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A Method for Preliminary Assessment of the Masking Potential of Anthropogenic Noise to Baleen Whale Calls

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Abstract

Models of cetacean communication range reductions associated with anthropogenic noises are complex. They often require assumptions related to the hearing abilities and vocalization source levels of the species concerned. The maximum range of a call is limited by transmission losses which reduce the signal amplitude until it is masked by ambient noise. We propose a simple method to estimate the proportional reductions in communication range associated with anthropogenic noise sources, relative to the maximum range under ambient noise-level conditions, that can be calculated using only noise-level measurements and is independent of the hearing sensitivity of the species concerned. The remaining communication range (% of maximum) = $10^{-\Delta/k} \times 100$ where Δ is the dB difference between the anthropogenic noise level and the ambient noise level while assuming a spreading loss of $k\log_{10}$(range). This enables indexing the remaining communication ranges and, by observation of plots of the data, identifying duty cycles associated with anthropogenic noises. The proposed method was tested with the analysis of underwater ferry noise in a baleen whale habitat in the Bay of Fundy, Canada. The relative communication range and duty cycle were estimated using data from autonomous underwater recorders. Three one-third octave band levels at the same frequencies as vocalizations of the local mysticete species were analyzed. Calls at 20 Hz would not be masked by ferry noises. Calls at 125 and 500 Hz would have severely reduced communication ranges for eight one-hour periods per day when the ferries were operating. Collection and analyses of only noise-level data are faster and much less expensive than more sophisticated studies. Computing remaining communication range analyses may be a useful first step in identifying and ranking anthropogenic noise sources and their potential for animal communication masking.

Key Words: remaining communication range, ambient noise, masking, vessel noise, duty cycle, baleen whale communication

Introduction

Every summer, fin (*Balaenoptera physalus*), minke (*Balaenoptera acutorostrata*), humpback (*Megaptera novaeangliae*), and right (*Eubalaena glacialis*) whales feed in an area to the north and east of Grand Manan Island in the Bay of Fundy, Canada. In this region, underwater noise is produced by commercial shipping, fishing, and other small boat activities. Comprehensive studies of underwater noises and baleen whale communication masking issues have been conducted in a few locations (e.g., Clark et al., 2009; Parks et al., 2009; Hatch et al., 2012; Erbe et al., 2016). Communication space models can be computationally complex, often employing large datasets and estimates related to detection thresholds and related hearing attributes. These may include source levels and frequencies of the calls; ambient noise levels; bathymetry; sound speed profiles; sea floor sedimentation characteristics; transmission loss characteristics; and the source levels, frequencies, and distances of noise sources, among other features (Clark et al., 2009; Farcas et al., 2016; Putland et al., 2018). In areas where such information is lacking, a less expensive preliminary survey that would identify the potential masking and duty cycles of anthropogenic noise to mask cetacean calls would indicate if undertaking an expensive detailed study is warranted.

Additionally, it is currently not possible to directly measure the impact of anthropogenic noise masking on baleen whale communication systems because there are few estimates and no direct measurements of their hearing sensitivity (i.e., audiograms; but see Southall et al., 2019). Furthermore, there is little or no information related to baleen whale hearing features such as critical ratios, temporal integration times, comodulation masking release, or spatial release from masking (Erbe et al., 2016).

Clark et al. (2009) define "bioacoustic space" as "the effective 3-dimensional space over which bioacoustic activity occurs" (p. 203). However, there is some confusion with the term "space." For some authors, space is a distance (range; Putland et al., 2018); while, for others, it can be an area (Clark et al., 2009). To avoid confusion and because some studies may be conducted in coastal areas or between islands where the sampling area is not circular, in the present study, we present the calculations of remaining communication range (% of maximum) as the range at which a signal could be detected referenced to the maximum range of detection under low ambient noise levels.

In the case of acoustical communication, a call will be perceived until the transmission losses reduce the received level to a point where it is masked by the ambient noise or it reaches below the detection threshold of the receiver (Møhl, 1981). Therefore, increases in ambient noise levels will reduce the communication range. Sufficient data are often not readily available to assess the communication range reduction, or listening range reduction, of anthropogenic noise on a species or population. Using noise-level measurements alone, it is possible to determine if noise masking could be occurring and, if so, its relative magnitude and duty cycle (Møhl, 1981; Barber et al., 2009; National Park Service, 2010).

The amplitudes of calls or other sounds that would be important to the receiver will decrease over the range based on the transmission loss in the region. In cases of spherical spreading, the received call amplitude will decrease by 6 dB with every doubling of the distance from the source. Thus, for a call whose range is limited by ambient noise, a 6 dB increase in noise reduces the range over which the call can be heard by 50%. For example, if a call with a source level of 170 dB re 1 µPa at 1 m has a maximum communication range of 100 km when the ocean is very quiet, that range will be reduced to 50 km if the ambient noise level is increased by 6 dB.

