 100 m in Trial 2, and disappeared in Trial 3. This could be an indication of habituation or increased tolerance, either to the playback sound or the vessel presence.

Our finding of no significant effect of turbine noise on harbor seals contrast with the findings in a previous study by Hastie et al. (2017) conducted in United Kingdom waters. However, due to substantive differences in source levels and propagation loss, seals in our study would need to have been within 10 m of the playback location to experience similar received levels to those in the Hastie et al. study. Consequently, the two studies may actually be in agreement.

Our findings of significant effect of turbine noise on harbor porpoise are in line with previous studies suggesting the harbor porpoise are sensitive to noise. However, we note that, due to cost

[1] The playback periods were continuous, but the control periods either preceded or followed the playback periods depending on availability of personnel and vessels. Consequently, the control periods were pseudo-randomized.

and logistical constraints, the playback vessel was only mooring during the playback periods. Consequently, we cannot definitively ascribe the changes in porpoise behavior to the simulated turbine noise, playback vessel presence, or a combination of both factors. This methodological limitation and other lessons learned are discussed to benefit future studies that explore the effects of acoustic stressors on marine mammals.

Table of Contents

Executive Summary ... ii
1 Introduction ... 1
2 Background and Methods ... 2
2.1 Study Location ... 2
2.2 Simulated Turbine Sound ... 3
2.3 Data Collection to Describe Co-Temporal Environment ... 7
2.4 Marine Mammal Observations ... 8
3 Results ... 17
3.1 Trial Periods ... 17
3.2 Location Accuracy Assessment ... 18
3.3 Received Levels ... 19
3.4 Signal Excess Model ... 20
3.5 Marine Mammal Observations ... 25
4 Study Synthesis ... 40
4.1 Playback Context ... 40
4.2 Harbor Seals ... 41
4.3 Harbor Porpoise ... 42
4.4 Extrapolation to Lower and Higher Source Levels ... 43
5 Lessons Learned ... 44
5.1 Simulation of Marine Energy Converter Source ... 44
5.2 Signal Excess ... 44
5.3 Vantage-point Surveys ... 45
5.4 Strengths and Weakness of Playback Studies ... 47
5.5 Study Costs ... 47
6 Conclusions ... 48
7 Acknowledgements ... 49
8 References ... 50
9 Appendix ... 53

List of Figures

Figure 1: Project study area, as viewed from vantage-point. Credit: Frances Robertson (SMRU Consulting)........ 3

Figure 2. J11 sound transducer after testing in a lab tank........ 4

Figure 3. Simulated turbine sound used for the playback study. The blue spectrum represents the driving signal supplied to the amplifier and the other spectra represent three deployments, as characterized in quiescent water in the harbor at Port Townsend, Washington........ 5

Figure 4. Illustration of vessel configuration for playback operations........ 5

Figure 5. Mooring wheel stack and Sea Spider aboard the R/V Jack Robertson prior to deployment........ 6

Figure 6. C-DAISY acoustic measurement system........ 8

Figure 7. Vantage-point equipment setup. Cannon DSLR camera capable of both still image and video footage mounted with compass-reticule binoculars in a custom-built frame. The tri-pod legs were marked to ensure that the system was set up in the correct position at the start of each day above our surveyor's mark and the height measured to ensure that the camera was always at the same height. A specialized video panning tripod mount allowed for smooth panning across the survey area........ 10

Figure 8. Vantage-point station on Admiralty Head. Credit: Frances Robertson (SMRU Consulting)........ 10

Figure 9. Screen capture from the PAMGuard Landmark module showing the selection of two known and visible landmarks (in green) and the selection and localization of a harbor seal (in blue).........13

Figure 10. Audiograms of harbor porpoise and harbor seals. The harbor porpoise audiogram is a combined mean from two publications. The one-third octave bands of interest are shown in vertical dotted lines........ 14

Figure 11. Schematic of signal excess calculations........ 15

Figure 12. The location error estimates resulting from comparing GPS locations of the playback vessel research RHIB and DAISY drifts........ 18

Figure 13. Spatially representation of location error. Error estimates across the study area were interpolated using the individual error points and spatial kriging........ 19

Figure 14. (left) received levels for drifts passing quality assurance and (right) empirical transmission loss coefficients. The origin of all drifts is referenced to the mean position of the *R/V Inferno* during each drift........ 20

Figure 15. Median radial range-dependent transmission loss coefficient for the 100 Hz band.... 20

Figure 16. Histogram plots of one-third octave measured noise levels (top row) and predicted noise levels (bottom row) in the 1 kHz (left) and 4 kHz (right) one-third octave bins. 21

Figure 17. Plot of one-third octave noise levels versus current velocity during flood tides (top) and ebb tides (bottom) in the 1 kHz (left) and 4 kHz (right) one-third octave bins. Empirical data is in blue. Modelled predictions in red. 22

Figure 18. Histogram plots of one-third octave measured noise levels (top row) and predicted noise levels (bottom row) in the 0.1 kHz (left), 1 kHz (middle) and 4 kHz (right) one-third octave bins. 23

Figure 19. Plot of one-third octave noise levels versus current velocity using all the data with AIS vessel present (top) and the subset data with current < 0.5 m/s (bottom)................................... 24

Figure 20. Histogram plots of predicted minus observed one-third octave band noise levels in the 0.1 (top), 1 (middle) and 4 (bottom) kHz bins. 25

Figure 21. Distributions of the range (m) of sightings of harbor seals (left), harbor porpoise (mid), and Steller sea lions (right) from the vantage-point station. The red vertical lines indicate the median range for each species. 27

Figure 22: Location of useable pinniped sightings across the spring, summer and autumn playback trials. The red stars denote the average playback location on ebb and flood tides and the black cross denotes the land-based observation station. Harbor seals are shown as black circles and sea lions as magenta squares.. 28

Figure 23. Location of useable harbor porpoise sightings across the spring, summer and autumn playback trials. The red stars denote the average playback location on ebb and flood tides and the black cross denotes the land-based observation station. Porpoise locations are shown as green circles. 29

Figure 24. The distributions of sighting distances for harbor seals (left) and harbor porpoise (right) from the playback location during control periods (Playback Off: blue), and those times when the playback signal was operating (Playback On: red)... 31

Figure 25. The distribution of distances of harbor seals from the playback location for trial 1, 2 and 3 when playback was on and off. 31

Figure 26. The distribution of distances of harbor porpoise from the playback location for trial 1, 2 and 3 when playback was on and off. 32

Figure 27. Boxplots for the closest point of approach (top), directivity index (middle), and deviation index (bottom) for harbor porpoise focal follows by group activity state collected the playback was on (red) and when the playback off (green). 34

Figure 28. Probability of sighting per unit effort of harbor seals (left), harbor porpoise (middle) and probability of acoustic detection of harbor porpoise (right) by time of day. 37

Figure 29. Probability of sighting per unit effort of harbor seals (left), harbor porpoise (middle) and probability of acoustic detection of harbor porpoise (right) by current speed. Negative speeds are ebb tides. 37

Figure 30. Probability of sighting per unit effort of harbor seals (left), harbor porpoise (middle) and probability of acoustic detection of harbor porpoise (right) by water height above mean lower low water.. 38

Figure 31. GAMM predictions of the mean and 95% CI by trial and playback status (on/off) for harbor seal visual scans (top), harbor porpoise visual scans (middle), and harbor porpoise acoustic detections (bottom). The predictions assume it is noon and at average current speed and average water height.. 40

Figure 32. Distribution of estimated signal excess for harbor seals (top) and harbor porpoise (bottom) during playback trials in the 100 Hz (left), 1,000 Hz (middle) and 4,000 Hz (right) one-third octave bins. Negative signal excess suggests that the turbine noise was not audible to the animal.. 41

List of Tables

Table 1. Summary of the total number of hours of useable scan data from each trial, along with a breakdown of the number of hours of control and playback periods. 18

Table 2. Median one-third octave measured and predicted sediment noise levels and their difference. 21

Table 3. Median one-third octave measured and predicted vessel noise levels and their difference. 23

Table 4. Median difference in predicted and measured one-third octave noise levels in the 0.1, 1 and 4 kHz bins. 25

Table 5. The sum number of useable pinniped and porpoise sighted (N) during each trial period, and the mean number of animals recorded during each scan ($\boldsymbol{x}$). 26

Table 6. Summary of the number of useable scans and % of those scans that harbor seals, harbor porpoise, and Steller sea lions were observed in over the course of the three trials.................... 26

Table 7. Summary of on-effort sightings for harbor porpoise, harbor seal and Steller sea lion. Summary includes the number of groups observed (N), the total number of animals observed (Sum), the mean group size ($\boldsymbol{x}$), standard error of the mean (se) and the group size range (range). 30

Table 8. Summary of harbor porpoise tracks by playback trial. The numbers of tracks are given for each key activity state and also for playback on and playback off periods. 33

Table 9. Summary of harbor porpoise focal follow data, including closest point of approach, directivity index, and deviation index by porpoise group activity state and playback status....... 35

Table 10. Results of GAMM for harbor seal visual scans... 38

Table 11. Results of GAMM for harbor porpoise visual scans. 39

Table 12. Results of GAMM for harbor porpoise acoustic detections (C-POD)......................... 39

Table 13. Study cost summary on a per survey basis 48

Table 14: Third Octave Source Levels (dB re 1µPa @ 1m) from Veirs et al. 2016 and used in the signal excess model.. 53

Table 15: Summary of marine mammal scan sampling and focal follow data collected, including codes and definitions... 54

Table 16: Summary of environmental data collected at the start and end of each scan. 55

List of Abbreviations

AIS: Automatic Identification System: a collision avoidance transponder used on some classes of vessels that broadcasts vessel position and characteristics.

CPA: Closest Point of Approach

DAISY: Drifting Acoustic Instrument SYstem: a drifting hydrophone system used to characterize received levels as a function of range from the playback source.

DI: Directness Index

DE: Deviation Index

GAMM: Generalized Additive Mixed Model

J11: A specific model of acoustic projector developed by the US Navy and used in this study to simulate turbine sound.

PAMGuard: An open-source software package for analysis of acoustic and visual marine mammal data.

RHIB: rigid hull inflatable vessel

1 Introduction

Interactions between marine mammals and marine energy converters are an area of high scientific uncertainty (Copping et al. 2016). Considerable resources have been devoted to characterizing how installation and operation of tidal energy projects affect marine mammals. Acoustic effects are of particular concern within the context of behavioral ecology (Richardson et al. 1995, Copping et al. 2016) as marine mammals are dependent on sound. They conduct their lives in an acoustic environment using sound to communicate, find food, detect predators and navigate; therefore, the potential for disturbance from anthropogenic sound is high.

Sound produced by marine energy converters may result in changes to local habitat use and foraging behavior through displacement (the movement of an animal out of the local area, or their avoidance of that area) and variation in normal movement patterns (Leeney et al. 2014, Copping et al. 2016). While measurements to date suggest that operational sounds of marine energy converters will not rise to levels that will cause injury, sounds are expected to periodically rise to a level that may cause behavioral changes (Garel et al. 2014, Copping et al. 2016). Interference with navigation and communication may also occur via acoustic masking (Erbe et al. 2016, Garel et al. 2014, Samuel et al. 2005, Wilhelmsson et al. 2010). Potential effects of a marine energy project will vary depending on its scale, location and the stage of development (Leeney et al. 2014). For example, the operational phase may add to the normal background acoustic environment over a period of years, whereas the installation phase may temporarily elevate acoustic levels over a period of months (Boehlert and Gill 2010, Gill 2005). The severity of any potential acoustic disturbance will depend on the frequency, intensity, and duration of the sounds in relation to the sensitivity of the animal (Gill 2005, Copping et al. 2016). Given the potential variability in marine mammal response, assessing and characterizing the behavioral responses of marine mammals to the noise from marine energy converters has been identified as a priority area for research.

Recently, researchers in Scotland have conducted a playback of tidal turbine sound to harbor seals (Hastie et al. 2017). They used vantage-point techniques to quantify seal relative abundance within their study area, and attached GPS tags to a number of seals to analyze the finer scale movements of individual seals. Vantage-point observations indicated no significant change in the relative abundance of seals within the observable area during playback of simulated turbine noise relative to control periods. However, using tag data, Hastie et al. (2017) did identify a reduction of seal usage between 11 and 41% in close proximity to the simulated turbine sound source. This reduction decreased to almost zero at 500 m from the source.

The objective of this project is to observe the relative abundance, presence, absence, and behavior of harbor seals (serving as an archetype for pinnipeds) and harbor porpoise (serving as an archetype for high-frequency cetaceans) in an area ensonified by simulated turbine sound and assess any changes in relative abundance, presence, absence, and behavior as a consequence of this sound. Among marine mammals, harbor porpoise are of particular concern, due to their demonstrated sensitivity to acoustic disturbances (Tougaard et al. 2014). The effects of the sound in this project are evaluated in the context of signal excess, a metric that describes the difference between the simulated turbine sound levels and ambient noise levels, to provide an estimate of the received sound signal at an animals' location. The latter is estimated by a forward acoustic model that uses vessel proximity and current speed as inputs and verified by in-situ acoustic observations.

The primary differences between the Hastie et al. 2017 study and the one discussed here are the playback signal (frequency content and amplitude), the explanatory variables, the phasing of control and playback[2], and the inclusion of two primary species. The Hastie et al. playback was a filtered and modified recording of the Marine Current Turbines SeaGen turbine that was deployed in Strangford Lough, Northern Ireland. The signature is substantially more tonal than the one used here with at least seven tonal peaks between 100 and 4,000 Hz. These tones also exhibit frequency modulation over time. The playback here is broadband, with a single tonal peak around 100 Hz. In addition, the Hastie et al. (2017) study assessed marine mammal abundance through shore observations, but relied on GPS tag data to establish animal density, while the present study uses photogrammetric techniques to obtain animal density and abundance using lower-cost shore observations alone.

Our hypothesis is that harbor seals and harbor porpoise may avoid areas with high signal excess from tidal turbine playbacks. The decision to develop a signal excess model (i.e., a continuous variable) for our explanatory variable should provide improved statistical power over the binary explanatory variable used by Hastie et al. (2017) Our playback is also intended to validate their result for a different sound source and harbor seal population, as well as extend our knowledge of marine mammal response to a species of odontocetes (harbor porpoise).

2 Background and Methods

2.1 Study Location

The study was conducted in Admiralty Inlet (Figure 1), a relatively narrow, shallow channel connecting the main basin of the Puget Sound to the Strait of Juan de Fuca. This is a major shipping lane for several ports in Puget Sound and experiences regular cross-channel ferry traffic, as well as traffic associated with fishing vessels, tugs, military operations, and recreational users. The channel is approximately 5 km wide at its narrowest point and, on average, approximately 60 m deep. The constriction in Admiralty Inlet produces tidal currents that can exceed 3 m/s. As a consequence, a tidal energy demonstration project, consisting of two turbines, was advanced over a multi-year period by a local utility district and an international technology developer. Ultimately, cost considerations led to the termination of that project. However, the location remains attractive, in the longer-term, for tidal energy development and the demonstration project produced a significant quantity of baseline observations describing the natural and physical environment. The combination of existing data and future potential motivated its selection for this study.

[2] In Hastie et al. (2017), six playbacks, each one hour in duration, were interspersed with the control periods over a 12-hour period with the support vessel present throughout. Here, the majority of the playbacks occurred over a multi-day period, either preceded or followed by control periods with the support vessel absent. Further discussion of this difference are discussed in Section 4.2.

Figure 1: Project study area, as viewed from vantage-point. Credit: Frances Robertson (SMRU Consulting)

2.2 Simulated Turbine Sound

Turbine sound was simulated using a vessel-based playback from a US Navy J11 acoustic projector (Figure 2). The basis for this sound were observations of the Ocean Renewable Power Company's RivGen river current turbine, obtained in 2014 (Polagye et al. 2015). This was chosen as a representative current turbine sound from potential playbacks, including the signal used in Hastie et al. (2017), on the basis of recording quality. A three-second recording from the point of closest approach was band-pass filtered from 30 Hz to 10 kHz, with the lower limit set by the frequency-response of the J11 and the upper limit set by the identified range of frequencies attributable to the current turbine. As shown in Figure 3, the sound is relatively broadband, with a characteristic peak at 100 Hz associated with noise from the electrical generator. Because the RivGen turbine is relatively small in comparison to a utility-scale tidal turbine suitable for deployment at the site, the sound was amplified to be more representative of a utility-scale project and to increase the signal excess. The final playback signal had a mean-square sound pressure level of 158 dB re 1μPa (set by the current limit on the amplifier and a permit ceiling of 160 dB to limit "acoustic take") and played on a continuous loop during the playback periods. The amplitude and pressure spectral density of the sound was measured in situ and compared to the intended signal by suspending a hydrophone (OceanSonics icListen HF) 1 m from the J11 in quiescent water. As shown in Figure

3, agreement between the signal supplied to amplifier and the signal measured *in situ* is acceptable and consistent across the three trials.

Figure 2. J11 sound transducer after testing in a lab tank.

During the study, a small support vessel (R/V Inferno, a 22-foot fireboat) was moored in Admiralty Inlet and used to deploy the J11 from its stern at a depth of approximately 10 m. A 2 kW Honda generator ("Super Quiet" model) provided power to the amplifier, projector, and control computer while all other vessel systems were shut down. The arrangement is illustrated in Figure 4. To minimize transmission of generator sound into the water, the generator was suspended above the deck with bungee cords. In air, the generator manufacturer reports a noise level of 62 dB re 20 µPa, similar in amplitude to human speech at a range of 1 m. While this may have been audible in air to nearby harbor seals, given that their amphibious lifestyle that requires good hearing in air and in water (Lucke et al. 2016), this mean-square sound pressure level is substantially lower than emissions from the J11 and, therefore, unlikely to have biased observations. Harbor porpoise, being fully aquatic, have ears that are specialized for underwater hearing. They have no external pinnae (outer ear), their ear canals are narrow, plugged with debris and dense wax and do not connect to their ear drums (Ketten 2000). Harbor porpoise would, therefore, not have been able to hear the generator noise when they surfaced.

Given the current speed and water depth in Admiralty Inlet, the playback vessel could not deploy a mooring heavy enough to hold position. The playback vessel mooring, along with an autonomous instrumentation tripod shown in Figure 5 were deployed by a larger (50 foot) research vessel prior to each 2-week trial and recovered at the trial conclusion. While it would have been desirable to keep the playback vessel on the mooring during the control periods, due to cost considerations, the vessel could not be staffed for the complete two-week period and navigational safety considerations precluded leaving it on the mooring without a crew.

During each playback period, the location of the support vessel was logged using a GPS receiver. The position of the support vessel varied by approximately 200 m between flood and ebb due to the scope in the mooring line, with the vessel positioned at its taut extent.

