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Passive acoustic localization techniques of Eastern Pacific grey whales

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Eastern Pacific grey whales (*Eschrichtius robustus*) thrive in shallow water environments where visibility is reduced but apparently do not actively echolocate. Along their migration route and in their feeding grounds these whales are exposed to high levels of ambient noise, highly turbid waters and many underwater obstacles. To test possible passive acoustic localization mechanisms (e.g. Acoustic Daylight Imaging and Passive Synthetic Aperture), we made extensive acoustic measurements during comprehensive field studies of these whales on their summer feeding grounds in British Columbia (Canada). In combination with visual observations of the whales and their behaviours, we investigated the acoustical sources available to the whales when navigating within a feeding bay. First, we measured ambient noise levels to construct the acoustic landscape around the whales. Second, we investigated how sound is altered when objects such as kelp beds and rocks are present. We also measured acoustic changes induced by direct, controlled modifications of the near-shore environment. The aim of this research is to understand how grey whales might be finding their way around, and what impact, if any, increased levels of ambient noise might have on the whales' ability to find food and navigate within the feeding grounds.

1 Introduction

It is likely that marine mammals, in particular those that do not use active echolocation, use passive acoustic navigation. We have chosen to concentrate on grey whales (*Eschrichtius robustus*) due to their close association with coastal waters [1, 2, 3] and their remarkable ability to locate prey in a complex and acoustically active environment without the apparent use of echolocation. The principal food source of the grey whale along the coast of British Columbia, Canada is mysid crustaceans (*mysidacea*) [4, 5]. These crustaceans usually form large aggregations (swarms), frequently associated with underwater features such as rocks or kelp beds [4, 6, 7]. There have been many suggestions as to how cetaceans find their way along long migratory routes, using landmarks and topography, celestial and solar cues, magnetic fields, ambient noise, and ocean currents [3, 8]. It has been commented that specific geographic regions have their own distinctive sound characteristics, and that grey whales could be exploiting this to their advantage in passive acoustic navigation [9].

The focus of our research is to examine the shallow water sound field and investigate how grey whales navigate and locate food without the use of active acoustics by testing passive localization techniques such as Acoustic Daylight Imaging (ADI) and passive synthetic aperture (refer to references 10, 11 for detailed description of these processes). Section 2 presents the two characteristically distinct bays studied, and how ambient noise measurements were taken. Section 3 analyses the power levels and frequency composition of the recordings, specifically in deep water, shallow water, near kelp beds and along the shore in both bays, and examines how the presence of rocks and kelp beds affects the signature of a sound signal. Section 4 discusses the results presented and the future experiments to be done, and Section 5 concludes by showing the implications for further studies of passive localization techniques of grey whales and marine mammals in general.

2 Methods

Ambient noise recordings were collected in two bays along the central coast of British Columbia, Canada, between July and September 2007. These sites were chosen due to their frequent use by foraging grey whales in previous years.

North Bay (51° 02' N, 127° 34' W) is cluttered with many rocks and kelp beds, and has a rocky shoreline. The kelp beds, which are mainly composed of *Nereocystis luetkeana*, are where mysids are predominantly found. North Bay is also relatively sheltered from the predominant NW winds. Burnett Bay (51° 07' N, 127° 41' W) on the other hand, has a 4.8-km long sandy beach and is relatively exposed to NW winds and ocean swell. The bottom is a mix of sand and boulders, and there is one large patch of kelp near the middle of the bay.

We used a fixed 2-hydrophone array, with SQ26-07 receivers horizontally separated by a small distance, analogous to a set of ears, which we deployed from a kayak. The hydrophone cables were run inside a 2-m long PVC pipe to the surface where they were connected to a M-Audio Microtrack 24/96 digital recorder (sampling at a frequency of 44.1 kHz). The acoustic signals were recorded at a broadband frequency range of 0 Hz to 22 kHz near the surface in water approximately 3 m to 70 m deep, in several distinct environments (deep water, shallow water with kelp beds, shallow water with bare seabed, and surf zone). The depth of the hydrophones during deployment was roughly 1.5 m, restricting surface contributions to very local effects and privileging underwater sources of noise [12].