The equation to calculate the proportional range reduction is

$$\text{remaining communication range} = 10^{-\Delta/k} \quad (1)$$

where Δ is equal to the signal level (dB) above the ambient noise level, and k is the constant related to the spreading loss (spreading loss = $k \times \log_{10}$(range); Jensen et al., 2009). By definition, the lost listening range (Barber et al., 2009) is equal to 1 minus the remaining communication range.

In the presence of an anthropogenic noise source, the remaining communication range relative to the maximum range under ambient noise-level conditions can be calculated using only noise-level measurements and is independent of the hearing abilities of the species concerned as will be shown. This approach has the advantage of simplifying the many factors that contribute to the distribution of the ranges over which calls, or other sounds, can be recognized by the receivers. These factors are all included and assumed to present consistent distributions over time within a geographic region. Thus, it will be possible to use the remaining communication range associated with anthropogenic noise to identify when masking of baleen whale calls may occur and to indicate the potential duty cycle of that masking.

One important aspect of the present approach is determining the ambient noise levels to be used in the analyses. The long communication range calculations for baleen whales (Payne & Webb, 1971) assumed very quiet ambient noise levels, potentially at the quietest ambient levels described by Wenz (1962). Quiet ambient noise levels can be approximated by determining the 5th percentile (95% of the levels are higher than this value) of the noise levels overall where the measurements are taking place. Such measures could be made over long periods (e.g., months) or other temporal durations. Measuring the 5th percentile of the ambient noise levels on a daily basis would take the impact of natural noise variation associated with storms into account. In their study, Møhl (1981) used the mean ambient levels recorded when no anthropogenic activity was occurring within the study area.

The goal of this study was to determine if remaining communication range calculations would provide a useful tool to identify the duty cycle of anthropogenic noise and its potential interference with the ranges of baleen whale acoustical communication in a region. As an example of the method proposed herein, remaining communication ranges were calculated at two locations. We used the model to determine if it would be possible to identify anthropogenic noise sources that might reduce cetacean communication (and listening) ranges and to estimate the duty cycle in a specific location.

This study examines the advantages and disadvantages of a simple and less expensive analysis technique to consider baleen whale communication masking in the presence of shipping noise. It does not present a detailed analysis of the masking potential of underwater noises in the study area.

Methods

Data Collection

An icListen HF® autonomous recorder (Ocean Sonics Ltd., Truro Heights, Nova Scotia, Canada) was deployed at 44.95206° N, 66.80949° W, 1 m above the bottom, 83 m deep, in the Bay of Fundy, Canada (Figure 1). Fin, humpback, and minke whales regularly frequent this area, and right whales were seen closer to Grand Manan Island (K. Miller, pers. comm., January 2016). The recorder was 1.5 to 3 km from the ferry crossing route from Blacks Harbour, New Brunswick, to Grand Manan Island as determined using AIS locations of the ferry track routes (Marine Traffic, 2017). The recorder was deployed between 31 May and 31 October 2015. To avoid problems with recording the noise of the boat used to deploy and recover the recorder, only data without this noise from complete days (midnight to midnight) were used in the analyses. There were data gaps when the recorder was recovered for data downloading and battery replacement. A sampling rate of 32.0 kHz, 24 bits, was used, and wav files were recorded for 2 min every 10 min for up to 4 wks at a time. Typically, a single ferry (*Grand Manan Adventure*, Ro-Ro/Passenger ferry, IMO 9558103, 6,580 gross tonnage, average speed 15 kts [Marine Traffic, 2017]) operated throughout the study. A second ferry (*Grand Manan V*, Ro-Ro/Passenger ferry, IMO 8902591, 3,833 gross tonnage, average speed 14 kts [Marine Traffic, 2017]) also operated from 23 June to 20 September. One or two ferries (operating in opposite directions along the route at the same time) made eight trips per day. Each trip took ~1.5 h, and the ferries departed every 2 h between 0730 and 1730 h and then 15 min earlier for each of the last two crossings.

A second icListen HF® autonomous recorder was deployed 1 m above the bottom, 25 m deep, in Passamaquoddy Bay (45.01750° N, 67.01833° W) between 26 May and 28 October 2015 (Figure 1). The recorder sampling rate was 32.0 kHz, 24 bits, with a duty cycle of 2 min every 10 min. This site was 18 km from the Bay of Fundy location but on the other side of Deer Island. Deer Island blocks the entrance to Passamaquoddy Bay except for narrow passages at the northeast and southwest ends of the island. This location was chosen so that noise measurements in a location with less vessel noise could be made under the same wind and weather conditions as the first site in the Bay of Fundy. The sampling dates and recording times at the two locations overlapped, except for a few days when either or both devices were taken ashore to download data and replace batteries.