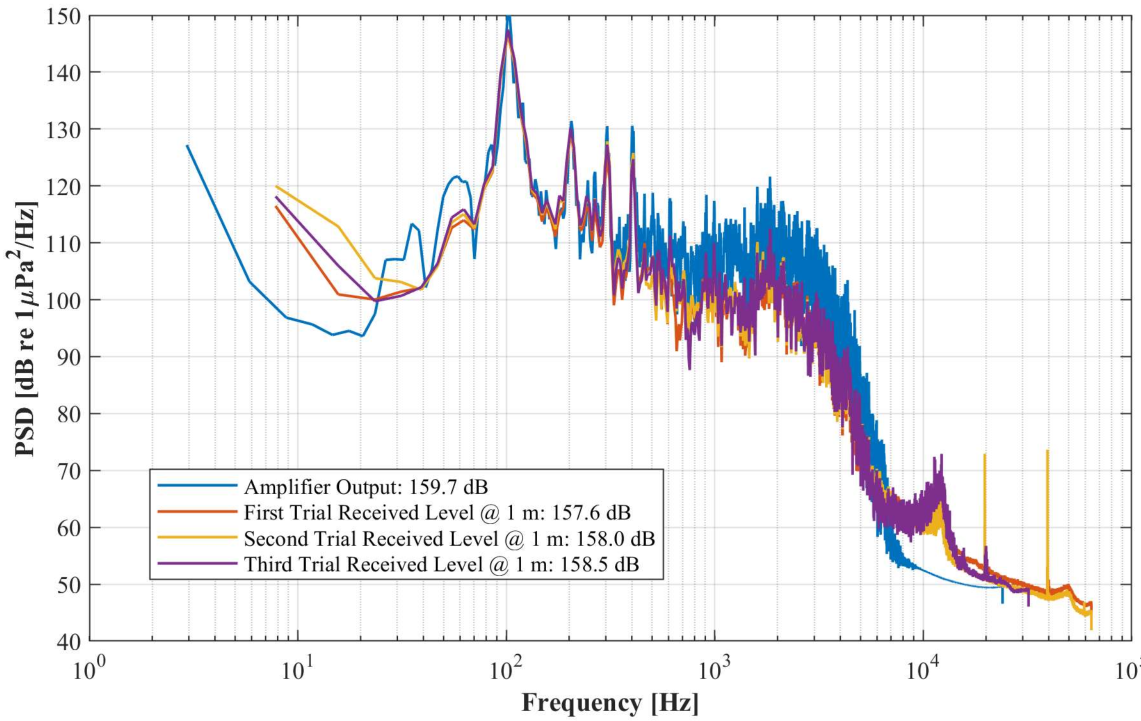

Figure 3. Simulated turbine sound used for the playback study. The blue line is the signal output by the amplifier and the other lines are *in situ* measurements during each of the three trials, as characterized in quiescent water in the harbor at Port Townsend, Washington.

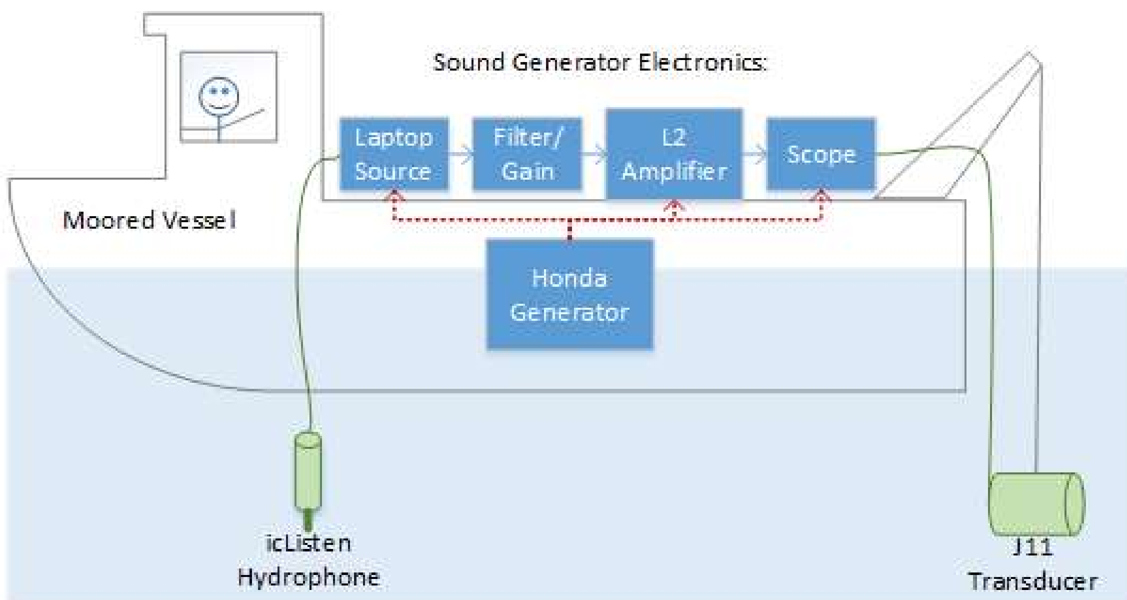

Figure 4. Illustration of vessel configuration for playback operations

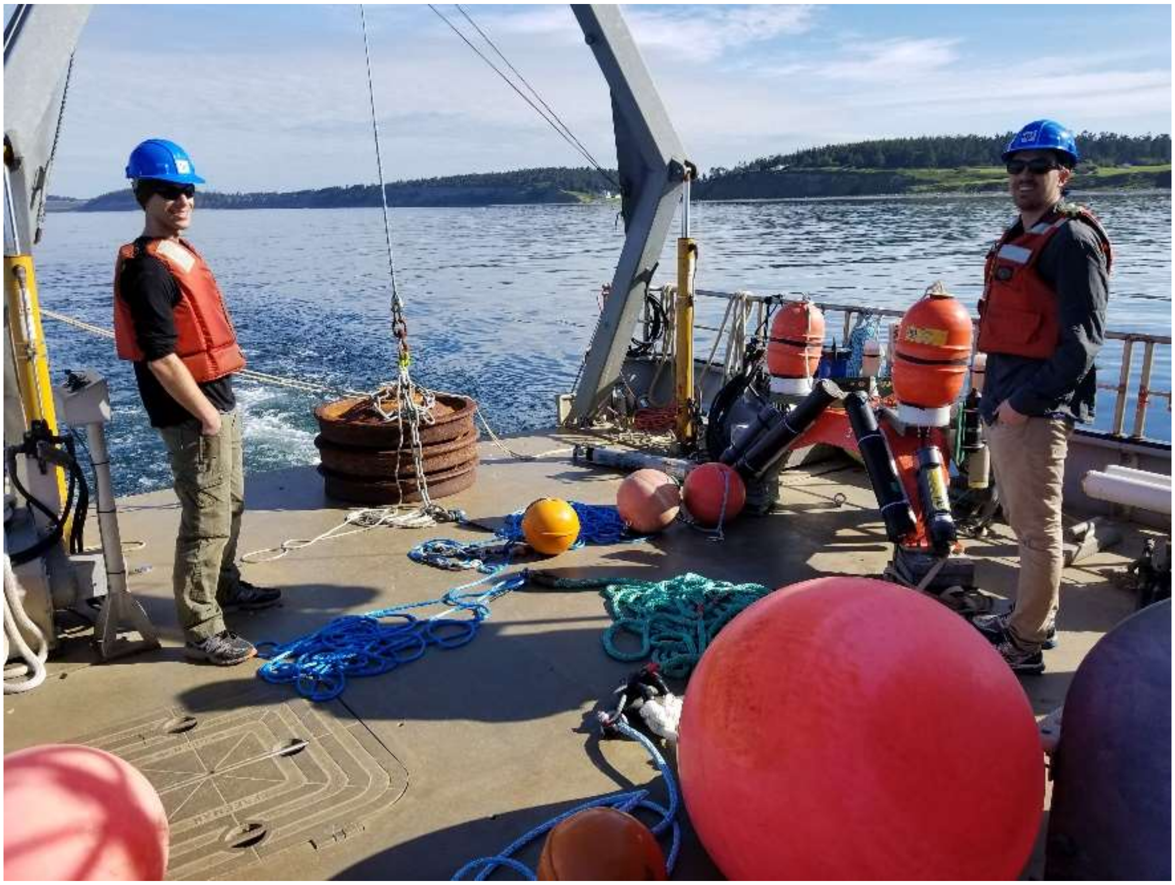

Figure 5. Mooring wheel stack and Sea Spider aboard R/V Jack Robertson prior to deployment

For each day with a playback period, the playback vessel would moor at the site for approximately 6 hours. Each playback period would start with a 10-minute ramp up period during which the sound projection level was increased from 120 dB re 1 µPa to 158 dB re 1µPa. The projector was only operated when sighting conditions were sufficient for the shore observers to warn against the approach of Southern Resident killer whales or baleen whales. If such species were detected, the playback was suspended until the animal(s) had left the area as per protocols listed in our National Marine Fisheries Service Permit #20452 which covered this research.

The received levels as a function of range from the playback vessel were characterized by Drifting Acoustic Instrumentation SYstems (DAISYs) during the first trial. These measurements obviated the need for a range-dependent propagation model to predict received levels at observed marine mammal locations. Each DAISY consisted of a surface expression with a GPS logger connected by a compliant cord to a sub-surface drogue. Suspended beneath the drogue was a hydrophone, augmented by a pressure sensor and inertial measurement unit. A schematic of the system is shown in Figure 6. A rigid hull inflatable vessel (RHIB) was used to deploy DAISYs, which then drifted until they could be recovered. A total of 19 drifts were conducted on May 26, 2017. The recorded acoustic data were processed using a Discrete Fourier Transform and reviewed (manual audio review superimposed on the acoustic spectra). Sequences were quarantined from further analysis if:

- Received levels were biased by the transit of the Washington State ferry crossing between Coupeville and Port Townsend. A ferry arrives in Coupeville approximately every hour, unloads/loads cars and passengers, and passes back through the ferry site approximately fifteen minutes later.;
- They contained obvious contamination from vessel engine noise associated with commercial, recreational, or military vessel traffic; or
- The location of the playback vessel was changing rapidly during a drift (surface currents swinging from ebb to flood or vice versa).

Thirteen of the drifts produced usable data (i.e., instruments functional, limited masking of acoustic source from nearby vessel traffic). The playback signal at 100 Hz was fit to a simple model for a range-dependent propagation loss coefficient (*N*) where

$$TL = N \log_{10} D$$

TL is the propagation (transmission) loss between the source and a receiver, in dB, and *D* is the slant distance between the source and a receiver in m. Transmission loss was estimated using this frequency because of its superior signal-to-noise ratio.

2.3 Data Collection to Describe Co-Temporal Environment

To provide context for shore-based marine mammal observations, co-temporal environmental metadata were collected on shore and subsurface.

At the observation point, an Automatic Identification System (AIS) receiver logged location, type, and speed of AIS-enabled vessels. AIS transponders are required on vessels over 300 gross tons and passenger vessels. Some recreational and military vessels voluntarily broadcast AIS data. As discussed later in the report, these data were used to model ambient noise in the study area generated by passing ships.

In-situ data were collected using a Sea Spider platform equipped with several autonomous sensors. The platform is shown in Figure 5. The sensor payload included a Nortek Continental 470 kHz ADCP to measure currents, a Loggerhead DSG recording hydrophone, and redundant Chelonia C-PODs to characterize porpoise presence/absence below the water surface by detecting their echolocation clicks.

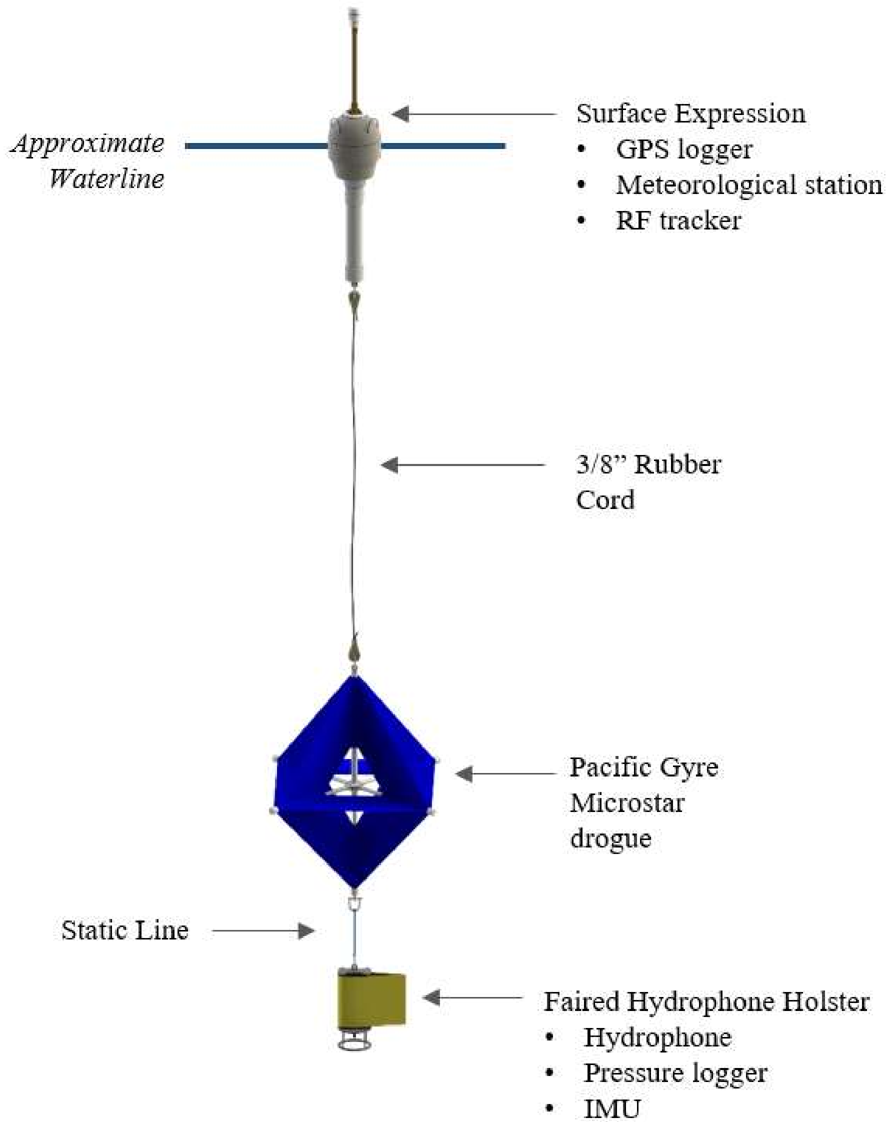

Figure 6. C-DAISY acoustic measurement system

2.4 Marine Mammal Observations

Marine mammal observations were conducted from a land-based vantage point overlooking the playback location. Admiralty Head (48.155N, -122.678W) was chosen based on its proximity to the playback site and because marine mammal observations had been successfully conducted at this location in 2011. Marine mammal observations were conducted by SMRU Consulting marine mammal biologists Drs. Frances Robertson and Jason Wood, supported by several undergraduate students.

Harbor seal and harbor porpoise populations in Puget Sound are known to be present in Admiralty Inlet year-round (Jeffries et al. 2000, Calambokidis and Baird 1994, Smultea et al. 2015), but there is evidence for seasonal patterns in animal occurrence throughout the year. Therefore, unlike Hastie et al. (2017), this study was designed to incorporate a seasonal component. Each trial was conducted over a period of two weeks that allowed for a sequential control period and a playback period, each of approximately the same duration. Control-playback trials were conducted during the spring (18 – 31 May), summer (26 July – 9 August), and autumn (18 September – 1 October 2017) of 2017. Marine mammal observations were conducted over 11 days during the first trial, 14 days during the second, and 13 days during the third. During the first trial, weather conditions impeded data collection on two days, the 23 and 30 May, and acoustic verification trials with the DAISY drifts impeded data collection for much of the 24 May. During the second trial, weather conditions and poor visibility resulting from forest fire smoke impeded data collection on the 6 of August. During the third trial, poor weather conditions hampered data collection on 29 September.

During each trial, shore-based observations used a scan sampling technique to study pinnipeds (e.g., harbor seals) and a focal follow technique to study the cetaceans (e.g., harbor porpoise). Scan sampling involves systematically scanning a survey area to obtain point information about marine mammals, while focal follows attempt to track individuals or groups as they move through a survey area. Focal follow methods were only used for cetaceans because their dive patterns are more predictable and, for species other than harbor porpoise, their size makes them easy to track.

2.4.1 Data Collection

Shore based observations were conducted following vantage-point methodologies. Vantage-point surveys have the advantage of being cost effective to run (compared to boat-based surveys) and require fewer observers. There is also no risk of the observer's behavior or presence influencing the focal animals – this is crucial when trying to assess potential impacts of specific human activities such as tidal turbine operations.

We employed a combination of systematic scan sampling and focal follow survey techniques using a photogrammetric approach. This method required only a camera and binoculars, as opposed to more traditional methods involving a surveyors' theodolite. Reticle-compass binoculars were mounted on a custom-built frame above a Cannon D80 SLR camera (Figure 7 & Figure 8). The camera was capable of both still images and video data capture allowing us to collect still images of pinnipeds and video tracks of harbor porpoise using the same equipment. Based on the known location and height above sea surface of the camera and known locations of landmarks captured in the images, the geographic position of the animal at the sea surface can be estimated. Targets with known locations (e.g., a vessel equipped with GPS) can be used to quantify the error in estimated marine mammal locations.

To obtain the required measurements of the vantage-point station and the landmarks a surveyor was hired. They provided accurate GPS (latitude and longitude) and elevation measurements of our vantage-point location. In addition, they provided vertical and horizontal bearings from our vantage-point to each landmark on the far side of our study area. The horizontal bearings (referenced to North) were based on the Washington State Plane Zone 4601 North (NAD83) projection. As with all projections, the further from the central meridian, the more distorted they become. To compensate for this distortion from True North, we subtracted 1.62° from our measurements of horizontal angle before calculating an animal's latitude and longitude.

Figure 7. Vantage-point equipment setup. Cannon DSLR camera capable of both still image and video footage mounted with compass-reticule binoculars in a custom-built frame. The tripod legs were marked to ensure that the system was set up in the correct position at the start of each day above our surveyor's mark and the height measured to ensure that the camera was always at the same height. A specialized video tripod mount allowed for smooth panning across the survey area.

Figure 8. Vantage-point station on Admiralty Head. Credit: Frances Robertson (SMRU Consulting)

Scan sampling was conducted in a systematic manner every ten minutes from north to south across the study area during daylight hours and acceptable sighting conditions. Each scan lasted approximately two minutes. Standard environmental and sighting condition data were collected at the start and end of each scan; these, included Beaufort sea state, the percentage of glare obscuring the study area, percent cloud cover over the study area, and an overall "sightability" score on a scale of 1 – 4 (from best to worst sightability). The sightability score was a subjective measure that combined the sea state, percent glare, and other factors that might hamper visibility such as rain, fog or smoke. The sightability score allows for a systematic method of reviewing data quality.When a pinniped was detected during a scan an image was collected and data on the species, group size, group composition (e.g., whether or not a calf or pup was present), activity state, behavior, heading and speed of movement were recorded using a digital audio recorder. Scans were paused to undertake focal follows when harbor porpoise were detected. Focal follows were performed using the same vantage-point equipment used for scan sampling (Figure 7 & Figure 8); on detection of an individual or group of harbor porpoise the Cannon D80 SLR was switched to video mode and the group was followed for a minimum of two minutes where possible. Data on porpoise group size and composition, activity state, behavior, heading and speed of movement were recorded directly onto the video file through an external microphone connected to the Cannon D80 SLR. Each surfacing was also noted to aid in the detection of harbor porpoise during localization processing.

2.4.2 Data Analysis

2.4.2.1 Location Accuracy Assessment

Prior to processing the marine mammal sighting data, a location accuracy assessment was undertaken to quantify the location errors associated with the vantage point methods. We used a combination of images of the playback vessel collected during each trial, DAISY drifts that were deployed on 24 May to characterize received levels from the projector, and the research RHIB working with the DAISY drifts. Nine DAISY drifts, 15 locations of the RHIB, and 198 locations of the playback vessel were available for comparison between known GPS locations and those estimated using the landmark photogrammetry method in PAMGuard (additional details of this method follow). The playback vessel location shifted between ebb and flood but on average was ~661 m (range: 556 m – 763 m) from the vantage-point station. The DAISY drifts were an average of 619 m from the vantage-point station (range: 352 m – 953.1 m), and the RHIB was an average of 323 m (range: 133 m – 504 m) from the vantage-point station. The location accuracy analysis also allowed for an assessment of landmark selection to determine which, if any, combinations of landmarks should be avoided.