Over a period of 2 months, over 100 acoustical recordings were taken throughout the two bays in order to create composite maps of the sound fields in each bay. Averaged power levels were plotted with respect to GPS position in Matlab, and interpolated where needed to create a continuous map of the areas which can be compared to nautical charts of the topography. We specifically looked at the surf noise in both bays, recorded seaward, as this is a major contributor to the ambient noise spectrum.

A second part of the field study included the testing of a simplified version of ADI. This involved keeping the receivers stationary while a boat passed by the array, emitting a broadband signal. This was done to examine how the sound was perceived differently due to the presence of rocks and kelp beds between the boat and the hydrophones, possibly creating acoustic shadows. The frequency spectra of the received signals were analysed to examine the changes in frequencies and their relative intensities as a function of the objects present. Numerous tracks were performed with different kelp beds varying in expanse and density.

3 Results

3.1 Average sound maps

Maps of the average sound field were created by combining all recordings and dividing them somewhat arbitrarily into six frequency bands; 0-500 Hz, 500-1000 Hz, 1-1.5 kHz, 2-8 kHz, 8-10 kHz, and 10-20 kHz, averaged for representation. These bands were chosen for differentiating between the different sound sources of ambient noise, such as surface generated noise, surf action and biologicals. Despite the different times at which the measurements were acquired, the limitations of the recording platform (kayak) meant that all the recordings corresponded to relatively similar weather conditions.

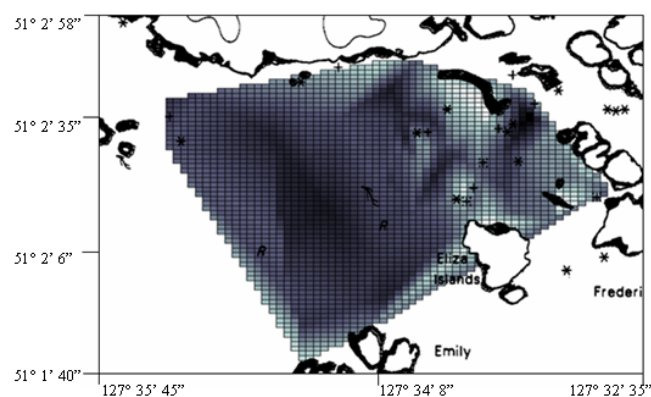


Fig.1 Average sound map for North Bay using all 71 recordings taken in this bay from 0 Hz to 20 kHz.

Lower levels of sound are darker. Note the artefact from interpolation in a poorly sampled area (between Eliza and Emily Islands).