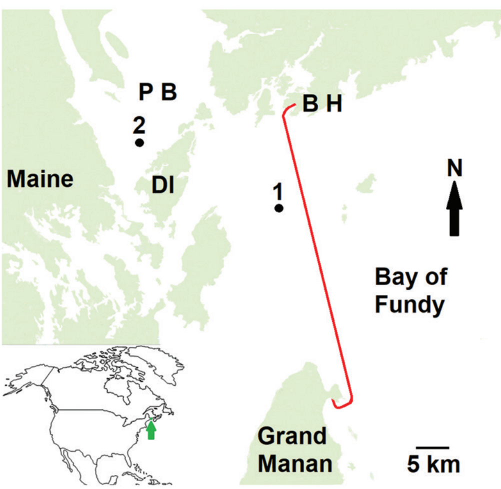

Figure 1. The study area showing the recorder locations: #1 at the Bay of Fundy site and #2 at the Passamaquoddy Bay (PB) site. The nominal ferry route from Blacks Harbour (BH) to Grand Manan Island is shown as a red line. Deer Island (DI), New Brunswick, is between the two recorder locations.

Acoustic Analyses

The wav files were analyzed with *NoiseLAB® Capture*, Version 4.0.4, and *NoiseLAB® Batch*, Version 4.0.1 (Delta, Hørsholm, Denmark) using 1/3 octave band, linear, 10 to 16,000 Hz settings. The mean level of each 2-min wav file was determined with the limitation that the first second of each file was not included in the analysis. The system was previously calibrated using recordings of known signal levels on the icListen. Three representative frequency bands were selected for analysis: 20, 125, and 500 Hz. The 20-Hz 1/3 octave band was selected because it has the same frequency range as the 20-Hz contact calls of fin whales (Weirathmueller et al., 2013). The 125-Hz 1/3 octave band was selected because various right (Parks et al., 2009) and minke (Risch et al., 2013) whale calls are around this frequency and because it is one of the preferred indicator frequencies to monitor underwater noise levels (Van der Graaf et al., 2012). The 500-Hz 1/3 octave band was selected because some humpback whale (Au et al., 2006) calls are in this frequency range.

At the Bay of Fundy location, the communication range reductions at 20, 125, and 500 Hz, using three ambient noise levels—(1) the 5th percentiles of the entire deployment period, (2) the 5th percentiles of daily measures (to help account for seasonal variations in noise sources and levels), and (3) the mean of measures at times with no ferries operating—were examined. As a simple example of an absence of a regular anthropogenic noise source, the remaining communication ranges in Passamaquoddy Bay were calculated at 500 Hz using the mean ambient noise level with no ferries found operating in the Bay of Fundy.

The equation used to calculate the % of remaining communication range assumed a spherical spreading loss of $20\log_{10}(\text{range})$ so

$$\text{remaining communication range (\% of maximum)} = 10^{-\Delta/20} \times 100 \qquad (2)$$

where Δ is the number of dB the noise level was above the ambient noise level.

Statistical Analyses

The 1/3 octave band level measurements were added to a spreadsheet that also included time of day, day of year, and operation times of the ferries. Spearman product-moment correlations between the 20, 125, and 500 Hz noise levels recorded at the same time were calculated. The daily patterns of the mean noise levels over the study period were calculated for the three frequencies using the 144 recordings made each day. A single series Fourier analysis was performed on the longest series of consecutive days of recordings to determine if there was evidence of a daily or tidal component contributing to the recorded noise levels (either via a water current impinging on the hydrophone or gravel being swept along by the current).

The remaining communication range percentages were calculated for the three 1/3 octave band noise levels from the Bay of Fundy using each of the three ambient noise levels. When any noise levels of the 2-min recordings were below the ambient noise level at that time, the remaining communication range calculations exceeded 100%, and they were manually changed to 100% prior to any further analyses.

One-way ANOVA was used to assess if the presence or absence of the ferry traffic had an impact on the remaining communication ranges for the three frequency bands and each of the three reference ambient noise levels. The mean values of the remaining communication ranges for each of the 144 samples per day per frequency and ambient noise-level assignment were graphed for visual analysis. The remaining communication ranges (% of maximum) were calculated for the 500 Hz dataset from the Passamaquoddy Bay site using the Bay of Fundy site's mean overall ambient noise level when the ferries were not operating.

Results

Bay of Fundy Site

The Bay of Fundy recorder was operational for 127 d (on days in the year 152 to 175, 188 to 210, 218 to 258, and 262 to 300 inclusive) during the 5-mo sampling period. There were 9,468 2-min recordings when the ferries were not running and 4,098 when one, or 4,722 when two, were operating. The Fourier analysis of 41 consecutive days identified a pronounced 24 h cycle in the 125 and 500 Hz sound levels but only a slight 24 h cycle in the 20 Hz band. There was no evidence of a tidal cycle at any of the three frequencies.