All vessel and DAISY images were analysed in the specially designed PAMGuard Landmark module. Data on the vantage-point station (location and height above sea level), location of landmarks and tide data were uploaded to the PAMGuard module prior to image processing. Each image/video frame must include a minimum of two visible landmarks for an object's position at the sea surface to be estimated. The estimated locations, along with estimated range and bearing to the object were stored in an external database that allowed for further analysis in Excel and R (v 3.4.1; R Core Team 2013). The difference between the known and estimated bearings for each vessel or DAISY location were calculated, along with the difference in known range and estimated range. Location error was determined by calculating the distance between the known location (provided by GPS) and the location estimated by PAMGuard.

2.4.2.2 Marine Mammal Sightings Data Processing

Prior to image and focal follow data processing, sighting and effort data were filtered to retain only those data collected during good sighting conditions. Scans conducted where the average sightability score was ≤ 2 were retained for analysis. This ensured data used for analysis were collected under conditions with:

- Sea state of Beaufort 2 or less;
- Less than 30% of the study area obscured by glare;
- No precipitation; and
- Landmarks visible on the far side of Admiralty Inlet (limited low clouds, fog, or smoke).

In addition to sighting conditions, scans were filtered to exclude those where small or medium private motorboats had been recorded within the study area, as they contribute to received levels but their contribution could not be modeled in the same manner as larger vessels equipped with AIS transponders.

Images of pinnipeds recorded during scans that met the requirements for usable data were processed in the PAMGuard Landmark module using the same methods employed to localize the positions of the vessels and DAISY drifts in the location accuracy assessment. In brief, the image associated with a useable sighting was selected within the PAMGuard module, a minimum of two visible, known landmarks were selected via mouse click and the animals' location at the water's surface was selected. PAMGuard then estimated the location of the animal at the sea surface based on the location of these landmarks, vantage-point station height above sea level and tidal height using trigonometric relationships (Figure 9). The estimated range and location of the animal was added to the sightings database and the distance from the animal to the playback location (determined by the presence of the marker buoy during control periods, or the playback vessel during playback periods) was calculated.

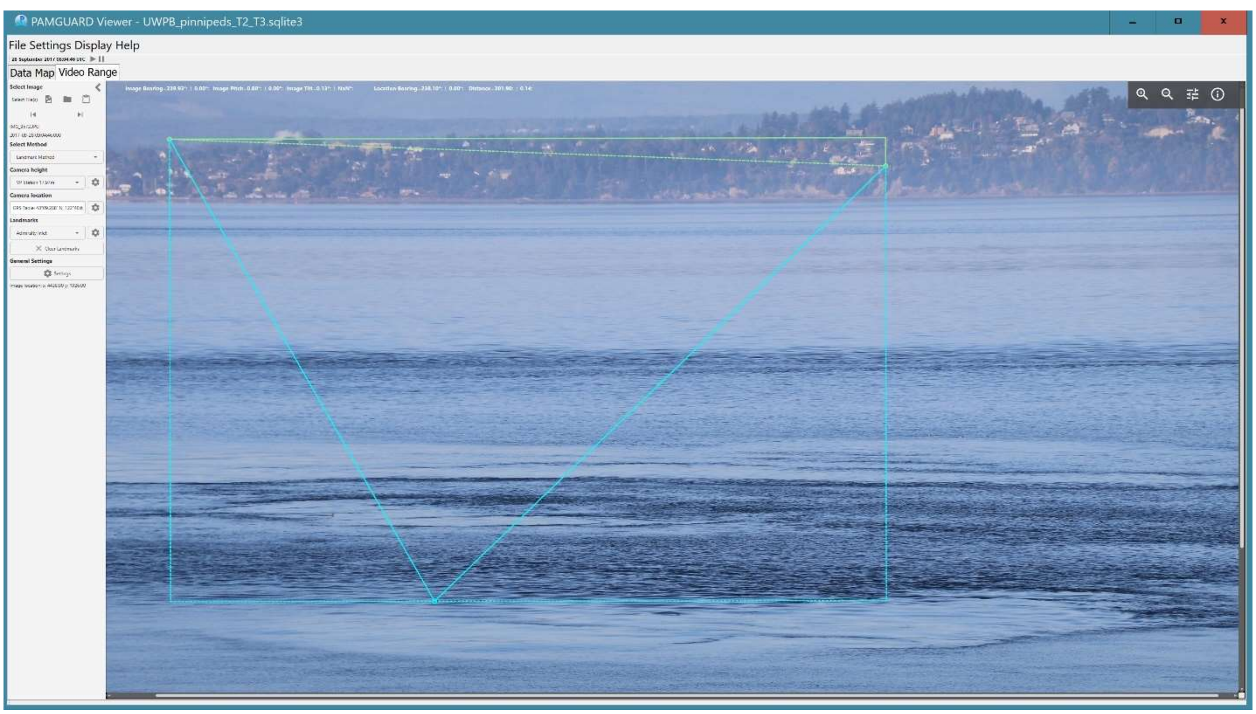

Figure 9. Screen capture from the PAMGuard Landmark module showing the selection of two known and visible landmarks (in green) and the selection and localization of a harbor seal (in blue).

A similar approach was used to process harbor porpoise focal follows. Video files for tracks collected during acceptable sighting conditions were selected within the PAMGuard Landmark module. Using the same approach as Hoekendijk et al. (2015), video footage was run until a porpoise or group of porpoises were visible at the sea surface (aided by the observers' acoustic cue for a surfacing event). The video file was then re-wound frame by frame until the animal was at the highest point in its surfacing. The location of the animal was then estimated using the same approach as for pinnipeds within PAMGuard.

2.4.2.3 Signal Excess Model

A frequency-dependent forward acoustic model for ambient noise and turbine playback sound was used to correlate "signal excess" with animal behavior. In brief, signal excess corresponds to the degree to which playback sound exceeds background noise levels as:

$$SE(x,t,f) = RL(x,f) - NL(x,t,f)$$

where the signal excess (*SE*), in dB, at location x (two-dimensional position), time *t* and frequency *f* is equal to the received level (*RL*) at location *x* and frequency *f* minus the noise level (*NL*) at the same position, time, and frequency. In cases where the animal's hearing threshold (*HT*) was higher than the noise level, noise level was replaced by hearing threshold in the above equation. The hearing thresholds used are shown in Figure 10. Received level of playback turbine sound was calculated from the source level (*SL*) and transmission loss (*TL*) estimated from the DAISY drifts during Trial 1 where

$$RL = SL - TL\,.$$

NL was modeled by the contributions from sediment noise (a function of near-seabed current velocity) and vessel noise (a function of vessel type and position) which prior studies have shown to dominate the soundscape at this site. This was chosen over a measurement of received levels for two reasons. First, vessel traffic produces gradients in received levels within the survey area, particular when vessels are at close range. A spatially-distributed array of hydrophones could measure these gradients directly, but was not logistically feasible for reasons of cost. Second, during periods of high currents, non-propagating flow-noise would be recorded by the hydrophone. Since marine mammal hearing may be adapted to mitigate flow-noise, measured noise levels might reduce the actual signal excess. Measurements of received levels by the hydrophones on the Sea Spider were, however, used to validate the model, as described in Section 3.4.

Sediment noise is typically generated above 1 kHz and is correlated with near-bed water velocity. Using the ADCP data collected on the Sea Spider and relations from Bassett et al. (2013) we estimated the one-third octave noise levels associated with sediment transport. Ship noise levels were estimated using source levels by vessel type from Veirs et al. (2016), and *TL* loss estimates (15dB/decade of distance) from Basset et al. (2012), with some modifications based on validation testing (see Section 3.4.2). Vessel noise inclusion was based on vessel class and position obtained from AIS data.

Because mammalian cochlea act as band pass filters, signal excess is calculated in one-third octave frequency bands. Further, to avoid complicating and weakening our statistical analyses, signal excess was only included in the behavioral model for two sets of frequencies of biological relevance to each species. Figure 10 shows published hearing thresholds of harbor porpoise and harbor seals (Andersen 1970; Kastelein et al. 2002; Götz and Janik 2010). Based on the frequency overlap between the turbine playback sound (Figure 3) and the hearing of these two species, signal excess was calculated for harbor seals in the one-third octave bands centered at 100 and 1,000 Hz. Since harbor porpoise are unlikely to hear the tone at 100 Hz, regardless of the ambient noise level, signal excess was calculated in the one-third octave bands centered at 1 and 4 kHz. The signal excess model was validated against the acoustic measurements made by the Loggerhead DSG located on the Sea Spider.

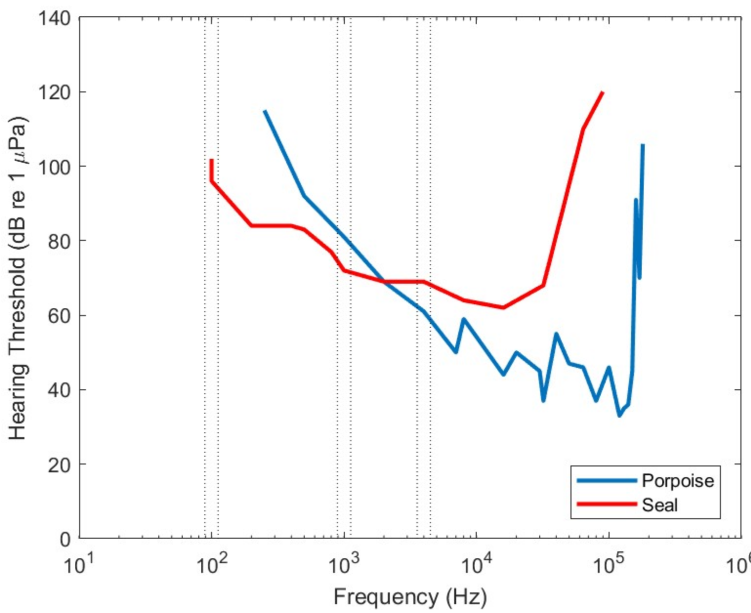

Figure 10. Audiograms of harbor porpoise and harbor seals (Gotz and Janik 2010). The harbor porpoise audiogram is a combined mean from two publications (Anderen 1970; Kastelein et al. 2002). The one-third octave bands of interest are shown in vertical dotted lines.

The signal excess model was implemented with custom Matlab scripts following the flow depicted in Figure 11. Signal excess was calculated for each animal sighted at location (*x)* and time (*t)* in two one-third octave frequency bands (*f)* in the following sequence:

1) Current velocity, estimated from the ADCP measurement and assumed valid over the observed area, was averaged over 10 minutes centered on time *t*. This was used to calculate $NL_{sed}(x,t,f)$ for the one-third octaves centered at 1 and 4 kHz. Currents are insufficient to mobilize "sediments" of sufficient size to produce sound at 100 Hz (Basset et al. 2013).
2) Data from the closest point of approach of AIS-enabled vessels within 10 km and travelling faster than 1.5 knots (to exclude stationary fishing vessels, etc.) over 3 minutes centered on time *t* were used in vessel noise estimates. One-third octave source levels by vessel type were taken from Veirs et al. (2016, see Appendix Table 14). Distance from the vessel to the animal at position (*x*) and transmission coefficient from Bassett et al. (2012, with some modification) were used to estimate $NL_{ves}(x,t,f)$. If there were multiple vessels present, their

noise levels were summed following equation (4) from Bassett et al. (2012), which assumes that the sounds from multiple vessels represent incoherent acoustic sources at different ranges relative to the receiver position.

3) $NL_{sed}(x,t,f)$ and $NL_{ves}(x,t,f)$ were summed in pressure space to estimate $NL(x,t,f)$.
4) $RL(x,f)$ was calculated from knowledge of the distance between the animal at location (x) and the J11 underwater speaker, transmission loss estimated from the DAISY drifts, and the one-third octave source levels of the playback signal (characterized in quiescent water at a range of 1 m from the J11). As source level was not varied, no time component (t) is included in this estimate.
5) Depending on the noise level relative to the species-specific hearing threshold, signal excess was estimated as:

$$NL(x,t,f) > HT(f) \qquad SE(x,t,f) = RL(x,f) - NL(x,t,f)$$

$$NL(x,t,f) < HT(f) \qquad SE(x,t,f) = RL(x,f) - HT(f).$$

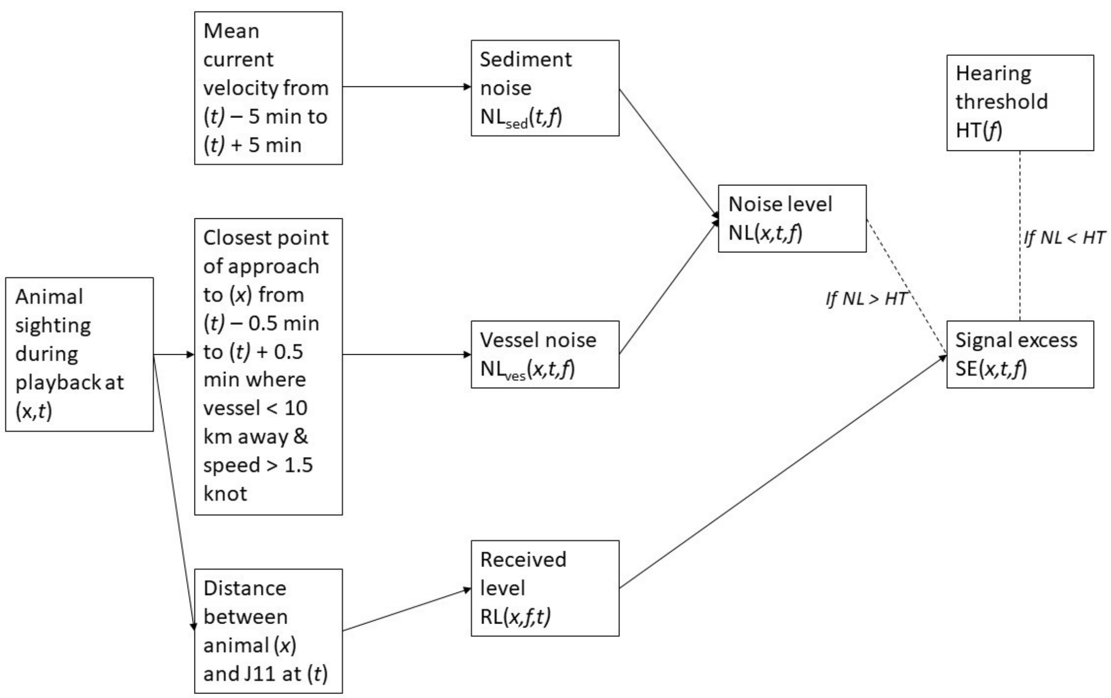

Figure 11. Schematic of signal excess calculations.

2.4.2.4 Marine Mammal Sightings Analysis

2.4.2.4.1 General Observations

Only those sightings that occurred during acceptable sighting conditions were retained for analysis. These sightings were summarized to provide the numbers of animals observed during useable scans, the number of animals, and average group size observed during trial periods.

Harbor seals and harbor porpoise sightings were analysed in further detail to determine the effect of the playback signal on their abundance within the study area. Steller sea lions were not considered for further analysis due to the low number of sightings during the first and second trials.

2.4.2.4.2 Distance from Playback

For those sightings where locations were estimated using the PAMGuard Landmark module, the distance of each sighting to the playback location was calculated and summarized to provide the mean distance to the playback location during each trial period.

2.4.2.4.3 Porpoise Focal Follows

Harbor porpoise focal follows collected during useable sighting conditions were analyzed. Tracks with four or more estimated locations per group were selected and for each track the closest point of approach (CPA) to the playback location along with directness and deviation indices were calculated based on methods presented by Williams et al. (2002).

The directness and deviation indices provide a means to measure the path of predictability of the animal or group (Williams et al. 2002). The directness index (*DI*) is calculated on the scale of the tracking session and is calculated by dividing the distance between the endpoints of a track by the cumulative surface distance covered by all dives (Williams et al. 2002)

$$DI = 100\left(\frac{T}{\sum d_n}\right)$$

where T is the overall straight-line distance between the start and end of the track, and d_n is the dive number in the track. The directness index ranges from 0 to 100, where 0 represents a circular path and 100 represents a straight-line path, it is the ratio of the diameter of a track to its perimeter.

The deviation index measures the track predictability from one surfacing to the next (Williams et al. 2002). It is the mean of all angles between adjacent dives and can be considered the inverse measure of a track's smoothness. For each surfacing in a track the angle is calculated based on the straight-line path predicted by the previous dive. The deviation index (*DE*) is calculated as the mean of all surfacing angles in a track

$$DE = \frac{\sum a_n}{Z}$$

where a_n is the angle per surfacing in a track and Z is the number of surfacings in a track. A low deviation index indicates a smooth track while a high deviation index indicates an erratic track (Williams et al. 2002).

The CPA, directness index and deviation index were summarized by trial, porpoise activity state (e.g., foraging, travelling or combined travel and forage) and compared to playback periods and control periods.

2.4.2.4.4 Statistical Models

We fit a generalized additive mixed regression model (GAMM) to test whether there was a difference in harbor seal and harbor porpoise abundance across trials run in spring, summer, autumn. Additional covariates were considered both as linear and smoothed terms. Each sighting was assumed to be a 'count' of presence, and counts were then summed within each scan. This count data was assumed to follow a Poisson distribution, and modeled using a log link function within the GAMM framework. An offset term was included in both models to account for the duration of the scan (i.e., the effort put into each scan). GAMM models accounted for repeated sampling within a day by including a random effect for day, and an autoregressive term to account for within day temporal correlation. Model selection was performed using AIC. This method determined both which covariates to include in the model, and whether these terms should be linear or smoothed. The choice and form of the covariates that influenced seal and porpoise abundance was based on selecting the model with the lowest AIC. Significance of regression terms was tested using Wald chi-square statistics for each of the linear and smoothed coefficients. An ANOVA F-test considered the collective significance of model factors with multiple factor levels.

C-POD click detections from the Sea Spider were downloaded after each trial and processed using CPOD.exe V2.044 to classify narrow band high frequency (i.e. porpoise) click trains. Only high and moderate quality click trains were retained. These porpoise detection positive minutes were exported in 10-minute periods associated with the time of each scan and added to our dataset. This resulted in a covariate that ranged from 0 (no porpoise click trains detected in that 10-minute period) to 10 (porpoise detected in every minute of that 10-minute period). We then fit a GAMM to test whether there was a difference in harbor porpoise occupancy as measured using the C-POD across trials run in spring, summer, and autumn. The C-POD measurement unit was constant across all data, accounting for presence absence of porpoise over a 10-minute time unit. These data were assumed to be drawn from a binomial distribution and modeled using logit link within the GAMM. As with the previous analyses, the model accounted for repeated sampling within a day by including a random effect for day, and an autoregressive term to account for correlation within measurements on the same day. The choice and form of the covariates that influenced porpoise occupancy in the final model was based on AIC selection criteria. As before, an ANOVA F-test was used to report significance of factors with multiple levels.

3 Results

3.1 Trial Periods

Table 1 summarizes the vantage-point effort after removing scans with poor sighting conditions and scans with private motor vessels within the study area. Overall, 749 useable scans, averaging 2.49 minutes in duration and totaling 31.08 hours of effort were collected during the trials in spring, summer, and autumn.