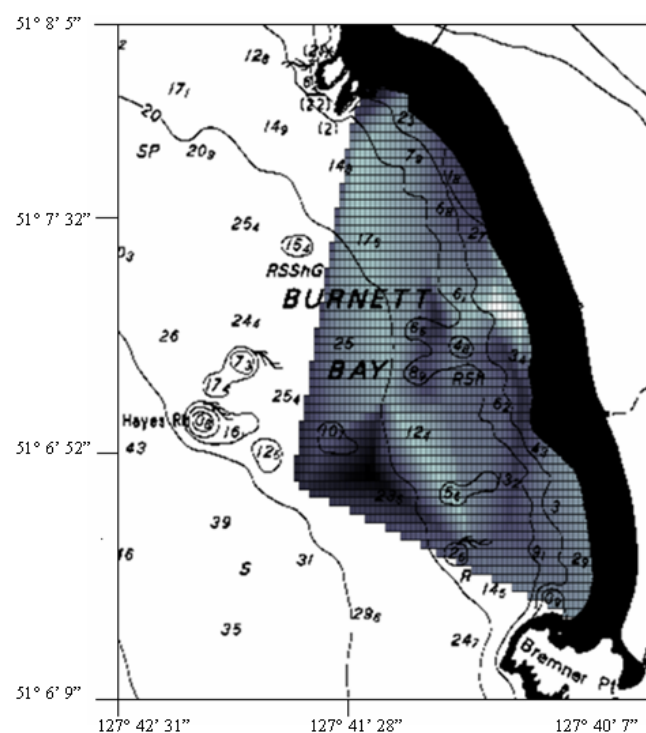


Fig.2 Average sound map for Burnett Bay, using the 38 recordings taken throughout the bay from 0 Hz to 20 kHz.

Lower levels of sound are darker, and the numbers on the chart represent depth in meters.

Due to the limit of the number of recordings, this map may not be as true a representation of the sound field as the map of North Bay. Future work will improve this.

These maps, especially North Bay, are generally consistent with the expectation that noise levels increase where rocks are exposed at the surface, near kelp beds, in shallow water, and along the shore where surf is present. Comparison with documented whale tracks already shows correlations of the general sound field with whale navigation and foraging patterns [13]. More swell is present in Burnett Bay, due to its exposure to the open ocean, and this affects the lower-frequency components of these measurements.

3.2 Frequency variations between bays

The average sound maps give a rapid assessment of broadband ambient noise and its variations, but are limited as they give only 1 set of measurements per recording, of slightly different durations. Further analyses segmented the recordings into 4,096-point intervals (2^{12} points, for FFT processing). With the sampling rate used, this corresponds to ~ 92 ms each time, in line with other studies [14, 15]. Overlaps of 10% between segments were chosen to avoid cutting potential processes of interest, and values of the power spectra were averaged over 1-kHz bands between 1 kHz and 22 kHz.

Systematic comparison of frequency bands reveals that each environment, and each bay, can be distinguished by comparing two distinct frequencies. Ambient noise recordings in open deep water are noisier for North Bay than for Burnett Bay (Fig. 3). Different clusters of points in Burnett Bay are likely associated to local environmental variations (related to wind, because of the lower frequencies) [14, 15]. The difference between the bays increases with frequencies.

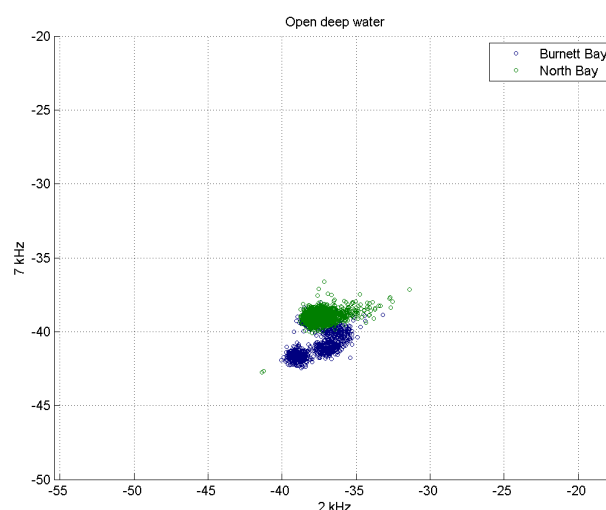


Fig. 3 Frequency variations (2 kHz vs. 7 kHz) of deep-water recordings.

A clear distinction is shown between the bays (also visible for other frequency combinations).

Frequency comparisons of shallow-water measurements also allow to distinguish between the two bays (Fig. 4).

North Bay measurements exhibit higher variations at all frequencies, whereas Burnett Bay recordings are always lower and more tightly clustered.