The daily 5th percentile ambient noise levels ranged between 66.6 to 83.6, 64.3 to 82.5, and 60.4 to 89.3 dB re 1 μPa (1/3 octave bandwidth) at 20, 125, and 500 Hz, respectively. The largest difference in daily 5th percentile ambient noise levels between consecutive days was 12.9 dB at 20 Hz, 10.3 dB at 125 Hz, and 20.2 dB at 500 Hz. The 5th percentile ambient noise levels over the entire deployment period of the three frequencies using the entire dataset were 72.7, 71.5, and 68.2 dB re 1 μPa (1/3 octave bandwidth) at 20, 125, and 500 Hz, respectively. The mean overall noise levels measured when the ferries were not running (but other boats and ships were occasionally in the area) were 87.0, 82.5, and 82.4 dB re 1 μPa (1/3 octave bandwidth) at 20, 125, and 500 Hz, respectively (Figure 2).

The mean noise levels throughout the day for each of the three frequencies at the Bay of Fundy site are shown in Figure 3. The eight peaks in the noise levels reflect the passages of the ferries near the recorder location. It appears that the *Grand Manan Adventure* produced higher noise levels than the *Grand Manan V*. The 1st, 3rd, 5th, and 7th noise peaks at 125 and 500 Hz have a small peak when the *Grand Manan V* was closest to the recorder that is followed by a larger peak 30 min (3 samples) later when the *Grand Manan Adventure* was closest to the recorder. Similarly, the 2nd, 4th, 6th, and 8th peaks have a much smaller second peak. The larger peak matched the time when the *Grand Manan Adventure* was closest to the recorder and the second, smaller peak was when it was farther away.

At the 20-Hz 1/3 octave band, the ferry noise was only reducing the percentage of maximum communication range when the ferry was close to the recorder (Figure 4). There are statistically significant differences in the remaining communication range with and without ferry traffic when the calculation used daily ambient 5th percentile noise levels ($F_{1, 18{,}286} = 14.80$; $p = 0.001$) or the overall 5th percentile noise levels ($F_{1, 18{,}286} = 15.04$; $p = 0.0001$). There are no differences between the remaining communication ranges at 20 Hz (calculated using the mean ambient level with no ferries operating) with and without the ferry traffic ($F_{1, 18{,}286} = 1.3$; $p = 0.26$).

The 125-Hz 1/3 octave band ferry noise was reducing the percent of maximum communication range throughout most of the run (Figure 4). There are statistically significant differences in the remaining communication ranges with and without ferry traffic when the calculations used the daily ambient 5th percentile noise levels ($F_{1, 18{,}286} = 4{,}191$; $p < 0.0001$), the overall 5th percentile noise levels ($F_{1, 18{,}286} = 3{,}972$; $p < 0.0001$), and the mean noise levels measured when no ferries were running ($F_{1, 18{,}286} = 3{,}893$; $p < 0.0001$).

The 500-Hz 1/3 octave band ferry noise was also reducing the percent of maximum communication range throughout most of the run (Figure 4). There are statistically significant differences in the

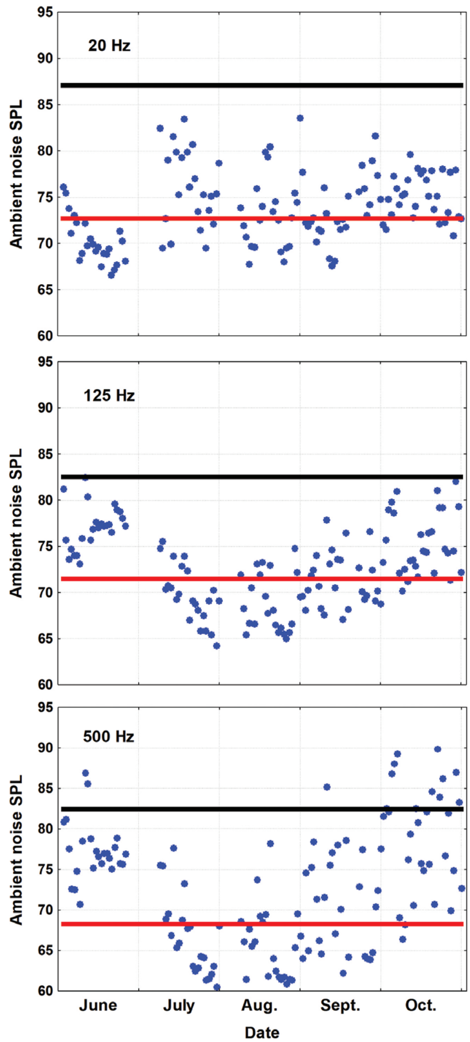

Figure 2. Ambient noise sound pressure levels (SPLs, dB re 1 µPa, 1/3 octave band) centered at 20, 125, and 500 Hz recorded in the coastal Bay of Fundy that are used in the remaining communication range calculations. The upper horizontal line (black) is the mean noise level recorded when the ferries were not running, the lower horizontal line (red) is the overall 5th percentile ambient noise level, and the individual data points are the daily 5th percentile ambient noise levels.