Harbor porpoise focal follows were attempted whenever a porpoise or group of porpoise were sighted within or approaching the study area. This resulted in 125 successful tracks conducted over the three trials (where tracks consisted of more than four surfacings). Of these, 24 focal follows were conducted between scans and therefore considered opportunistic focal follows. Harbor porpoise focal follows averaged 1.72 minutes but their lengths ranged from 0.13 – 8.69 minutes.

In general, more usable scan effort was obtained during control periods than playback periods. There are several reasons for this asymmetry. Vantage-point observers were often able to be continuously on site for the six days preceding or following the playback period. On days during the playback period, observers were able to collect additional control scan effort if they were on site before the playback vessel arrived and started transmissions or after the vessel had departed.

Shore observers also experienced fewer timing restrictions than the playback vessel (e.g., they could stay an extra day in the event of poor weather, setup not constrained by the stage of the tide). Finally, unusable sighting conditions and recreational vessel presence occurred disproportionately during playback periods.

Table 1. Summary of the total number of hours of useable scan data from each trial, along with a breakdown of the number of hours of control and playback periods.

	Spring Trial [hours]	Summer Trial [hours]	Autumn Trial [hours]
Useable Scan Effort			
Total	9.89	9.99	11.21
Control	6.19	5.52	7.55
Playback	3.70	4.47	3.66

3.2 Location Accuracy Assessment

Location accuracy of the vantage-point photogrammetry approach was assessed using known locations of the playback support vessel, RHIB used to deploy and recovery the DAISYs during the first trial, and DAISY drifts themselves. The mean location error over 9 DAISY drifts was 16 m (sd=7.2, range=0.1-32 m, Figure 12), for the RHIB, location error was 8 m (sd=2.6, range=2.2-12 m), while the mean location error of the playback support vessel was 14 m (sd=6.4, range=1.3-30 m). The overall combined average location error was 14 m. The estimated location error as a function of spatial position is shown in Figure 13. In addition, the assessment determined which combinations of landmarks should be avoided in processing sighting images and focal follow video frames to minimize error.

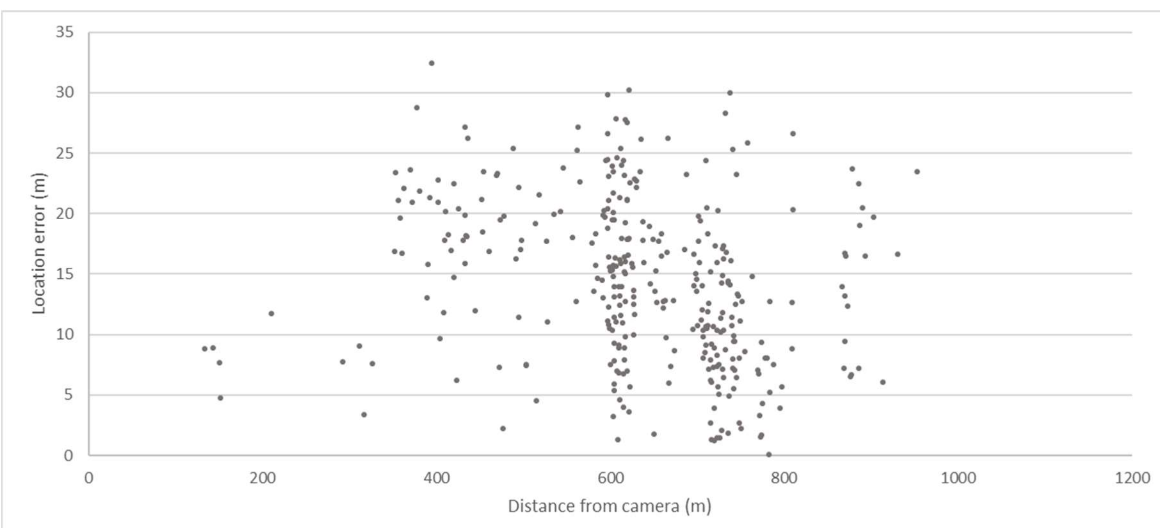

Figure 12. The location error estimates resulting from comparing GPS locations of the playback support vessel, RHIB, and DAISYs.

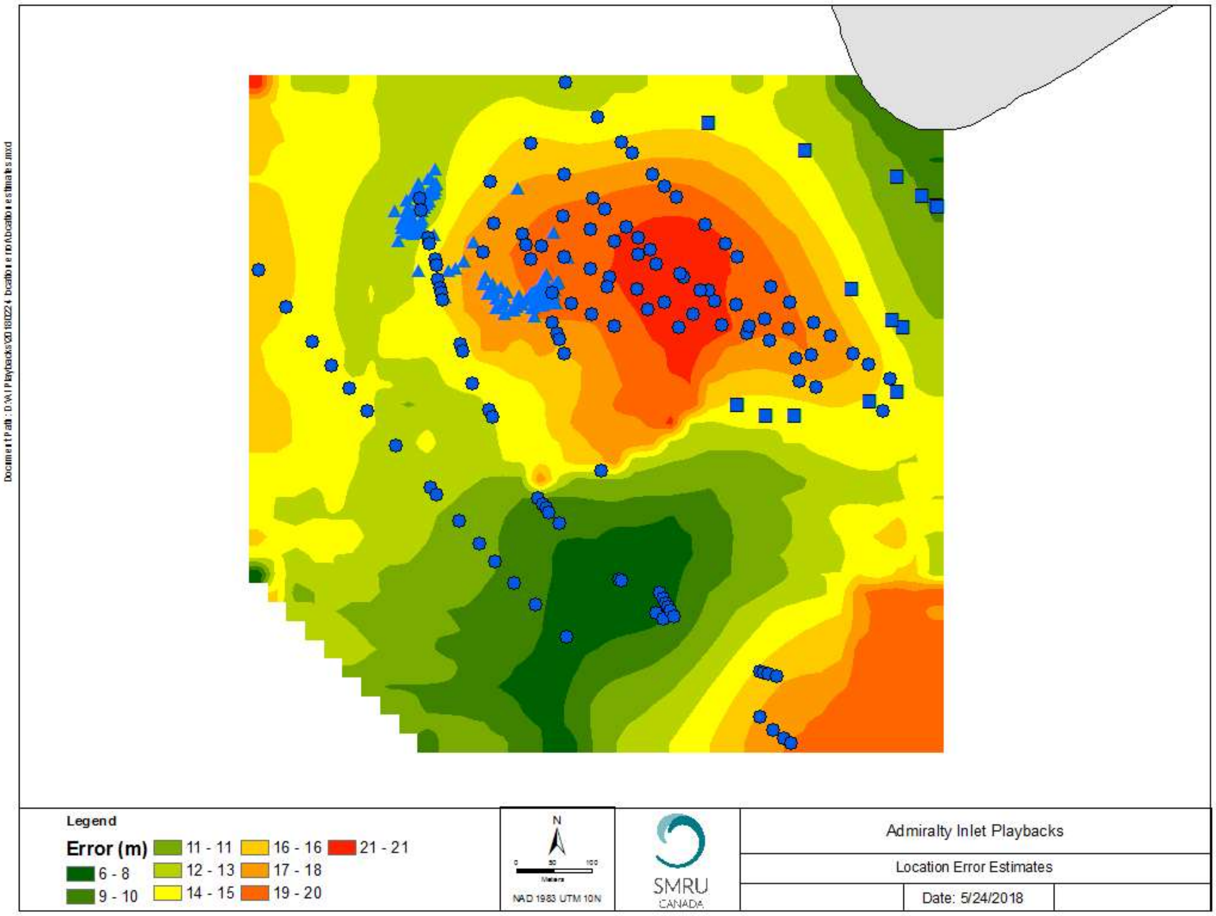

Figure 13. Spatial representation of location error. Error estimates across the study area were interpolated using the individual error points and spatial kriging. Blue error points are as follows: circle = DAISY, square = RHIB, triangle = playback support vessel.

3.3 Received Levels

Received levels in the playback band (30 Hz – 10 kHz) are shown in Figure 14 and have a realistic pattern of received levels and transmission loss. Because the 100 Hz tone in the source signal has the best signal to noise ratio and sound absorption by seawater is negligible at this frequency, the range-dependent transmission loss coefficient was estimated at this frequency using the median azimuthal value over a radially interpolated grid. The resulting transmission loss coefficient is shown in Figure 15. At close range, the transmission loss coefficient is approximately spherical, declining to approximately 17 beyond 200 m. This is consistent with prior estimates of the transmission loss coefficient associated with ferry vessel noise (Bassett et al. 2012).

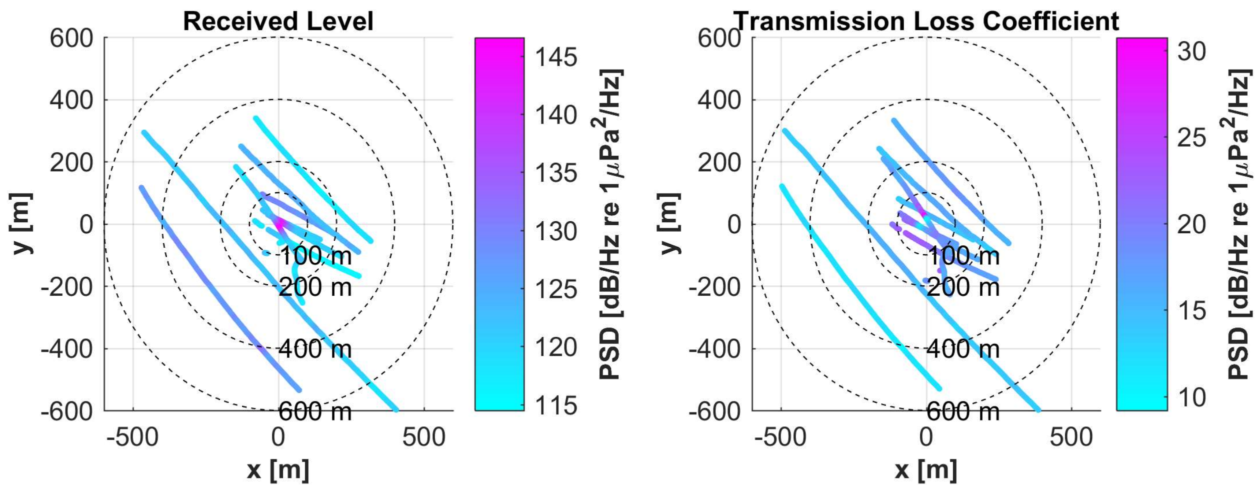

Figure 14. (left) received levels for drifts passing quality assurance and (right) empirical transmission loss coefficients. The origin of all drifts is referenced to the mean position of the support vessel during each drift.

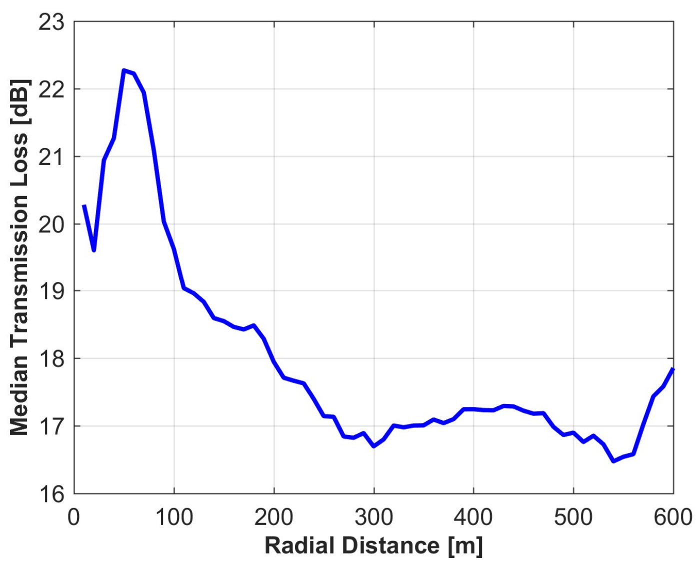

Figure 15. Median radial range-dependent transmission loss coefficient for the 100 Hz band.

3.4 Signal Excess Model

The adequacy of the signal excess model depends on the quality of the input data and the model assumptions. To evaluate model performance, we focused on sediment and vessel noise predictions and compared these to acoustic data collected during the final survey period of this study. Acoustic data were combined with ADCP current velocity, and AIS vessel data on a minute by minute basis. Predictions of sediment noise, vessel noise and combined noise (sediment & vessels) were then generated and compared to sound recorded by the hydrophone on the Sea Spider.

3.4.1 Sediment Noise

To focus on sediment noise, we selected time periods when there were no AIS enabled vessels within 10 km or travelling > 1.5 knots. This resulted in 1,095 (out of 5,078) minutes of data. The distribution of recorded noise levels was then compared to distribution of predicted noise levels in the 1 and 4 kHz one-third octave bins (Figure 16). The model predictions have a lower cutoff based on the model developed in Bassett et al. (2013) which does not go below the mean ambient noise during weak currents. On average, the sediment noise model over-predicts sediment related noise levels by 1.2 and 3.7 dB in the 1 and 4 kHz bins respectively (Table 2). A closer look at the performance of sediment noise model predictions is provided in Figure 17. While there is a wide spread (it can vary by up to 30 dB) in logger measurements, the sediment noise model appears to slightly over-predict noise levels, especially at lower current velocities. This is not surprising, as weak currents are unable to mobilize "sediments" of sufficient size (i.e., cobbles) to generate sound at these frequencies. The frequency of sound produced by a collision is inversely proportional to the size of the objects involved in the collision. Agreement between modeled and measured sediment noise improves at higher current velocity, but is generally better on flood than ebb.

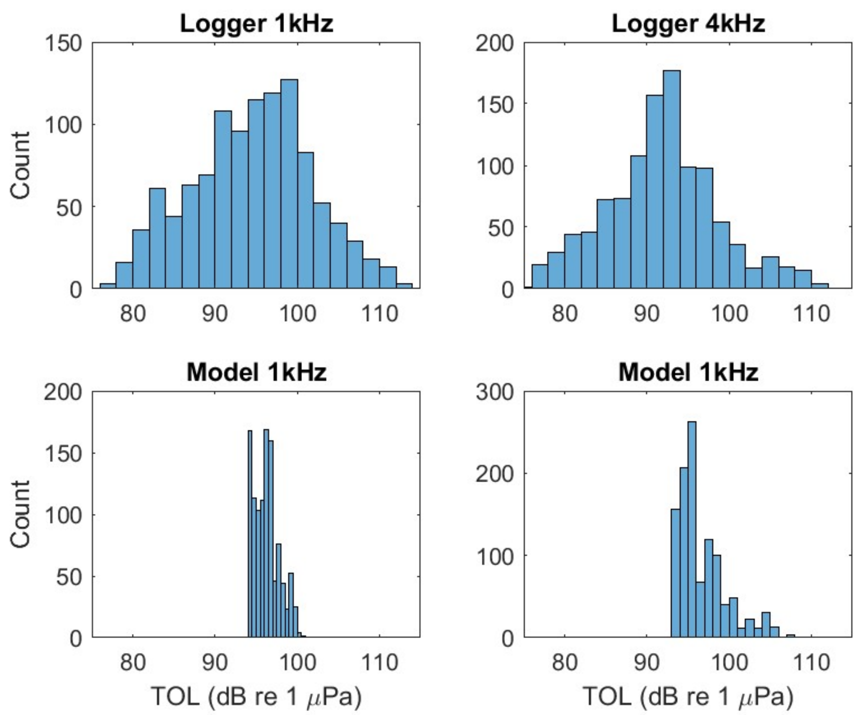

Figure 16. Histogram plots of one-third octave measured sediment-dominated noise levels (top row) and predicted sediment noise levels (bottom row) in the 1 kHz (left) and 4 kHz (right) one-third octave bins.

Table 2. Median one-third octave measured and predicted sediment noise levels and their difference.

One-third octave bin	1 kHz	4 kHz
Median TOL: Loggerhead data (dB re 1μPa)	94.9	92.0
Median TOL: Sediment model (dB re 1μPa)	96.1	95.7
Difference (dB)	1.2	3.7

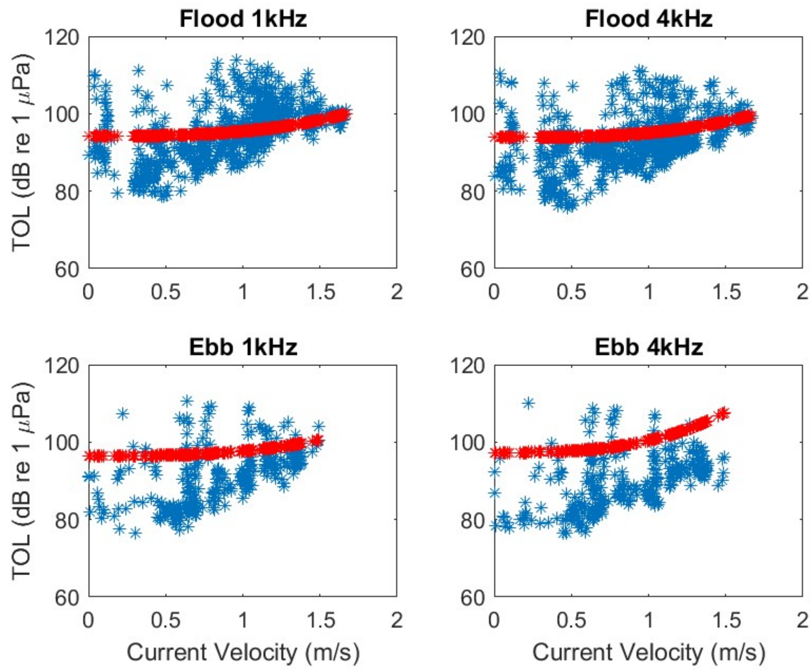

Figure 17. Plot of one-third octave noise levels versus current velocity during flood tides (top) and ebb tides (bottom) in the 1 kHz (left) and 4 kHz (right) one-third octave bins. Empirical data is in blue. Modelled predictions in red.

3.4.2 Vessel Noise

To evaluate the vessel noise model, we selected periods when current velocities were < 0.5 m/s (minimizing flow-noise and sediment noise) and when there were AIS-enabled vessels within 10 km travelling > 1.5 knots. This resulted in 649 minutes of data. Vessel noise predictions were made in the 0.1, 1 and 4 kHz one-third octave bins. The agreement between measured and predicted noise levels in the 1 and 4 kHz bins was quite good (Figure 18 and Table 3). However, initial results in the 0.1 kHz bin had a large average (~20 dB) under-prediction of vessel noise levels. We therefore used a higher transmission loss coefficient of 18 for this frequency bin, as opposed to 15 in Basset et al. (2012). This still produced an average under-prediction of vessel noise level of ~10 dB in this frequency bin (Figure 18 and Table 3). We did not adjust the transmission loss coefficient any higher, as the average difference between the measured and modeled vessel noise levels in the 0.1 kHz bin is likely affected by the relatively large number of measured noise levels above ~115 dB re 1μPa (Figure 18). To ensure that this was not caused by flow-noise on the hydrophone, we plotted measure noise levels against current velocity, using both the entire dataset with AIS vessel present and the smaller one with current velocities < 0.5 m/s (Figure 19). What is clear from this figure is that the high amplitude events are not being driven solely by currents at velocities < 0.5 m/s. A random subsample of these noise files were checked manually and found to be attributed to several factors. These included times when there were errors in the AIS data (i.e., a close ship did not transmit its location during this period, so the model only used more distant ships), times with impacts on Sea Spider recovery floats or line strum[3]; and times when flow-noise could be heard. Because these were either errors (AIS), aberrant events (self-noise), or pseudo-noise (flow-noise), we felt that the use of an even higher attenuation loss coefficient was not warranted. In other words, the model should not be tuned to these types of sound, since they would not be manifested in received levels for marine animals in the study area.