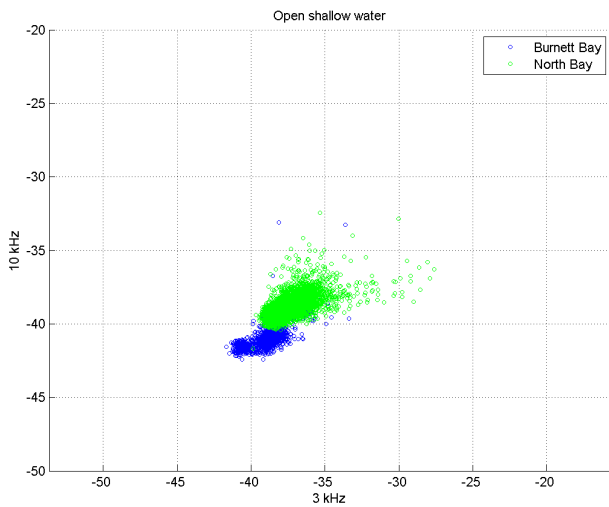


Fig. 4 Frequency variations (3 kHz vs. 10 kHz) of shallow-water recordings in the two bays. Other frequencies yield similar distinctions between the two bays.

Recordings of ambient noise taken in the kelp beds show similarly high sound levels in North Bay (Fig. 5). The large number of individual kelp patches throughout North Bay, with different sizes and kelp densities, seems to account for the higher variance.

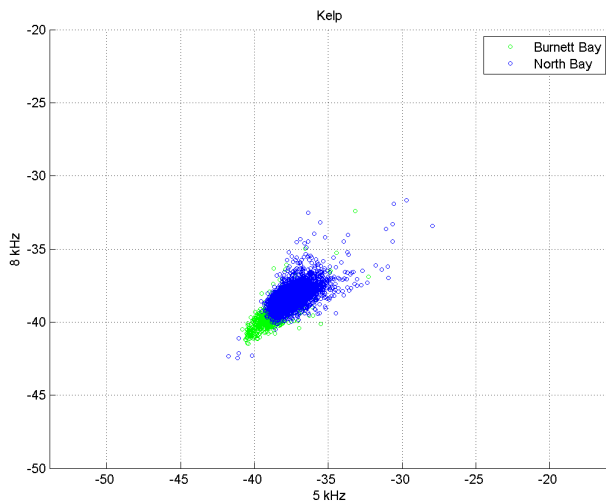


Fig. 5 Frequency variations (5 kHz vs. 8 kHz) for kelp bed recordings show a smaller difference between bays, and more overall variations within each bay.

Recordings of surf noise in the two bays also confirm these distinctions (Fig. 6), although not as obvious in the lower frequencies, which is typical of surf noise [16]. Comparison at higher frequencies (> 10 kHz) clearly shows differences of up to 5 dB.

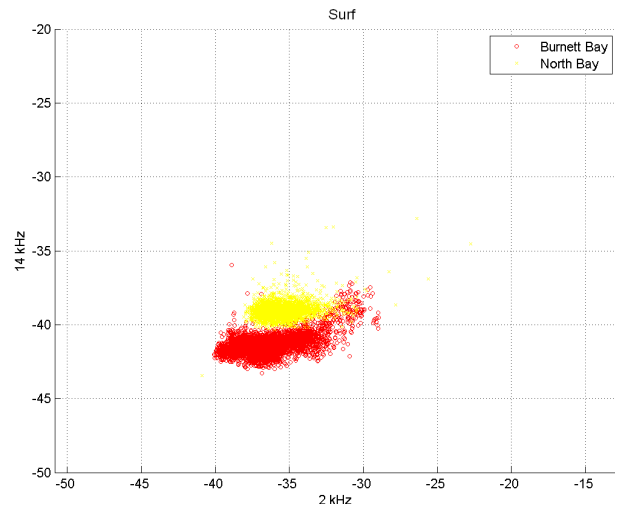


Fig. 6 Frequency variations (2 kHz vs. 14 kHz) for surf recordings. There is a clear difference between bays, increasing with frequency.