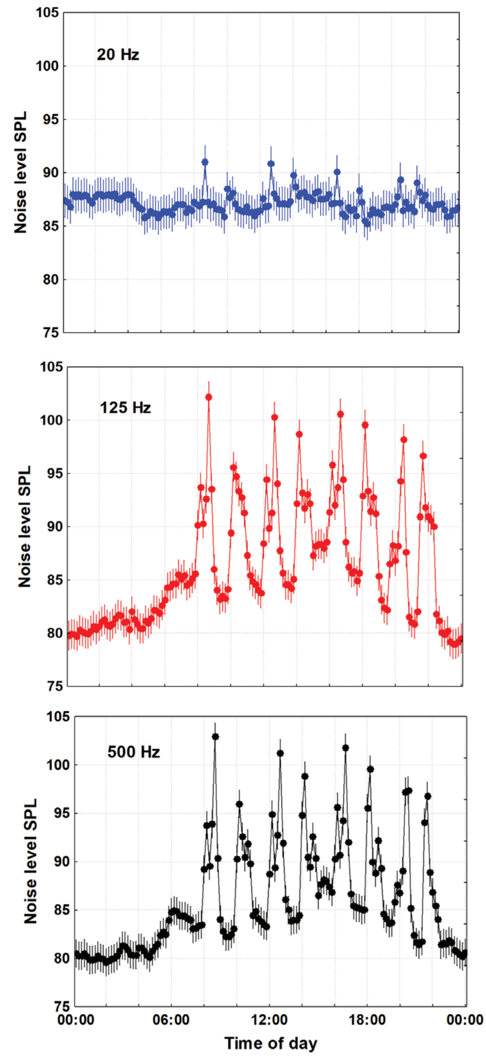

Figure 3. Mean noise levels (± 95% confidence levels, dB re 1 µPa, 1/3 octave band) in the coastal Bay of Fundy of the 1/3 octave bands centered at 20, 125, and 500 Hz of each of the 144 samples per day.

remaining communication ranges with and without ferry traffic when the calculations used the daily ambient 5th percentile noise levels ($F_{1,\ 18,286}$ = 2,325; $p < 0.0001$), the overall 5th percentile noise levels ($F_{1,\ 18,286}$ = 3,495; $p < 0.0001$), and the mean noise levels measured when no ferries were running ($F_{1,\ 18,286}$ = 3,912; $p < 0.0001$).

Ferry noise at 125 and 500 Hz was a major contributor to reducing the communication range while it was occurring. The duty cycles of the ferry noises were determined using visual inspection of the data plots. The first few and last few measures while the ferries were operating had little impact on the remaining communication ranges because the ferries were behind headlands and most distant from the recorder when close to port (Figure 4). The communication range reductions at 125 and 500 Hz (Figure 4) also indicate that there were

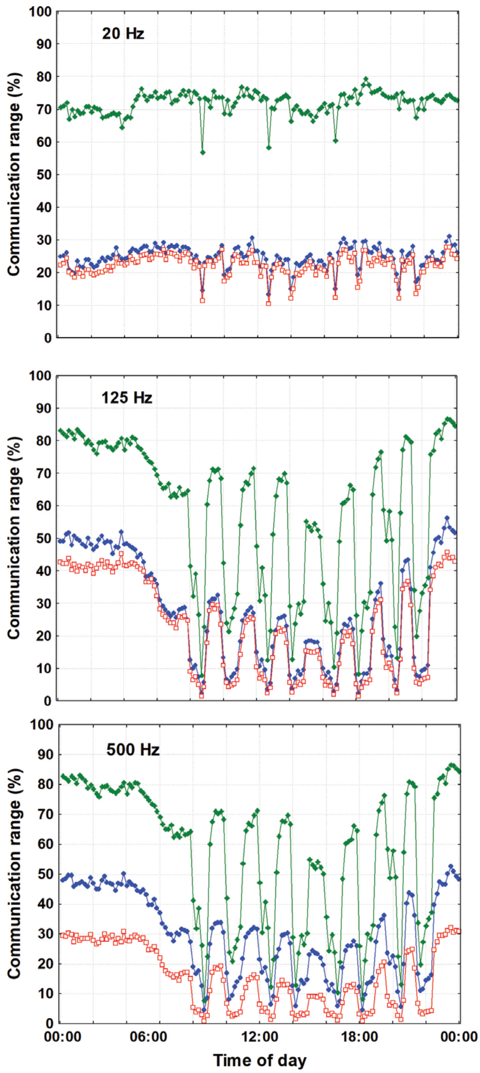

Figure 4. Remaining communication range (% of maximum) in the coastal Bay of Fundy per time of day for the 1/3 octave bands at 20, 125, and 500 Hz under three ambient noise-level situations: (♦) mean ambient noise level with no ferries operating, (●) daily 5th percentile levels, and (□) overall 5th percentile levels. The 95% confidence intervals have been removed for clarity and all were below 10.4%.

other noise sources (e.g., fishing boats, whale-watching boats, pleasure craft, etc.) during the day. The noise levels from other sources increased after 0600 h, were highest around 1500 h, and then decreased by 2100 h.