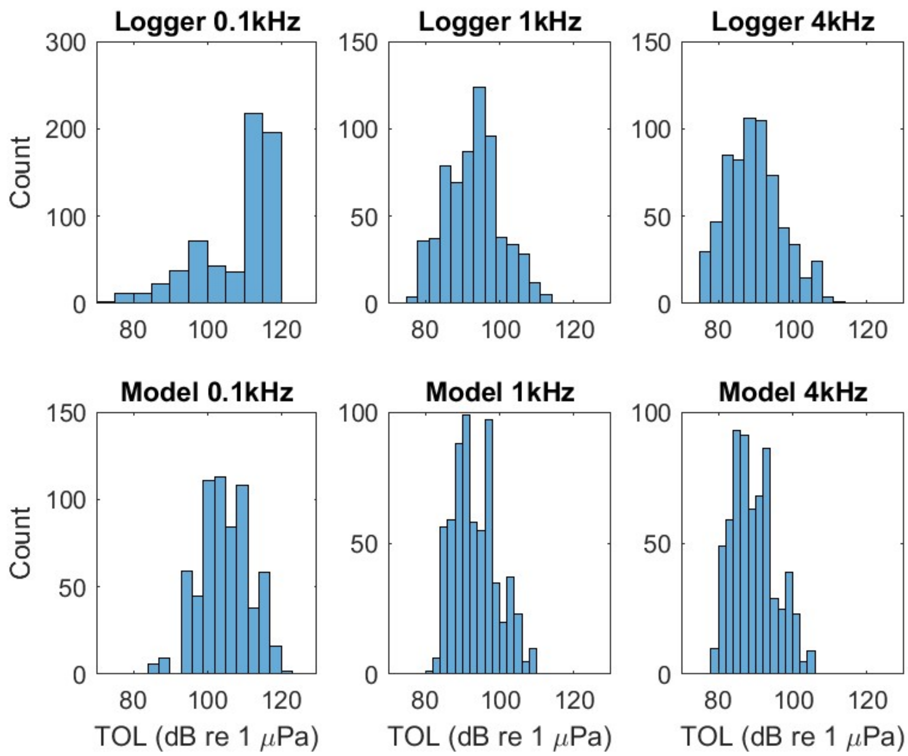

Figure 18. Histogram plots of one-third octave measured vessel-dominated noise levels (top row) and predicted vessel noise levels (bottom row) in the 0.1 kHz (left), 1 kHz (middle) and 4 kHz (right) one-third octave bins.

Table 3. Median one-third octave measured and predicted vessel noise levels and their difference.

One-third octave bin	0.1 kHz	1 kHz	4 kHz
Median TOL: Loggerhead (dB re 1μPa)	114.1	93.2	89.3
Median TOL: AIS Model (dB re 1μPa)	104.5	92.8	88.8
Difference (dB)	-9.6	-0.4	-0.5

[3] It is hypothesized that a loose fitting in a recovery line may have intermittently tapped against the recovery floats during low current periods but held taut and clear during periods of high currents.

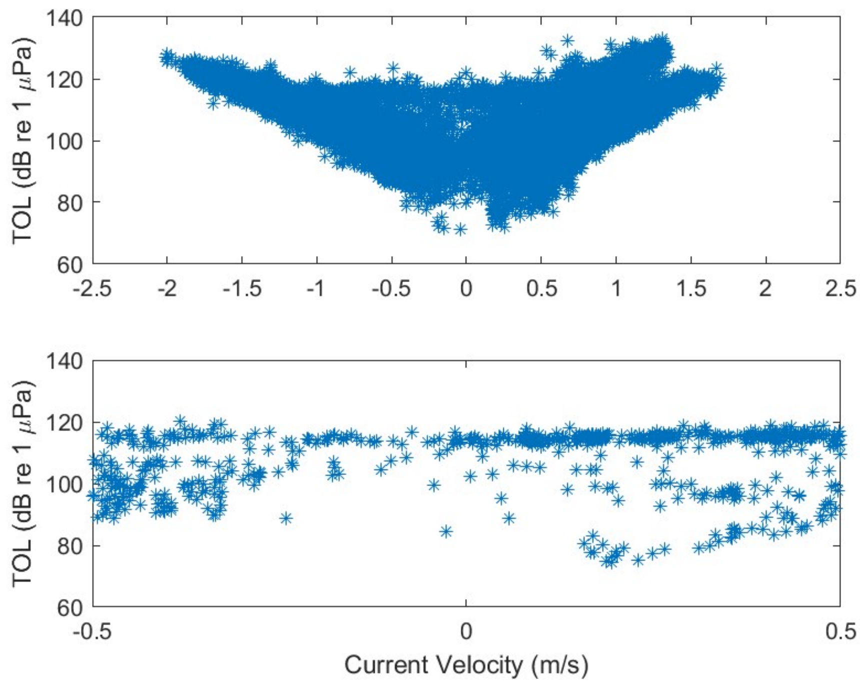

Figure 19. Plot of one-third octave noise levels versus current velocity using all the data with AIS vessel present (top) and the subset data with current < 0.5 m/s (bottom). The influence of flow-noise on received levels is clear during periods with bottom currents > 0.5 m/s.

3.4.3 Combined Noise (Sediment and Vessels)

Following the methods for estimating signal excess, the sediment and vessel noise estimates were summed (in pressure space) for each minute. When no AIS vessels were within 10 km and traveling > 1.5 knots, ambient noise data was estimated as the median one-third octave noise levels measured by the hydrophone when no AIS vessels were present and currents were < 0.5 m/s. This coarsely approximated received levels from other ambient sources, such as wind and waves. For each minute of data, we then subtracted the empirical noise measurement from the predicted noise measurement in each of the one-third octave bins. The distributions of those results are shown in Figure 20 and average differences provided in Table 4. To minimize flow noise in the 0.1 kHz bin, for that bin, we compared only periods with current velocity < 0.5 m/s. The combined noise model tends to under-predict received levels in the 0.1 kHz bin and over-predict in the 1 and 4 kHz bins. The under predictions in the 0.1 kHz bin are likely due to issues discussed above (AIS error, self-noise, and flow-noise). The over-prediction in the 1 and 4 kHz bin is likely due to the noted over-prediction in sediment noise.

This comparison suggest that signal excess is likely be over-estimated in the 0.1 kHz bin and under-estimated in the 1 and 4 kHz bins.

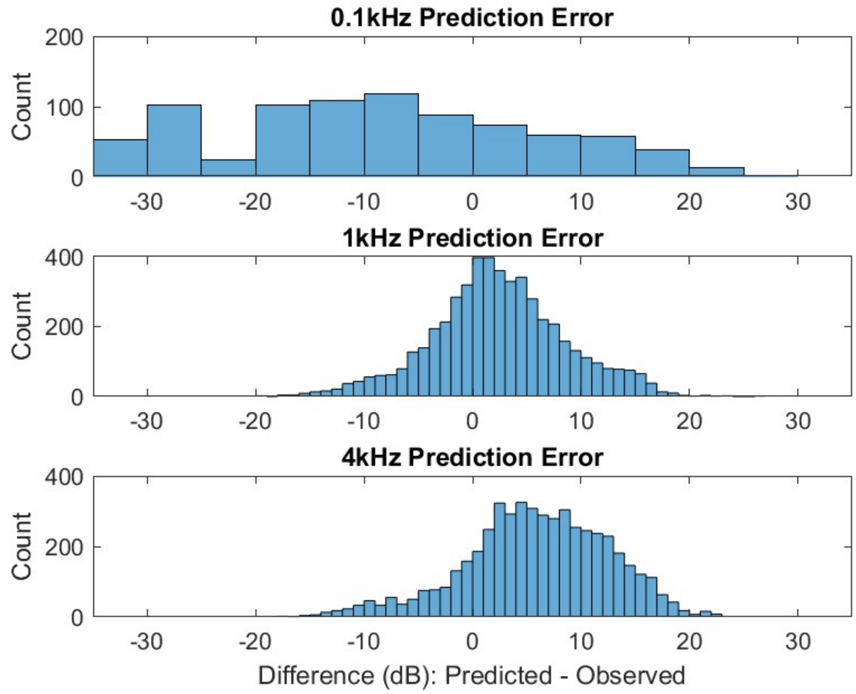

Figure 20. Histogram plots of difference between predicted and measured one-third octave band noise levels in the 0.1 (top), 1 (middle) and 4 (bottom) kHz bins.

Table 4. Median difference in predicted and measured one-third octave noise levels in the 0.1, 1 and 4 kHz bins.

One-third octave bins	Median Predicted – Observed (dB)
0.1 kHz	-9.0
1 kHz	2.2
4 kHz	6.0

3.5 Marine Mammal Observations

3.5.1 General Observations

Over the course of the three playback trials, ten species of marine mammal were recorded within or just outside the study area. These included harbor seal, Steller sea lion (*Eumetopias jubatus*), California sea lion (*Zalophus californianus)*, harbor porpoise, common dolphin (*Delphinus delphis)*, Southern Resident killer whales (*Orcinus orca)*, Transient killer whales, minke whales (*Balaenoptera acutorostrata*), humpback whales (*Megaptera novaeangliae*), and a gray whale (*Eschrichtius robustus*). No baleen whales were sighted during the autumn survey (third trial). Three playback shutdowns occurred due to sightings of baleen whales within the vicinity of the study area during the first two trials. No mitigation shut downs were required for killer whales as all sightings occurred during control periods.

Harbor porpoise and harbor seals were the most commonly sighted species followed by Steller sea lions, with the majority of Steller sea lions observed during the autumn survey. However, the number of *individual* animals present in the study area during the autumn surveys is likely to have been on the order of ten, with the relatively high counts (Table 5) associated with repeated observations of those individuals over multiple scans.

The vast majority of marine mammal sightings were recorded during scans and so are considered ‘on-effort’ sightings, as opposed to opportunistic sightings (e.g., opportunistic focal follows). Harbor seals were observed during 216 of 749 useable scans (or 29%) and harbor porpoise were observed during 201 useable scans (27% of useable scans), while Steller sea lions were observed during only 9% of useable scans (Table 6).

Table 5. The number of useable pinniped and porpoise sighted (N) during each trial period, and the mean number of animals recorded during each scan ($\bar{x}$).

	Spring Trial		Summer Trial		Autumn Trial		Total	
	N	$\bar{x}$	N	$\bar{x}$	N	$\bar{x}$	N	$\bar{x}$
Harbor porpoise	245	3.5	128	2.0	323	4.8	696	3.5
Harbor seal	233	2.3	45	1.2	100	1.3	379	1.8
Steller sea lion	7	1	2	1	216	3.5	225	3.5

Table 6. Summary of the number of useable scans (N) and % of those scans that harbor seals, harbor porpoise, and Steller sea lions were observed in over the course of the three trials.

	Scans	Harbor seals		Harbor porpoise		Steller sea lions	
	N	N	%	N	%	N	%
Control	465	121	26	140	30	37	8
Impact	284	95	34	61	22	33	12
Total	749	216	29	201	27	70	9

Of those animals observed and recorded during periods with acceptable sighting conditions and no private motor vessels (i.e., no vessels that would have elevated received levels without appearing on AIS), locations were successfully estimated in PAMGuard for 77.6% of harbor porpoise sightings, 75.1% of harbor seal sightings and 73.2% of Steller sea lion sightings. From these data, we were able to estimate the distance of each sighting from the vantage-point station, as well as the distance of each animal to the playback location. In some circumstances, sightings were recorded during nominally acceptable conditions, but images were either of too poor quality (e.g., locally poor lighting, landmarks not distinguishable), or the animal was not visible in the image. Such sightings represent the 22.4% that were not successfully localized in PAMGuard.

Harbor seals were observed during useable scans at distances from 96 m-1,064 m, as summarized in Figure 21 and Figure 22. The median distance from the vantage-point for harbor seals was 323 m. Harbor porpoise were generally recorded the furthest from the vantage-point station, at a median distance of 617 m, with sightings ranged from of 165 m - 1,532 m (Figure 21 and Figure 23). Steller sea lions were predominantly sighted close to shore at a median distance of 209 m from the vantage-point station at distances ranging from 107 m-1,024 m (Figure 21 and Figure 22). The fact that we observed harbor porpoises regularly up to ~1,300 m from the vantage-point station, that porpoise spend less time on the surface than harbor seals, and that both species are of similar size, suggests that the harbor seals are spending more time closer to the vantage-point station than harbor porpoise and that this pattern is not an artifact of missed offshore observations of harbor seals. The differences in distance from the vantage-point station is likely due to niche partitioning between the species we observed. These patterns of distance from the vantage-point station are also consistent with observations obtained during baseline evaluations for tidal energy development.

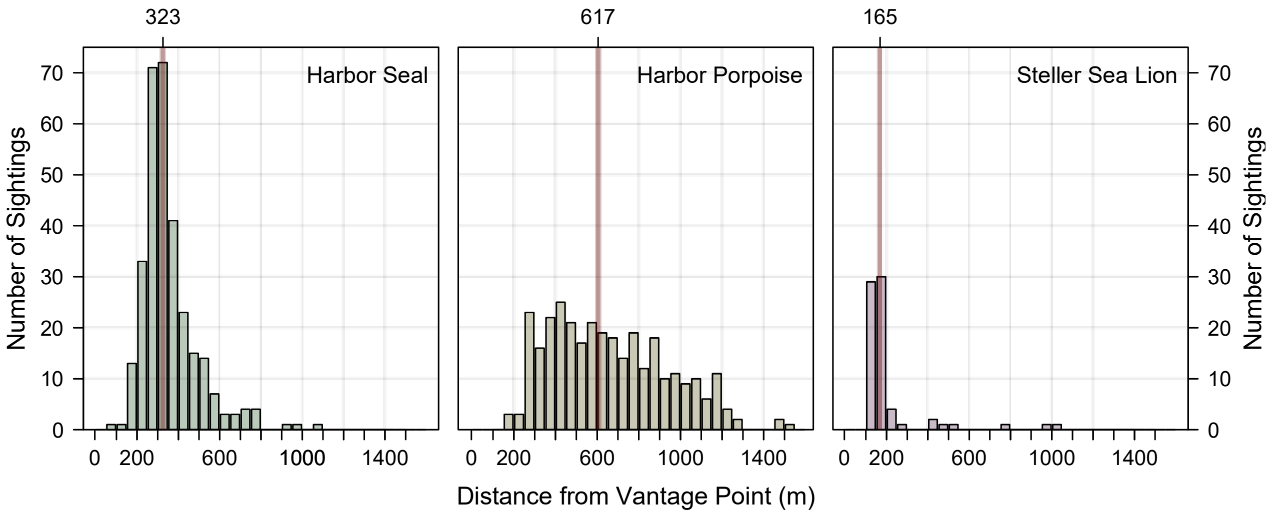

Figure 21. Distributions of the range (m) of sightings of harbor seals (left), harbor porpoise (mid), and Steller sea lions (right) from the vantage-point station. The red vertical lines indicate the median range for each species.

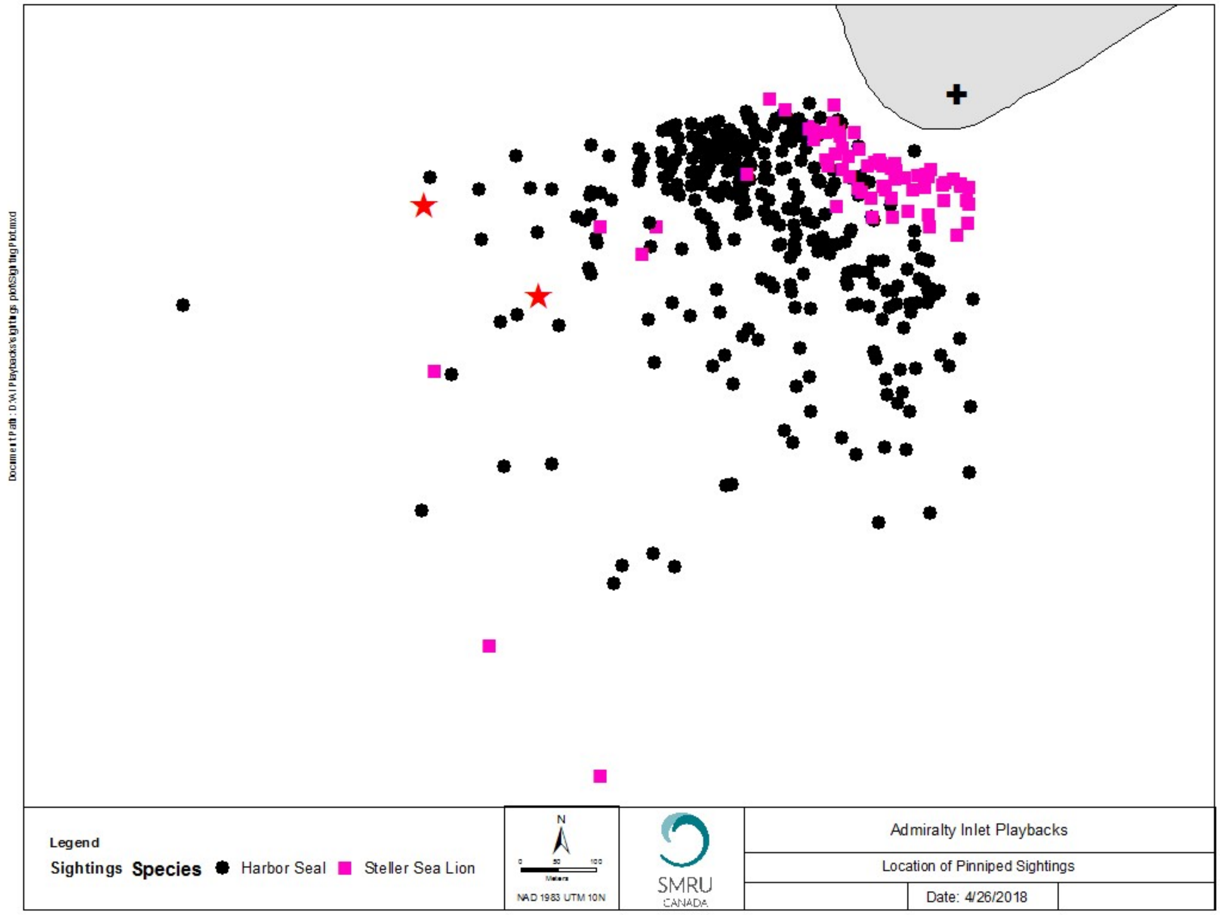

Figure 22: Location of useable pinniped sightings across the spring, summer and autumn surveys (aggregate of control and playback periods). The red stars denote the average playback location on ebb and flood tides and the black cross denotes the land-based observation station. Harbor seals are shown as black circles and sea lions as magenta squares.