The main conclusion from these analyses is that it is possible to distinguish between similar processes in different bays. Looking at each bay separately, it is possible to distinguish deep-water, shallow-water and kelp-bed noise by using two distinct frequency bands, although surf noise tends to recover all these variations. And, at least in this study, power levels of one setting in one bay (e.g. kelp in Burnett Bay) overlap those of another setting in the other bay (e.g. deep water in North Bay). A whale knowing which bay it is in (through past navigation) should therefore be able to distinguish noise sources by comparing frequencies.

Principal Component Analysis (PCA) provides a more rigorous framework for analysing these frequency variations. This approach was already used with success to identify noise sources in an Arctic fjord environment [17]. By maximising the variance between combinations of variables (i.e. frequencies), PCA can identify the most significant frequency bands. The PCA of all recordings in both bays shows that 2 frequency combinations explain 88.3% of the variance (Fig. 7) and an additional frequency combination explains 91.5% (all subsequent components contributing less than 1%). The main PCA contribution (labelled X_1) combines all frequencies > 1 kHz with the same weights. This means that the amount of ambient noise, rather than its frequency distribution, is a major factor in distinguishing between sites. This comforts the analyses of Section 3.1. The second PCA component (X_2) combines the lowest frequencies (mostly 1-5 kHz), with a smaller, negative contribution from higher frequencies (roughly 10 to 22 kHz. This particular frequency band is associated to wind- and bubble-related processes (small bubbles at the surface or in kelp beds, whitecaps, etc.) [14-17]. The third PCA component (X_3) contributes only marginally to the overall acoustic picture; it is marked mostly by noise below 1 kHz.

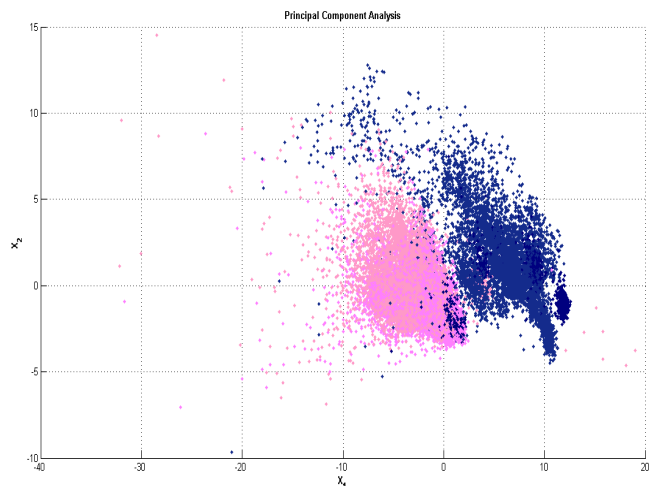


Fig. 7 PCA clearly distinguishes the two bays: X_1 corresponds to the overall sound level; X_2 to wind- and bubble-related processes.

All 38 Burnett Bay recordings are represented by the darker data points, and all 71 North Bay recordings are the lighter points.

3.3 Boat tracks (ADI)

We were interested in seeing how a sound signal is altered by the presence of rocks and kelp beds. Figure 8 shows the resulting rms levels of the boat signal as it travels around a rocky reef. We used an outboard boat motor which only extends up to approximately 7.5 kHz. Along the track where no rocks or kelp is present, the signal clearly has a higher rms value.