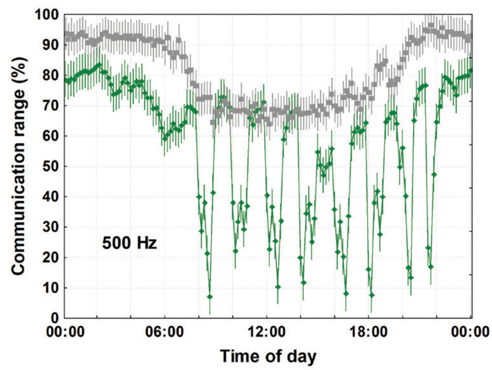

Figure 5. Remaining communication range (% of maximum) at 500 Hz per time of day at the Passamaquoddy Bay site (■) and the Bay of Fundy site (♦). Both were calculated using the Bay of Fundy mean ambient noise level with no ferries operating. The error bars indicate 95% confidence intervals.

Passamaquoddy Bay Site

The Passamaquoddy Bay recorder was operational for 130 full days (on days in the year 147 to 173, 178 to 198, 214 to 256, and 262 to 300 inclusive) during the 5-mo sampling period. Vessel traffic in the area was predominantly imputed to small boats associated with fishing or tending aquaculture cages, whale-watching tours, and a few cargo ships.

The remaining communication ranges at the Bay of Fundy site and the Passamaquoddy Bay site, calculated at 500 Hz using the mean noise level (82.4 dB re 1 μPa [1/3 octave bandwidth]) are shown in Figure 5. The higher noise levels between 0600 and 2000 h reflect the increase in small boat traffic in Passamaquoddy Bay. Throughout the day and night, the noise levels were lower than those at the Bay of Fundy site which resulted in relatively higher remaining communication ranges. No regularly occurring anthropogenic noise source was identified at the Passamaquoddy Bay location.

Discussion

Baleen whales have long-range communication abilities, especially at low frequencies where sound absorption is low (Richardson et al., 1995; Širović et al., 2007). It is possible that evolution and the natural noise levels in the ocean have limited the sensitivity of the hearing systems of baleen whales to be just above the quietest ambient levels (Payne & Webb, 1971). In the case of long-range acoustical communication, the maximum range will be limited by ambient noise levels, or under extremely quiet conditions, the hearing sensitivity of the receiver. It is assumed that under quiet conditions, the communication range is at a maximum and that the range will be reduced by increases in the ambient noise levels (Møhl, 1981; Barber et al., 2009). This approach has the advantage of simplifying the myriad factors that contribute to the distribution of the ranges over which calls, or other sounds, can be recognized by the receivers. These factors are all included and assumed to present consistent distributions over time. Thus, it will be possible to use proportional reductions in the maximum communication range to index the duty cycle and assess the masking effect of increased anthropogenic noise levels on baleen whales. Because of uncertainties in the masking effect of various noise sources and their relationship with the nature of the calls that are of interest, calculations of the remaining communication range (% of maximum) will only serve to index when masking may occur and indicate the potential duty cycle.

The remaining communication ranges were calculated as a percentage of the maximum distance in the presence and absence of a specific anthropogenic noise source (the ferries) using only measures of noise levels. The noise levels were not affected by tidal influences but reflected a consistent daily pattern associated with the ferry operations. At 20 Hz, the remaining communication range calculations reflect the relatively constant noise levels throughout the day and night. As a result, the 20 Hz contact calls of fin whales are unlikely to be masked by anthropogenic noises except when a whale is close to the ferry. Both the 125 and 500 Hz calculations of remaining communication ranges identify the ferries as the major potential masker of other baleen whale species' calls. The masking potentials of other anthropogenic sources, especially in the mid-afternoon, are evident but not as extreme. The communication ranges of baleen whales at these frequencies in this region of the Bay of Fundy are likely to be more reduced during the day and early evening, relative to the ranges at night due to the lower noise levels that occur then. In Passamaquoddy Bay, there is no evidence of regularly occurring anthropogenic noise sources beyond the general increase in vessel noise between 0700 and 2000 h (Figure 5). These results demonstrate that the remaining communication range model can be used to provide baseline information on potential sources and timing of communication masking of baleen whales and other species' calls.