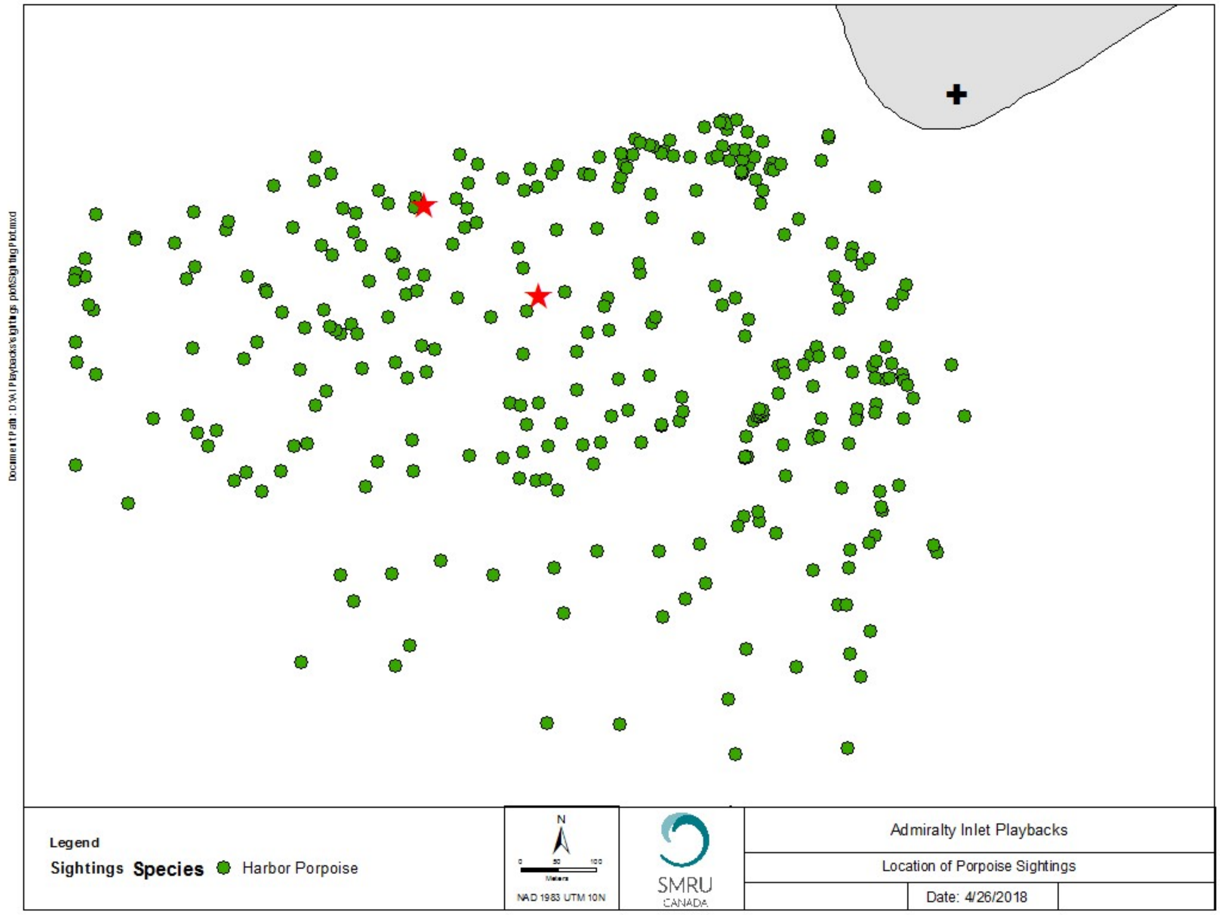

Figure 23. Location of useable harbor porpoise sightings across the spring, summer and autumn surveys (aggregate of control and playback periods). The red stars denote the average playback location on ebb and flood tides and the black cross denotes the land-based observation station. Porpoise locations are shown as green circles.

The total number of animals observed during scans, mean group size and the group size range for sightings are presented in Table 7. There were clear seasonal differences in both presence and group size for the species across the three trials. The majority of harbor seals were observed during Trial 1, while the fewest were observed during Trial 2 (Table 7). The majority of Steller sea lions and the largest group sizes of sea lions were observed during Trial 3 (Table 7). Harbor porpoise sightings were similar during Trials 1 and 3, but the fewest number of porpoise were observed during Trial 2 (summer survey) (Table 7).

Overall, a total of 425 harbor porpoise groups were observed during useable sighting conditions across the three trials. The majority of these were encountered during scan effort and the 52 encounters that occurred between scans have been retained to provide additional opportunistic focal follow data (these produced 24 additional focal follows). While the majority of porpoise sightings were of individual animals, group sizes as large as 15 were recorded. Larger group sizes of porpoise were observed during Trial 3 (autumn survey). The highest number of calves were also recorded during Trial 3, where 20 sightings included a calf. Sightings of calves were first recorded during

Trial 2 (summer survey), where 8 calves were recorded, but no calves were recorded during Trial 1 (spring survey). Foraging activities were most commonly observed during Trial 1 (67%, n = 65 sightings), while during Trial 3, the majority of porpoise sightings where recorded as traveling (62%, n = 126 sightings), indicating that harbor porpoise use of the study area may vary seasonally. However, as discussed in Section 3.5.3, activity state does not appear to be statistically correlated with the closest point of approach to the location of the playback support vessel.

Table 7. Summary of on-effort sightings for harbor porpoise, harbor seal and Steller sea lion. Summary includes the number of groups observed (N), the total number of animals observed (Sum), the mean group size ($\bar{x}$), standard error of the mean (se) and the group size range (range).

	Harbor porpoise					**Harbor seal**					**Steller sea lion**				
	N	Sum	$\bar{x}$	se	range	N	Sum	$\bar{x}$	se	range	N	Sum	$\bar{x}$	se	Range
Trial 1	162	245	1.53	0.10	1-12	228	233	1.02	0.01	1-2	7	7	1	-	1-1
Trial 2	81	128	1.58	0.08	1-5	45	45	1	-	1-1	2	2	1	-	1-1
Trial 3	132	323	2.45	0.17	1-15	99	100	1.01	0.01	1-2	68	216	3.18	0.29	1-8

3.5.2 Distance from Playback

Distance from each sighting to the playback location was calculated, as shown in Figure 24. Harbor seals were observed at mean a distance of 410 m while harbor porpoise were on average slightly closer at a mean of 384 m but there does not appear to be a difference in the distribution of distance from playback when the playback was on versus off, for either species, as shown in Figure 24.

Figure 25 and Figure 26 segregate these distributions by trial period for harbor seals and harbor porpoises, respectively. For harbor seals, the distributions across trial periods do not indicate any effect from playbacks (Figure 25). However, for harbor porpoises, there does seem to be a shift in distributions for across trials (Figure 26). During Trial 1 playback periods, porpoise seem to have avoided the area within ~300 of the playback source. In Trial 2 this distance shrinks to ~100 m and it disappears entirely by Trial 3. This suggests a potential response to the sound generated by the playback or the presence of the playback vessel. The potential effect of playback is dealt with more formally in statistical models in Section 3.5.4.

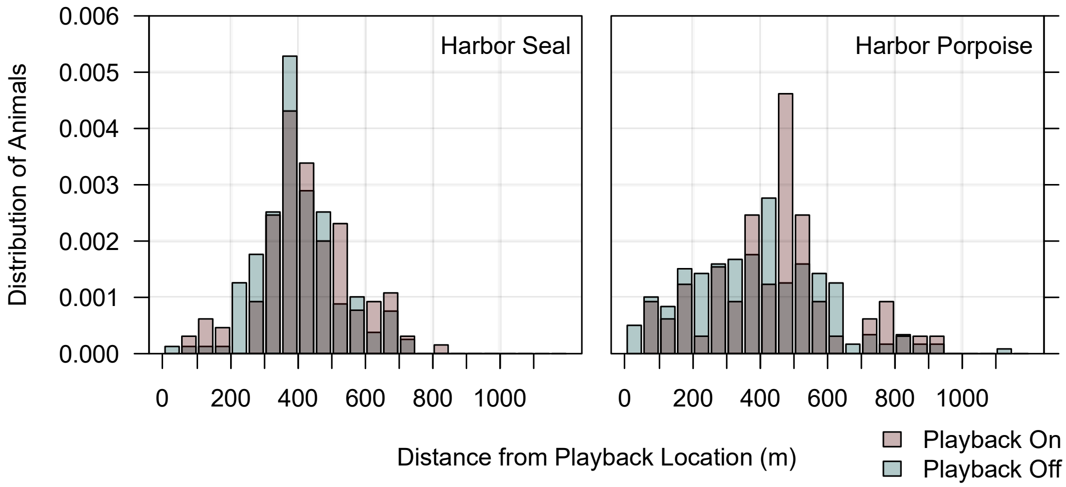

Figure 24. The distributions of sighting distances for harbor seals (left) and harbor porpoise (right) from the playback location during control periods (Playback Off: blue), and those times when the playback signal was operating (Playback On: red).

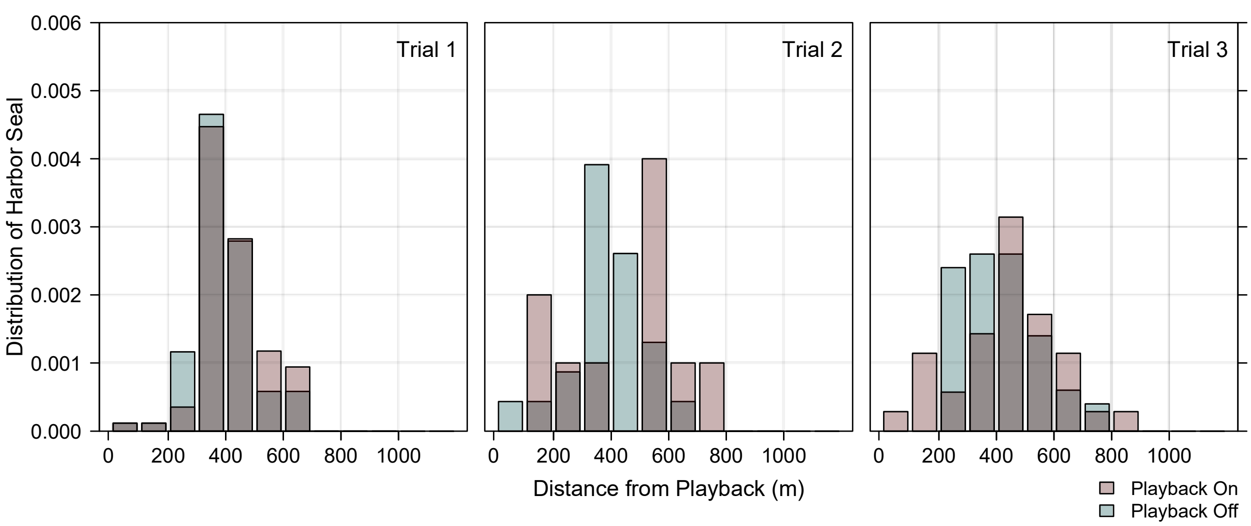

Figure 25. The distribution of distances of harbor seals from the playback location for Trial 1, 2 and 3 when playback was on and off.

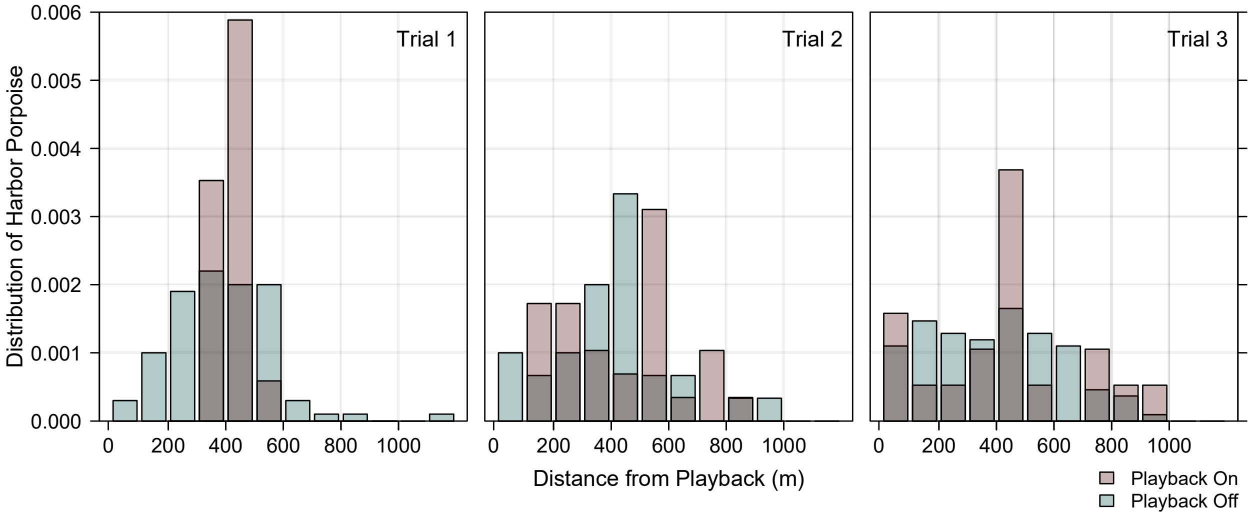

Figure 26. The distribution of distances of harbor porpoise from the playback location for Trial 1, 2 and 3 when playback was on and off.

3.5.3 Harbor Porpoise Focal Follows

In total, 208 focal follows were attempted during the spring trial, 139 during the summer trials, and 106 during the autumn trial. However, only 107 focal follows were of sufficient quality (i.e., collected during useable sighting conditions and included more than four surfacings) to be retained for analysis. Of these, one track had no activity state assigned to the group and another was recorded as “resting”, so these were also discarded from the analysis so that the main group activity states of “foraging”, “traveling” and combined “travel/forage” could be compared. The majority of useable porpoise focal follows were collected during control periods, with only 13% collected during playback periods (Table 8). This discrepancy is likely due to an effect of the playback, as is shown in statistical models in Section 3.5.4.

The mean CPA of all the tracks was 326 m (se =18m, range = 9-813m). A mean CPA was calculated for each activity state, as well as for those tracks collected during control and playback periods (Table 9, Figure 27). There was no significant difference in the mean CPA for animals engaged in foraging, traveling or combined travel/forage activities (Oneway anova, p-value = 0.3), and neither was there a significant difference in the CPA for tracks collected during control periods and tracks collected during playback periods (t = 0.2, df = 20, p-value = 0.8, Table 9).

Directivity and deviation indices were calculated for all harbor porpoise tracks where there were four or more locations estimated from surfacing. Mean measures of directivity and deviation were calculated separately for foraging, traveling and porpoise groups determined to be engaged in a combination of traveling and foraging, as well as for control and playback periods. These are summarized in Table 9 and Figure 27. There was no significant difference in either the directivity or deviation index between activity states (Oneway anova, $\text{p-value}_{DI} = 0.80$, $\text{p-value}_{DE} = 0.2$). There was also no significant difference in either the directivity index (t = -0.7, df = 20, p-value = 0.5) or the deviation index (t = 02, df = 20, p-value = 0.8) for tracks collected during control periods compared to those collected during playback periods (Table 9, Figure 27).

Table 8. Summary of harbor porpoise tracks by playback trial. The numbers of tracks are given for each key activity state and also for playback on and playback off periods.

Useable Focal Follows	Spring Trial	Summer Trial	Autumn Trial
Total	40	15	52
Forage	19	5	3
Travel	12	9	40
Travel/Forage	7	1	9
Other	2	-	-
Playback off	37	10	46
Forage	18	5	3
Travel	10	5	36
Travel/Forage	7	-	7
Other	2	-	-
Playback on	3	5	6
Forage	1	-	-
Travel	2	4	4
Travel/Forage	-	1	2
Other	-	-	-

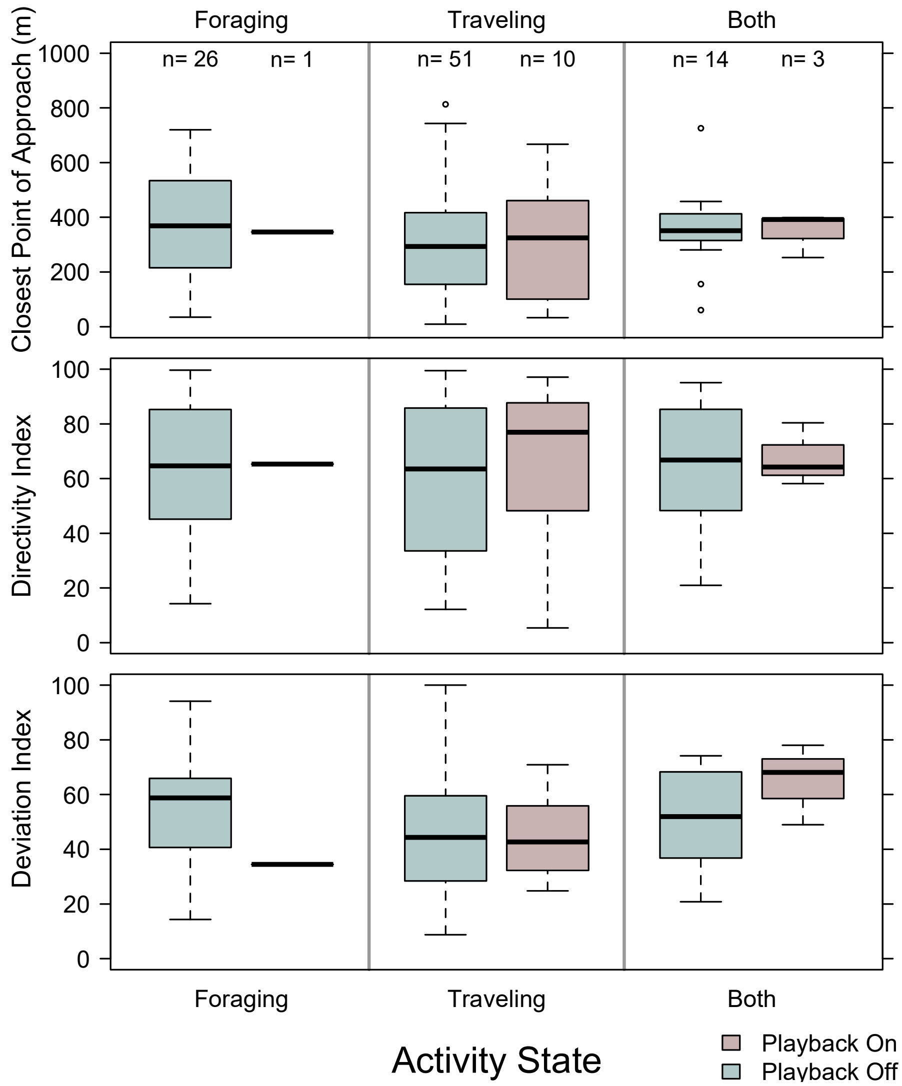

Figure 27. Boxplots for the closest point of approach (top), directivity index (middle), and deviation index (bottom) for harbor porpoise focal follows by group activity state collected the playback was on (red, playback periods) and when the playback off (blue, control periods).

Table 9. Summary of harbor porpoise focal follow data, including closest point of approach, directivity index, and deviation index by porpoise group activity state and playback status.