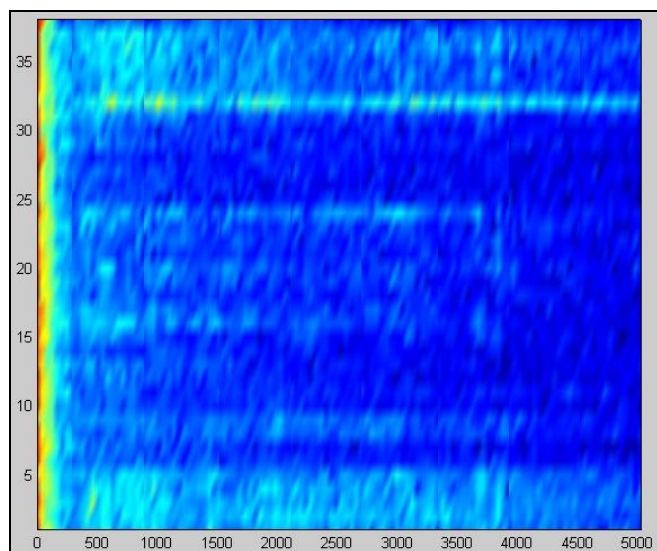


Fig. 8 Received rms values of the boat signal as it travels along the outer side of a rocky reef. There were 38 spots along the track (shown on the x-axis) where the signal was analysed, and frequency is on the y-axis.

Where there are no objects present between the boat and the hydrophones, higher rms values are given (lighter in colour). Where rocks and kelp exist, the boat noise is blocked and acoustic shadows are produced.

With a higher frequency sound source, more detail should be apparent. Future experiments will include this.

4 Discussion

Our research focuses on the coastal ambient noise soundscape with respect to how marine mammals could exploit it for their use when navigating and locating food.

The sound maps of the bays appear to be consistent with the prediction that there is an increase in the noise levels where rocks are exposed at the surface, near kelp beds, in shallow water, and along the shore where surf is present. When comparing the maps from the two bays, it is clear that the power levels of the ambient noise are higher in North Bay than in Burnett Bay. These maps can be used to relate whale movements through the bays with the acoustical sound field in order to discern if any correlation exists.

By comparing the frequency composition and overall power levels of the ambient noise recordings taken in North Bay and Burnett Bay, it is possible to distinguish between the two. North Bay is a more complex bay, with rocky shores and many partially submerged rocks and kelp beds; whereas Burnett Bay is a relatively simpler bay with a sandy beach and a cluster of kelp beds near the middle of the bay. Burnett Bay is also more exposed to the predominant NW winds and ocean swell. These different features thus create differences in the ambient noise soundscape. The PCA analysis shows that due to the variance between the ambient noise recordings being a contribution of all frequencies above 1 kHz, the difference in power levels is more important for distinguishing between the bays than the frequencies involved.

The results of the ADI experiment shows that rocks and kelp beds greatly affect the signal of a boat motor, and that where these objects are present acoustic shadows are created. This may be a useful strategy for marine mammals to use when navigating through an area.

Future work involves expanding on the average sound maps to include acoustic samples in a gravel/boulder bay. These files will also be used for another PCA comparison. We also plan on performing the ADI experiment in a relatively controlled environment with a simulated kelp bed. This will be done with a sound source ranging into the higher frequencies for greater resolution. This test will then be performed in the field with a real kelp bed, and the results of both situations will then be compared. We also propose to test the localizing ability of the 2-hydrophone system. We hypothesize that it is possible to estimate a bearing to a sound source by creating a passive synthetic aperture. This involves allowing the recording platform to drift along a track, taking samples as it moves, and then cross-correlating the received sound signals to estimate a bearing.

The ultimate aim of this research is to create a 2-hydrophone acoustic navigation system which makes use of passive acoustic localizing techniques. The development and testing of this bio-inspired system will further our understanding of noise in this particular environment. Additionally, its implementation will improve our understanding of the whales' ability to navigate and locate prey in the noisy nearshore environment.

5 Conclusion

Our analyses show that it is possible to acoustically distinguish between the two characteristically distinct bays. In general, North Bay has more variations in the ambient

noise soundscape compared to Burnett Bay. This could be due to its complexity and thus resulting in more locally distinct environments within the bay. Since the variance is an equally-weighted contribution of all frequencies above 1 kHz, the amount of ambient noise, rather than its frequency distribution, is a major factor in distinguishing between sites. Any alteration to the natural sound field could affect an animal's ability to orientate itself. ADI appears to be an effective passive acoustics method that would allow a navigating marine mammal to detect objects nearby.

Acknowledgments

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