The choice of which ambient noise level to use in the communication range calculations is important. The higher the ambient noise levels, the lower the communication range reductions, but also the lower the baseline maximum communication range. The remaining communication range calculations using the Bay of Fundy data show a separation of the results associated with the three different ambient levels. At 20 Hz, using the higher ambient noise level resulted in the ferry noises not statistically decreasing the remaining communication ranges. Using the mean ambient level with no obvious anthropogenic sources (i.e., no ferries operating) presents a conservative measure of the relative amount of anthropogenic noise masking. For all three ambient noise-level calculations, the patterns of the remaining communication ranges per frequency exhibit duty cycles of the ferry noises that are similar. The levels of the remaining communication ranges will vary with the choice of the ambient noise level. Which ambient noise level to use in the calculations is arbitrary, however. In some studies, ambient noise levels that were used to calculate reductions of communication range associated with anthropogenic noises have assumed that the quiet noise levels are associated with Beaufort sea state 0 (Jensen et al., 2009) or sea state 2 or below (Hermannsen et al., 2014). In this study, the daily 5th percentile noise levels were assumed to be the levels at which the maximum communication range would occur. These levels were often higher than those associated with sea state 2 and, thus, better reflect the ambient noise levels in the study area. Using the daily 5th percentile ambient noise levels in the remaining communication range calculations took daily and seasonal variation into account. This could be important if the ambient or anthropogenic noise sources vary with day of the week or season, etc. These issues aside, the duty cycles of any noise sources will be evident, or not, based on changes in the remaining communication range patterns.

The uses of a spherical spreading loss model ($k = 20$) in the calculations may present an underestimated measure of communication range reduction. Incorporating a cylindrical spreading loss ($k = 10$; 3 dB reductions per doubling of the distance) or a common intermediate value ($k = 15$; 4.5 dB reductions per doubling of the distance) would result in much smaller remaining communication ranges in the presence of anthropogenic noises (Richardson et al., 1995). If the transmission loss value in an area is already known, that should be used in place of the spherical spreading value of 20. While it is possible to measure spreading loss or model it in an area, additional data such as bottom topography, sediment types, etc., would need to be gathered. The initial findings of the remaining communication range analyses would indicate if developing a more sophisticated model was warranted.

Many calculations used to estimate the detectability of calls in noise contain a number of assumptions such as the source level of the calls (Clark et al., 2009; Jensen et al., 2009; Putland et al., 2018). These models are much more sophisticated than equation 2 in this study, but they also require a greater amount of information, and the calculated ranges are based on assumed source levels of calls and, in some cases, estimates of the masking associated with detection thresholds. These studies were undertaken after there was evidence of masking of calls by anthropogenic sources, however. The remaining communication range model presented herein is intended to be used in regions where the anthropogenic masking situation is unknown but a potential effect is suspected.

Employing the remaining communication range model as a first step in determining if anthropogenic noise sources could mask baleen whale communication has a number of practical advantages. The necessary data gathering is limited to obtaining underwater noise levels using a single autonomous recorder, and the communication range reduction calculations are straightforward. The noise-level data can then be used, along with additional information, to construct more comprehensive communication range models if warranted.

The remaining communication ranges will likely be underestimated because of factors associated with differences in call source levels, changes in sound propagation characteristics (e.g., depth, rocky vs sandy bottom, and bathymetry), the hearing abilities of the receiver, and differences between the signal detection abilities of the receiver for anthropogenic and ambient noises (Farcas et al., 2016). However, if the variabilities in the masking noise and the ambient noise do not change at different amplitudes, the relative audibility of a signal will be the same for a long communication range and one that is less because of higher noise masking levels.

One important limitation of this model is that high-frequency sound absorption cannot easily be considered. The amount of absorption that occurs is based on a linear function, while the spreading loss is a logarithmic function. Thus, the reduction in the sound level caused by high-frequency absorption can only be determined if the actual distance is known. While this would be less important below 500 Hz, the remaining communication range calculations would overestimate the impact of an increased masking noise level on high-frequency sounds.

The location of the listening whale is not considered in this study. By moving away from the anthropogenic noise sources, the whales could reduce the level of noise masking. Moving away from the noise source would mean that the remaining communication range would be greater than at the site of the underwater recorder, but the duty cycle of the noise would not be appreciably changed.

The remaining communication range analyses presented herein are much less precise than other methods, especially where more information is available on the structures of the noise sources and hearing abilities of the subject (e.g., Parks et al., 2009; Erbe, 2015). However, the remaining communication range (% of maximum) calculations have the advantage of identifying the duty cycle and relative masking potential of anthropogenic noise sources when supporting information is limited or unavailable. Such assessments have been used both in air (National Park Service, 2010) and under water (Møhl, 1981) to assess potential noise masking presence. The financial costs of such assessments are considerably less than performing very detailed data gathering and sophisticated analyses. Performing remaining communication range analyses will be a useful first step in identifying and ranking the duty cycle of suspected anthropogenic noise sources and their potential for masking a vocal communication channel. Preliminary results will indicate if more extensive and more expensive studies would be needed.