	N	Closest Point of Approach (m)			Directivity Index			Deviation Index		
		$\bar{x}$	se	range	$\bar{x}$	se	range	$\bar{x}$	Se	range
Activity state										
Forage	27	368	18	35-720	65	2	14-100	55	2	14-94
Travel	61	303	20	9-813	61	23	5-99	47	2	9-100
Travel/Forage	17	354	14	61-726	65	2	21-95	54	2	21-78
Playback										
Off	91	329	19	9-813	63	3	12-100	50	2	9-100
On	14	319	17	33-667	68	2	5-97	49	2	25-78
Forage										
Off	26	369	18	35-720	65	2	14-100	56	2	14-94
On	1	346	-	346-346	65	-	65-65	35	-	34-35
Travel										
Off	51	302	20	9-813	60	3	12-99	47	2	9-100
On	10	307	20	33-667	68	3	5-97	46	2	25-71
Travel/Forage										
Off	14	355	15.3	61-726	65	2	21-95	51	2	21-74
On	3	348	8.0	253-399	68	1	58-80	49	1	49-78

3.5.4 Statistical Models

Statistical model selection resulted in the inclusion of Trial Number, Sighting Time, Current Speed, Playback (on/off) and Water Height (i.e., tidal height above the station datum used by NOAA at their Port Townsend tidal station) in our models. Plots of the probability of sighting (or acoustic detection) for the covariates of sighting time, current speed and water height are provided in Figure 28, Figure 29, and Figure 30, respectively. The results of the GAMMs are provided in Table 10 for harbor seal visual scans,

Table 11 for harbor porpoise visual scans, and Table 12 for harbor porpoise acoustic detections by C-PODs. Water height has a significant effect on harbor seal sightings (Table 10) with a higher likelihood of sighting seals during high tide (Figure 30). Time of day (sighting time) had a significant effect on harbor porpoise sightings (

Table 11), with higher likelihood of sightings occurring in early afternoon and early evening (Figure 28). None of these covariates had a significant effect on porpoise acoustic detections (Table 12).

The effects of trial and playback status (on/off) are explored in Figure 31. Trial number has a significant effect on harbor seal sightings (Table 10) with more harbor seal sightings in Trial 1 compared to Trials 2 and 3 (Figure 31). However, there was no significant effect of playback on harbor seals (Table 10). There were significantly fewer harbor porpoise sighted during Trials 2 and 3 compared to Trial 1 and when the playback was on (

Table 11, Figure 31). The same pattern holds true for harbor porpoise acoustic detections, except that there is a significant interaction between Trial and playback status (Table 12, Figure 31). As for sightings, harbor porpoise acoustic detections are lower in Trials 2 and 3 compared to Trial 1 and in general, detections decrease when the playback is on, except during Trial 3 when acoustic detections increase when the playback is on (Figure 31).

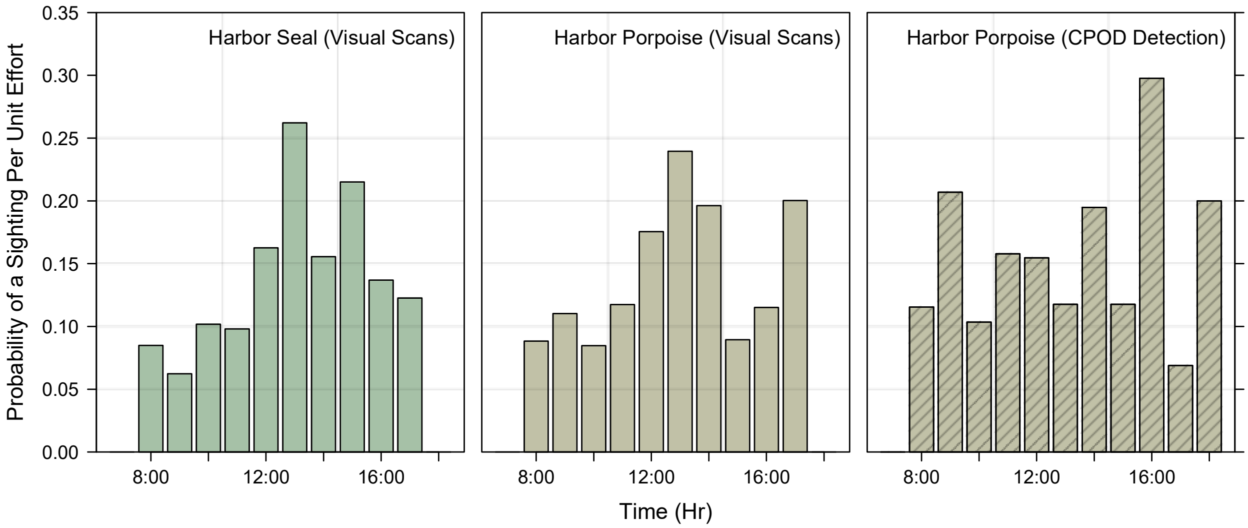

Figure 28. Probability of sighting per unit effort of harbor seals (left), harbor porpoise (middle) and probability of acoustic detection of harbor porpoise (right) by time of day.

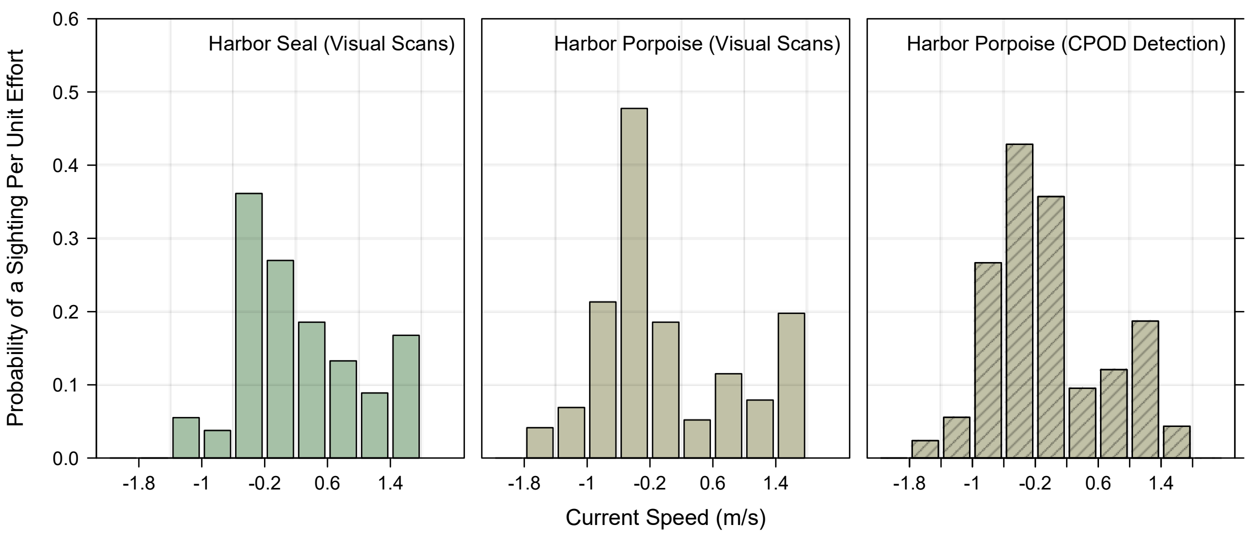

Figure 29. Probability of sighting per unit effort of harbor seals (left), harbor porpoise (middle) and probability of acoustic detection of harbor porpoise (right) by current speed. Negative speeds are ebb currents.

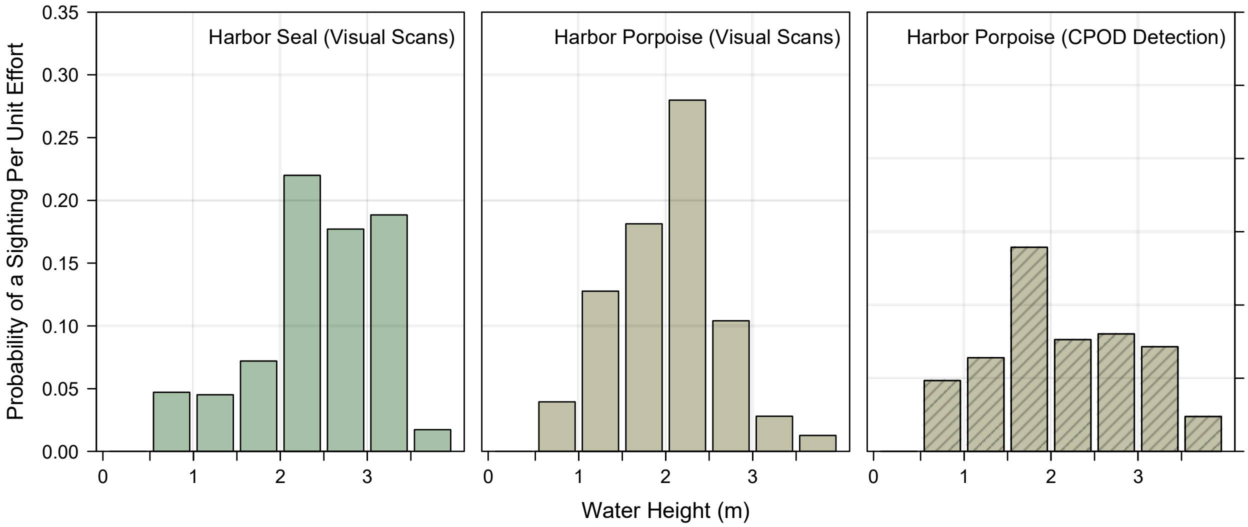

Figure 30. Probability of sighting per unit effort of harbor seals (left), harbor porpoise (middle) and probability of acoustic detection of harbor porpoise (right) by water height above mean lower low water.

Table 10. Results of GAMM for harbor seal visual scans.

linear terms				
Covariate	*Estimate*	*SE*	*t-value*	*P-value*
Intercept	-0.73	0.49	-1.49	0.140
Trial (2)	-2.09	0.32	-6.58	<0.0001
Trial (3)	-1.59	0.29	-5.47	<0.0001
Sighting Time	0.03	0.03	0.98	0.330
Current Speed	0.11	0.11	1.07	0.290
Playback (on/off)	0.01	0.19	0.04	0.970
smoothed terms				
Covariate	*edf*	*Ref.df*	*F*	*P-value*
Water Height	2.14	2.14	20.7	<0.0001***

Table 11. Results of GAMM for harbor porpoise visual scans.

linear terms

Covariate	*Estimate*	*SE*	*t-value*	*P-value*
Intercept	-0.32	0.37	-0.86	0.388
Trial (2)	-0.89	0.37	-2.42	0.021
Trial (3)	-0.8	0.38	-2.11	0.043
Water Height	-0.07	0.14	-0.55	0.584
Current Speed	0.16	0.1	1.66	0.097
Playback (on/off)	-0.66	0.24	-2.71	0.006

smoothed terms

Covariate	*edf*	*Ref.df*	*F*	*P-value*
Sighting Time	4.24	4.24	3.22	0.007

Table 12. Results of GAMM for harbor porpoise acoustic detections (C-POD).

linear terms

Covariate	*Estimate*	*SE*	*t-value*	*P-value*
Intercept	-1.60	0.79	-2.02	0.043
Trial (2)	-0.69	0.56	-1.24	0.224
Trial (3)	-1.80	0.61	-2.94	0.006
Sighting Time	0.06	0.06	1.06	0.289
Water Height	0.05	0.24	0.21	0.833
Current Speed	0.01	0.17	0.08	0.940
Playback (on/off)	-1.95	0.67	-2.93	0.004
Trial (2) * Playback	0.57	0.90	0.64	0.526
Trial (3) * Playback	2.83	0.84	3.36	<0.0001

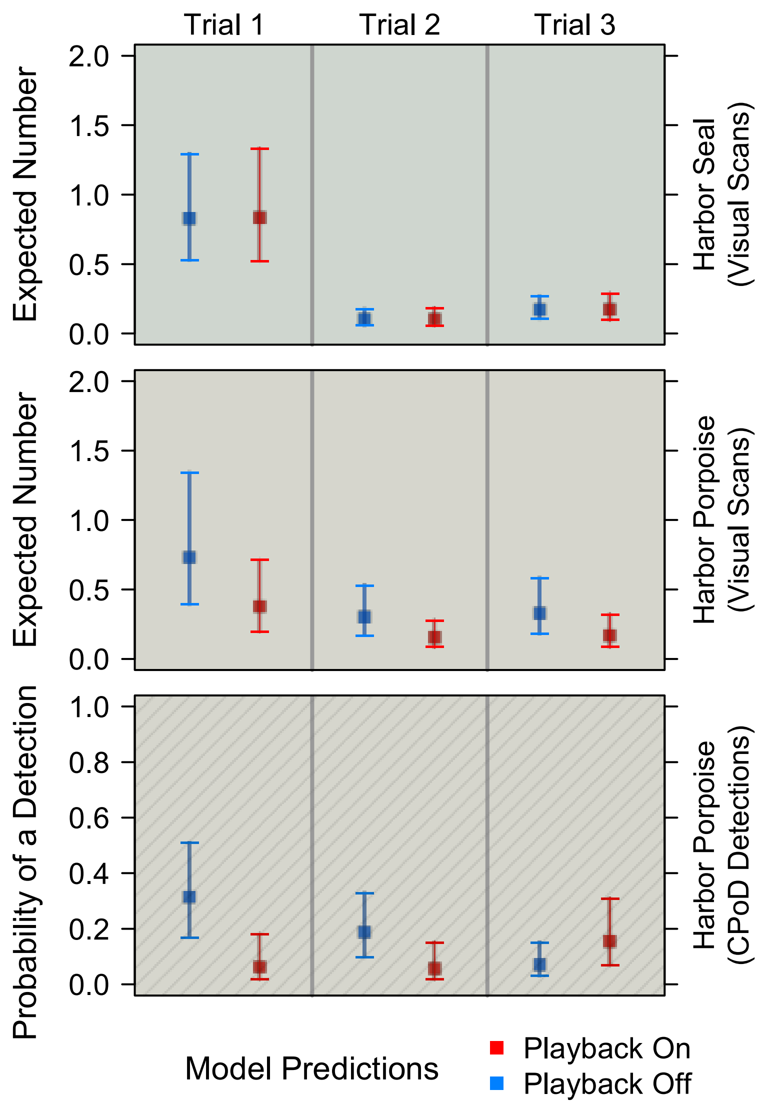

Figure 31. GAMM predictions of the mean and 95% CI by trial and playback status (on/off) for harbor seal visual scans (top), harbor porpoise visual scans (middle), and harbor porpoise acoustic detections (bottom). The predictions assume it is noon, at average current speed, and at average water height.

4 Study Synthesis

4.1 Playback Context

The signal excess model, as applied to animal locations during playback periods are provided in Figure 32. As discussed in Section 2.4.2.3, the 100 Hz band signal excess estimates are likely over-estimates and the 1000 and 4000 Hz band estimates are likely under-estimates on the order of 10-20 dB.

Despite these uncertainties in signal excess model, it appears that the majority of harbor porpoise we observed during playback periods were not surfacing in areas where received levels of simulated turbine noise were of sufficient amplitude to be audible above estimated ambient noise levels. This may indicate that, during Trial 1 and 2, harbor porpoise moved away from the playback source until the sound was no longer audible. This would explain the shift in spatial distribution between the playback and control periods in Trial 1 and Trial 2 that is shown in Figure 26. We further note that, to move away from the turbine sound, harbor porpoise must have been able to detect it underwater, but moved away before surfacing. Harbor porpoise only avoided the region around the playback source while the vessel was on site and transmitting sound from the J11. In other words, porpoise did not systematically avoid this location during both control and playback periods.

Our signal excess model suggests that the majority of harbor seals were exposed to audible turbine sound in the 100 Hz band, but not in the 1000 Hz band. In spite of this exposure, there was no significant effect of turbine noise on harbor seal sightings and no shift in spatial distribution.

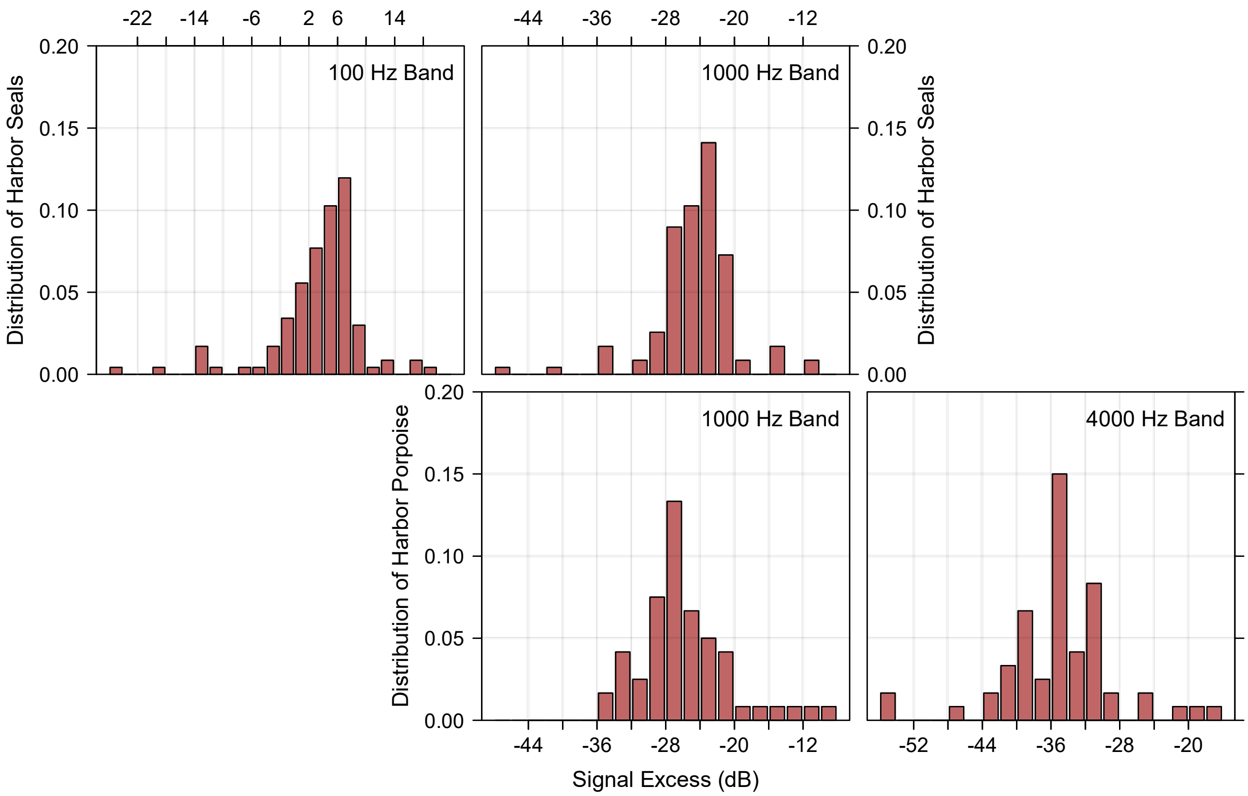

Figure 32. Distribution of estimated signal excess for harbor seals (top) and harbor porpoise (bottom) during playback trials in the 100 Hz (left), 1000 Hz (middle) and 4000 Hz (right) one-third octave bins. Negative signal excess suggests that the turbine noise was not audible to the animal.

4.2 Harbor Seals

Based on the analysis presented in Section 3, we find no evidence of any effect on harbor seals from the turbine noise. This is contrary to the findings of Hastie et al. (2017) who found a reduction in use by seals of areas up to 500 m from the playback source (using GPS tags on 10 animals, rather than scan sampling density). However, similar to this study, scan sampling by Hastie et al. found no effect on overall seal counts within their survey area. There are several potential reasons why we observed no avoidance but Hastie et al. (2017) did. First, the geographic scale of the study sites is dissimilar. Hastie et al. conducted their study in an inlet that is ~450 m wide and generally less than 30 m deep. In contrast, Admiralty Inlet is an order of magnitude wider and, on average, twice as deep. Second, and likely most importantly, there are substantive differences in the simulated turbine sound and acoustic environment (background noise and transmission loss). Hastie et al. (2017) used a turbine sound that is tonal with frequency modulation about the central tones. Our signal had one tonal peak but was otherwise relatively broadband and consistent in the playback frequency range. Hastie et al. (2017) simulated turbine sounds with a broadband source level of 175 dB re 1µPa @ 1 m, consistent with output from the Marine Current Turbine SeaGen, while our simulated turbine sound was 17 dB lower at 158 dB re 1µPa @ 1 m due to limitations on "acoustic take" of marine mammals.