Acknowledgments

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Literature Cited

Au, W. W. L., Pack, A. A., Lammers, M. O., Herman, L. M., Deakos, M. H., & Andrews, K. (2006). Acoustic properties of humpback whale songs. *The Journal of the Acoustical Society of America*, *120*, 1103-1110. https://doi.org/10.1121/1.2211547

Barber, J. R., Crooks, K. R., & Fistrup, K. M. (2009). The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology and Evolution*, *25*, 180-189. https://doi.org/10.1016/j.tree.2009.08.002

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: Intuitions, analysis and implication. *Marine Ecology Progress Series*, *395*, 201-222. https://doi.org/10.3354/meps08402

Erbe, C. (2015). The maskogram: A tool to illustrate zones of masking. *Aquatic Mammals*, *41*(4), 434-443. https://doi.org/10.1578/AM.41.4.2015.434

Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., & Dooling, R. (2016). Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin*, *103*, 15-38. https://doi.org/10.1016/j.marpolbul.2015.12.007

Farcas, A., Thompson, P. M., & Merchant, N. D. (2016). Underwater noise modelling for environmental impact assessment. *Environmental Impact Assessment Review*, *57*, 114-122. https://doi.org/10.1016/j.eiar.2015.11.012

Hatch, L. E., Clark, C. W., Van Parijs, S. M., Frankel, A. S., & Ponirakis, D. W. (2012). Quantifying loss of acoustic communication space for right whales in and around a U.S. national marine sanctuary. *Conservation Biology*, *26*, 983-994. https://doi.org/10.1111/j.1523-1739.2012.01908.x

Hermannsen, L., Beedholm, K., Tougaard, J., & Madsen, P. T. (2014). High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, *136*, 1640-1653. https://doi.org/10.1121/1.4893908

Jensen, F. H., Bejder, L., Wahlberg, M., Aguilar Soto, N., Johnson, M., & Madsen, P. T. (2009). Vessel noise effects on delphinid communication. *Marine Ecology Progress Series*, *395*, 161-175. https://doi.org/10.3354/meps08204

Marine Traffic. (2017). *Marine traffic, vessels*. www.marinetraffic.com

Møhl, B. (1981). Masking effects of noise: Their distribution in time and space. In N. M. Peterson (Ed.), *The question of sound from icebreaker operations: The proceedings of a workshop* (pp. 259-266). Arctic Pilot Project. 350 pp.

National Park Service. (2010). *Soundscape management plan, Zion National Park, Utah*. https://parkplanning.nps.gov/document.cfm?parkID=113&projectID=30628&documentID=36422

Parks, S. E., Urazghildiiev, I., & Clark, C. W. (2009). Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas. *The Journal of the Acoustical Society of America*, *125*, 1230-1239. https://doi.org/10.1121/1.3050282

Payne, R., & Webb, D. (1971). Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Science*, *188*, 110-141. https://doi.org/10.1111/j.1749-6632.1971.tb13093.x

Putland, R. L., Merchant, N. D., Farcas, A., & Radford, C. A. (2018). Vessel noise cuts down communication space for vocalizing fish and marine mammals. *Global Change Biology*, *24*, 1708-1721. https://doi.org/10.1111/gcb.13996

Richardson, W. J., Greene, C. R., Jr., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise*. Academic Press. https://doi.org/10.1016/B978-0-08-057303-8.50011-2

Risch, D., Clark, C. W., Dugan, P. J., Popescu, M., Siebert, U., & Van Parijs, S. M. (2013). Minke whale acoustic behavior and multi-year seasonal and diel vocalization patterns in Massachusetts Bay, USA. *Marine Ecology Progress Series*, *489*, 279-295. https://doi.org/10.3354/meps10426

Širović, A., Hildebrand, J. A., & Wiggins, S. M. (2007). Blue and fin whale call source levels and propagation range in the Southern Ocean. *The Journal of the Acoustical Society of America*, *122*, 1208-1215. https://doi.org/10.1121/1.2749452

Southall, B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P., & Tyack, P. L. (2019). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals*, *45*(2), 125-232. https://doi.org/10.1578/AM.45.2.2019.125

Van der Graaf, A. J., Ainslie, M. A., André, M., Brensing, K., Dalen, J., Dekeling, R. P. A., Robinson, S., Tasker, M. L., Thomsen, F., & Werner, S. (2012). *European marine strategy framework directive – Good environmental status (MSFD GES): Report of the Technical Subgroup on Underwater Noise and Other Forms of Energy*. Technical Subgroup on Underwater Noise and Other Forms of Energy, Brussels.

Weirathmueller, M. J., Wilcock, W. S. D., & Soule, D. C. (2013). Source levels of fin whale 20 Hz pulses measured in the Northeast Pacific Ocean. *The Journal of the Acoustical Society of America*, *133*, 741-749. https://doi.org/10.1121/1.4773277

Wenz, G. M. (1962). Acoustic ambient noise in the ocean: Spectra and sources. *The Journal of the Acoustical Society of America*, *34*, 1936-1956. https://doi.org/10.1121/1.1909155