It is difficult to directly compare ambient noise levels between the two study sites given limited information about ambient noise at the Hastie et al. site, but it seems likely that noise levels are higher in Admiralty Inlet. Admiralty Inlet is a major shipping lane and long-term (1 year) acoustic monitoring there reported mean broadband noise levels of 119.2 dB re 1µPa (Bassett et al. 2012). Hastie et al. (2017) do not report any of their own backgrounds but do reference Wilson and Carter (2013) who reported noise levels from drifting measurements at this site ranging from 116 to 137 dB re 1µPa. These measurements were obtained on a single day and may not be representative of long-term trends. Further, Wilson and Carter's frequency bandwidth was wider than Bassett et al. (maximum resolved frequency of 48 kHz vs. 30 kHz) and collisions of fine-grained sediment at the Hastie et al. site may have substantially elevated received levels at frequencies on the order of 10's of kHz.

Transmission loss differences between the two sites are also substantial. In Admiralty Inlet we empirically estimated a transmission loss coefficient that approximately spherical at close range and declining to approximately 17 beyond 200 m. For Hastie et al., based on the reported source level (175 dB re 1µPa) and estimated received level at 500 m from the playback source (~138.7 dB re 1µPa), the average transmission loss is approximately 13, which is consistent with a shallower, reverberant environment. The combined difference in source level and transmission loss between the two studies results in large differences in received levels and, were it possible to compute, signal excess at comparable distances. For example, Hastie et al. estimate median received levels for harbor seals in their study within 500 m to be 142.4 dB re 1µPa, while, at our source level and transmission loss, received levels would drop below this value at a range of less than 10 m from the playback source.

Given the similar standard errors for the covariate 'playback' in both GAMMs for harbor seals and harbor porpoise (0.19 and 0.24, respectively), when that standard error was sufficient to find a significant effect in harbor porpoise, and the above comparison to the Hastie et al. (2017) study, a power analysis was not deemed necessary.

4.3 Harbor Porpoise

Harbor porpoise are known to be sensitive to noise (Southall et al. 2007). Therefore, it is not surprising that we found an effect of turbine sound playback on harbor porpoise, in spite of the source level, transmission loss, and background noise discussed in Section 4.2. During Trial 1, harbor porpoise appear to have avoided an area around the playback location to a distance of 300 m. This avoidance range decreased to 100 m in Trial 2 and there was no apparent avoidance in Trial 3 (Figure 26). In fact, during Trial 3, C-POD acoustic detections indicate a slight attraction of porpoise within the 100 m zone, while the probability of surface sightings were comparable between playback and control periods. There are a number of possible explanations for these changes, including the observed seasonal differences in activity states and group size, as well as the potential for habituation or tolerance to the playback over the course of the three trials.

There were notable differences in the predominant activity recorded for focal follows between the three trials. During the spring survey (Trial 1), the majority of porpoise groups were engaged in active foraging, primarily to the south of the playback source. The proportion of focal follows where travelling was recorded as the predominant activity increased through the summer (Trial 2) and fall surveys (Trial 3), with travel dominating during Trial 3. Group size also varied with season, with larger groups observed during the fall (Trial 3), which also coincided with the largest number of observed calves. While more data would be required to establish rigorous seasonal trends in Admiralty Inlet, it is important to consider the context (i.e., behavioral and seasonal) of an animal when assessing their behavioral response to a potential disturbance (Robertson et al. 2013, Christiansien et al. 2013).

Another explanation to the decreases in avoidance is habituation or tolerance, which would require the same porpoises to be resident in the study area during all three trials. Recent photo identification and site fidelity studies of harbor porpoise in neighboring waters, 20 miles north of the playback study area, suggest some level of residency with 35% of identified animals re-sighted in more than one month (Elliser et al. 2018). In addition, harbor porpoise in Admiralty Inlet appear to have a much greater tolerance for shipping traffic than elsewhere around the world (Bas et al. 2017; Wisniewska et al. 2018), especially given the apparent importance of the area for foraging, as we observed during the spring trials in this study.

We are not aware of any other studies that have published results on tidal turbine playbacks to harbor porpoise, so are not able to compare to other studies. However, it should be noted that the playback vessel was only moored in the study area during playbacks due to budgetary constraints. This means that the response of harbor porpoise could be attributed to the physical presence of the playback boat, or a combination of the turbine noise and the boat. However, given the significant vessel traffic in Admiralty Inlet and frequency of recreational fishing vessels in the nearshore area, a small moored vessel with its engines off seems unlikely to be considered a novel object for harbor porpoises.

The signal excess estimates for all porpoise locations during playback was negative, suggesting that turbine noise should not have been detectable by any harbor porpoise shortly before surfacing. Looking back at the apparent avoidance zone in Trials 1 and 2, we can estimate avoidance thresholds for received levels of turbine sound (Figure 26). At 300 m, the broadband noise in the playback band would have been approximately 110 dB re 1µPa. At 100 m the received level would have been approximately 118 dB re 1µPa. It seems plausible that some porpoise could have reacted to novel noise at these amplitudes, particularly if the turbine sound was continuous, while ambient noise from sediment transport would have temporal variability.

4.4 Extrapolation to Lower and Higher Source Levels

Based on the results of this study and Hastie et al. (2017), it seems plausible that turbines with source levels lower than those used in this study would be unlikely to have an acoustic effect on harbor seals. Similarly, a turbine with broadband source level of 140 dB re 1µPa at 1 m would approach the potential 118 dB re 1μPa porpoise threshold at a range of 10 m and would, therefore, be unlikely to produce observable effects, given the accuracy of photogrammetric location methods. This conclusion is, however, speculative, given the uncertainties discussed in this document. Conversely, more numerous turbines or turbines with higher source levels could have acoustic effects on either species. The results of Hastie et al. (2017) suggest that broadband received levels of approximately 140 dB re 1μPa can lead to a reduction in seal presence, as long as received levels exceed ambient noise levels. The current study suggests that porpoise may respond to received levels as low as 110 dB re 1μPa, but the response could also be related to physical presence of an unfamiliar object (the playback vessel) and may decrease over time. This reduction in dose-response relationship over time has also been observed in studies of harbor porpoise response to offshore wind pile driving (Graham et al. 2018).

5 Lessons Learned

5.1 Simulation of Marine Energy Converter Source

A general challenge to the simulation of marine energy converter sound is the variety of sounds that are possible and that the methods to record and measure them are an area of active research and development. Flow-noise and self-noise contamination often occur and, even when they are mitigated, prototype marine energy converters may not be operating in a "normal" mode when measurements occur (e.g., degraded bearing, misaligned shaft). This makes identification of truly representative marine energy converter sound a difficult problem. While imperfect, the recordings selected for use here are well-understood by the project team and do not require significant subjective assumptions about which parts of the spectrum are associated with the converter versus an ambient source.

Based on successful use in Hastie et al. (2017) and the present study, the J11 seems well-suited to reproducing the frequencies of interest for marine energy converters. Its integration with playback equipment was straightforward, though power consumption requires either a substantial battery bank or generator for multi-hour playbacks.

5.2 Signal Excess

Predicting background noise levels at low frequencies in a dynamic estuary with multiple anthropogenic noise sources is challenging. Validating signal excess models is also a challenge given flow-noise and self-noise contamination in acoustic recordings in these environments. In spite of this, signal excess does provide a first order estimate of audibility in these kinds of studies and does provide valuable context for interpreting results.

The following would be recommended to reduce the observed discrepancies between predicted and measured received levels:

- *Propagation loss modeling for all sources (playback and vessels) to minimize errors associated with empirical propagation loss estimates.* This would be relatively straightforward for the turbine sound playback, since this originated from two locations in the inlet (ebb or flood vessel position), but time-intensive for vessels, given that propagation loss would need to be modeled between each vessel and animal. Further, this would still include uncertainties in vessel source level, which depend on multiple factors (McKenna et al. 2013; Veirs et al. 2016) and transmission loss, which depends on seabed geology and the sound speed profile.

- *Formal inclusion of a model for low-frequency ambient noise in the absence of vessels*. This could be based, for example, on wave parameters (e.g., height, period) and wind speed.
- *Multiple validation points in the survey area*. Deploying multiple co-temporal Sea Spiders instrumented with hydrophones and C-PODs could provide a more robust validation data set and allow propagation loss models to be more readily verified.
- *Inclusion of mechanisms to reduce self-noise and flow-noise*. 100 Hz received levels appear to be biased by flow-noise and self-noise. The former might be mitigated through the use of a flow-shield, though this would require verification that the flow-shield did not attenuate higher-frequency sounds of interest. The self-noise (e.g., strum, contact sounds) observed at low currents during this study may have been a consequence of differences in rigging between this study and prior efforts (e.g., Bassett et al. 2012). Acoustic recordings should be reviewed following each trial to identify potential refinements to minimize self-noise.

5.3 Vantage-point Surveys

Vantage-point surveys proved to be a cost-effective way of collecting surface observations on marine mammals with no disturbance to the animals. These methods obviously only work when visibility conditions are good for viewing both animals and landmarks in the distance. The conversion of sighted animals to usable data (when animal locations are needed) is a multifaceted process in which any failure results in non-usable data. These facets include:

- *Capturing an image of the animal.* A good quality still picture or video is needed of the animal while it is at the surface. This is especially difficult for small marine mammals, but success rates do improve with experience. Therefore, either experienced observers or ones that have gone through adequate training should be used. **Error! Reference source not found.** provides an example of a good quality picture of a porpoise.

Figure 33. Moored playback vessel with individual harbor porpoise. Inset shows enlarged image. Credit: Frances Robertson (SMRU Consulting)

- *Visibility conditions.* Sea state, glare, fog, and smoke from distant forest fires periodically obscured both animals and landmarks during this study. Some of these conditions are more predictable and is why we did not attempt a winter trial period. These challenges can be overcome by longer observation periods or, when possible, flexible scheduling around poor visibility periods. However, this if often not possible given the logistics of scheduling both personnel and boats.
- *Landmark availability.* A minimum of two landmarks are needed to estimate the location of animals. Ideally the playback location would line up with the vantage-point station and the landmarks in the distance such that sighted animals could be localized across the area of interest. This was not the case in this study. Figure 23 clearly shows this. The north end of our harbor porpoise locations forms a straight line from our vantage-point station to our most northerly landmark. Although harbor porpoise and harbor seals were sighted to the north of the locations shown in Figure 22 and Figure 23, we could not estimate their locations as there were no landmarks beyond their locations (the horizon was open water). **Error! Reference source not found.** in the Appendix shows a harbor porpoise that was localized near the northern extent of our available landmarks. Two landmarks are visible (a lighthouse and radar antenna), but if the porpoise were further to the right (north), landmarks would not have been visible. When possible, the geometry of the vantage-point station, playback location and landmarks should be carefully planned. However, many sites will have a limited number of feasible vantage points.

It was also clear that it is important to conduct location measurements in the study area of objects of known location. This allows the validation of software, techniques and landmarks. During this validation, different combination of landmarks should be tested to weed out landmarks that consistently lead to poor location estimates.

5.4 Strengths and Weakness of Playback Studies

There is an inherent strength to playback studies in that the study can be conducted as a controlled experiment which presents only the stimulus of interest (such as a turbine sound), although, due to budgetary constraints, the presence of the playback vessel could not be controlled for by keeping it moored during control periods in this study. This provides more control over when and how the study is conducted and therefore also allows more control of confounding variables that are of no interest.

However, the cost of generating the playback signal is substantial. In Hastie et al. (2017), several factors minimized this cost. First, surveys were conducted in a single season, which allowed them to leave the mooring in place for the entirety of the survey, rather than recovering and redeploying it. Second, the playback support vessel was positioned outside the region of peak current flow, allowing a lighter-weight mooring to be used, further reducing deployment and recovery cost. Third, because their site was not an active shipping channel and the playback vessel was moored in an area of weak currents, the playback vessel did not need to be continuously crewed and playbacks could be remotely enabled and disabled from shore. These factors did, however, mean that seasonality and longer-term habituation could not be established and received levels in the channel would be substantially different for a turbine deployed in the high-current region. This may be important, since, as shown in our study, harbor porpoise and harbor seal use of the channel are not uniform.

In the present study, we chose to co-locate our playback source with the probable location of a turbine. The larger scale of Admiralty Inlet and flow intensification around the headland means that it would be generally impractical to moor the playback vessel in low-current water and achieve relevant received levels in the high-energy portion of the channel.

Ideally, playbacks would be conducted from a sub-surface mooring consisting solely of the J11, power amplifier, and batteries. This would eliminate the presence of the support vessel as a potentially confounding factor. However, this would require a substantial amount of non-recurring engineering effort to develop a reliable system ($0.5 - $1.0 M) and would further increase operational costs since the system would need to be recovered daily to recharge the battery bank. Consequently, “vessel-free” playback appears impractical in most circumstances of interest.

5.5 Study Costs

Table 13 summarizes the study costs by major activity. In addition, vantage point surveys have a fixed equipment cost of approximately $9k (camera, binoculars, tripod) and a fully-instrumented Sea Spider platform has a fixed equipment cost of approximately $80k. While the majority of the per survey costs are dedicated to observations of marine mammals and analysis of these data, provision of the playback source for this type of environment is substantial, constituting over 1/3 of the costs.

Note that these costs also assume that all marine operations go to plan. During our surveys, on one occasion, a Sea Spider could not be recovered by normal means due to binding of its recovery line and a marine construction firm was contracted to recover the platform by ROV for a cost of $20k. Contingencies for these types of situations should be considered when developing a survey plan.

Table 13. Study cost summary on a per survey basis

Study Element	Cost ($k)	%
Vantage Point Survey	**55**	**47**
Data Collection Supplies and Equipment	9	8
Data Collection Effort	37	31
Data Transcription and Quality Assurance	9	8
Playback	**40**	**34**
Transducer Lease (J11)[4]	2	1
Vessel Lease	3	3
Mooring Deployment & Recovery	20	17
Sea Spider Consumables	1	1
Crew Costs (playback period only)	14	12
Synthesis and Analysis	**23**	**20**
Total	**119**	**100**

6 Conclusions

Harbor seals and harbor porpoise were the most commonly seen marine mammal in our study area, and the focus of our efforts. This playback survey suggests that for turbines with broadband received levels less than 160 dB re 1 μPa that are deployed in locations where propagation loss is well-described by practical spreading, no avoidance or attraction as a consequence of underwater sound alone are likely to be observed for harbor seals. These results are consistent with outcomes from prior research. Under similar caveats, avoidance may be observed for harbor porpoises to a range of 300 m, though there are indications that this declines over time or varies with season and activity state.

The methodology used in this study was effective at determining acoustic effects of simulated turbine sounds on harbor seals and harbor porpoise, though the cost is high enough that we would not recommend conducting playbacks as a typical pre-installation activity for tidal or ocean current energy projects. Given the number of observations required to draw conclusions, this methodology could not be feasibly used to establish likely attraction or avoidance for rarely-occurring species, such as those listed as Threatened or Endangered. Results also emphasize the importance of spatial heterogeneity and seasonal variability in animal use and behavior at tidal energy sites.

Given the consistency of these results with similar research, this study adds to the evidence base required to understand acoustic risks and either retire or mitigate them.

[4] For our study, transducer lease cost was $5k for 12 months. Lease cost may be proportional to duration.

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9 Appendix

Table 14: Third Octave Source Levels (dB re 1µPa @ 1m) from Veirs et al. 2016 and used in the signal excess model.

Ship Type	TOL 100 Hz	TOL 1000 Hz	TOL 4000 Hz
All	159.6	157.4	153.2
Vehicle carrier	161.6	159.6	155.6
Container ship	162.7	162.7	158.5
Bulk carrier	158.9	154.7	150.8
Cargo	162.2	158.7	154.1
Tug	153.4	156.1	152.5
Fishing	147.7	155.0	149.5
Tanker	162.0	157.6	153.4
Military	144.4	154.5	151.2
Passenger	153.9	153.4	149.9
Miscellaneous	148.1	153.9	149.9
Research	151.2	156.7	149.9
Pleasure craft	143.7	148.4	148.6

Table 15: Summary of marine mammal scan sampling and focal follow data collected, including codes and definitions.

	Category	Code	Explanation
Species	**Harbor seal** **Steller sea lion** **California Sea lion** **Harbor porpoise** Killer whale Minke whale Humpback whale Pacific white-sided dolphin Dalls porpoise **Hybrid porpoise** **Unknown porpoise** Unknown toothed whale Unknown baleen whale	**HS** **SS** **CS** **HP** KW MW HW PWD DP **HP** **UP** UTW UBW	Species codes. The focal species that data will be collected on are highlighted in bold. Killer whale and baleen whale species require mitigation (i.e., the playbacks must be shut down when they are sighted approaching or in the study area).
Group size	1+		
# pups/calves	1+		Number or pups/calves in group
Activity	Feed	FE	Observed feeding/evidence of feeding – e.g. birds present
	Travel	TR	Moving in a steady direction at fast to moderate pace
	Socialize	SO	Often involving surface active behaviors & more than one animals
	Rest	RE	Animal motionless at surface/on land
	Mill	MI	Moving slowly but in no general direction, net movement is zero
	unknown	UK	Activity is not discernable or not recorded
Behavior	Swimming	SW	Animal seen swimming at surface –includes short dives between blows preceding a long dive. Not SA, LO, BL, DIV
	Diving	DIV	Animals submerges below surface for period of time
	Changing course	CH	Animal changes direction while swimming
	Surface active	SA	Splashing, fluke/flipper slaps, jumping/breaching out of water
	looking	LO	Animals look above surface of water, includes spyhopping
	Unknown	UK	Cannot determine or not recorded
	Blow	BL	Whale exhales
	Fluke-out dive	FO	Animals dive with flukes-out
	Hauled out	HO	Hauled out on land –pinnipeds only
	Other	OT	None of above, describe in comment
	Dead	DE	Note condition and location of animal
Heading	North Northeast	N NW	General direction of movement

	Category	Code	Explanation
	Northwest South Southeast Southwest East West	NE S SE SW E W	
Speed	Slow Moderate Fast Not moving	S M K N	Moving slowly, no wake seen Moving at moderate pace Moving fast, includes rapid dives, Animal is stationary – implies resting
Compass reading/bearing			
For Porpoise track			

- Start time of track
- Group size +1
- Calf presence
- Activity (see above)
- Heading (see above)
- Compass reading
- Surfacing (record audio cue for each surfacing, e.g. 'up')
- End time of track

Table 16: Summary of environmental data collected at the start and end of each scan.

Category	Scale
Sea State	Beaufort Scale, stop observations if sea states exceed BF 2.
% Cloud cover	% cloud over study area
% Glare	% glare obscuring the waters surface in each half of the study area.
Visibility: (An overall sightability score that is a subjective measure combining Sea State, %Glare and how visible landmarks are. If BF >2, Glare >50% and >1/2 the landmarks are hard to see observations would cease.)	Vis 1 – *BF0, Glare 0%, all landmarks clearly visible.* Vis 2 – *BF 1, Glare <10%, slight haze* Vis 3 – *BF 1-2, Glare >10%, <1/2 landmarks hard to distinguish on far shore*. Vis 4 – *BF >2, Glare > 50%, >1/2 landmarks hard to distinguish on far shore.*