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PASSIVE ACOUSTIC MONITORING OF SURFACE VESSEL ACTIVITY

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ABSTRACT

Monitoring human activity in remote marine areas is a challenging problem to which acoustic methods present a promising solution. This paper develops and demonstrates automated passive acoustic methods to estimate ranges to surface vessels using a single seafloor-mounted hydrophone. Surface vessels that use echosounders (to navigate or find fish, for example) are especially well suited for passive acoustic monitoring since they use high-energy, narrow-band, short-duration pulses. Examples of surface vessel ranges estimated using echosounder pulses recorded on a seafloor-mounted hydrophone are presented.

1 INTRODUCTION

Because of its vast and remote nature, monitoring the marine environment can present significant challenges to security and protection agencies. Since surface vessels are often noisy, they can be detected and monitored using passive acoustic receivers located well below the surface of the water where they are protected from the environment and vandalism. In this paper we focus on using a seafloor-mounted hydrophone to monitor vessels that use echosounders to find fish, navigate, and/or avoid running aground.

2 DATASET

The dataset used in this paper comes from Cross Seamount (18.7^{o}N and 158^{o}W) which is in the North Pacific, about 290 km south of the Hawaiian Island of Oahu. The summit of Cross Seamount is about 5 to 7 km across and is relatively flat with depths between 350 and 450 m. Data were collected between 26 April 2005 and 19 November 2005 using a High Frequency Acoustic Recording Package (HARP) [1]. The HARP was located on the seafloor of the summit at 400 m depth and sampled with a duty cycle of 5 min on, 20 min off at 200 kHz sampling rate. The hydrophone was about 11 m above the seafloor. Further details can be found in Johnston *et al*. 2008 [2] and McDonald *et al*. 2009 [3].

3 DETECTION AND CLASSIFICATION

Data were processed by creating spectrograms (using 1024 point Hanning windows overlapped at 50%) for 3 s subsamples. After applying a tonal detector (for boat and ship tonals, for example) spectrograms were de-noised and normalized by removing the mean of each frequency channel. A flood-fill algorithm was then applied to the spectrograms to detect high-energy transients. A brief description of flood-fill detection follows, and details can be found in Nosal 2008 [4].

Flood-fill algorithms are used by paint programs in the “bucket” tool to fill connected parts

of a multi-dimensional array (e.g. a bitmap) with a new color. Starting with a given node they connect all neighboring points that have the same (or similar) color (value) as the given node. All connected points are then replaced with the new color. In flood-fill detection, the multi-dimensional array is the spectrogram. After a point in the spectrogram whose values exceeds some threshold is identified, all neighboring points that meet or exceed this threshold are connected. This effectively "groups" spectrogram points that exceed the threshold into events separated by time and/or frequency. All groups consisting of 20 or more points are flagged as "detection" and stored. A relatively high threshold used here gave few false alarms but also resulted in many missed detections. Although not optimal for specific or known sounds, the flood-fill detector easily and effectively detected unknown and unexpected transients. It was chosen as a "first sweep" of the data while we didn't know what sounds to expect in the dataset and since the volume of data was quite high (about 1.5 TB). Future work will use a detector optimized for echosounder pulses.

Because the flood-fill detector found all transients (not only echosounders), detections were post-processed via an automated classification procedure. This procedure put each detection in one of 5 groups: (1) narrow-band, short-duration; (2) narrow-band, long-duration; (3) broad-band, short duration; (4) frequency-modulated; (5) other. The group of interest to this study was (2) (narrow-band short-duration) since these corresponded to echosounder pulses, and only these were kept for further analysis here. The other detection groups consisted of noise, ship tonals, and marine mammal vocalizations and are not discussed further in this paper.

4 VESSEL RANGES

Inspection of the echosounder detections revealed a clear, persistent and slowly varying second arrival immediately following (within about 14.5 ms) each direct arrival. Since the hydrophone was about 11 m off the seafloor, this arrival corresponds to a seafloor reflection. Figure 1 shows a spectrogram of a typical echosouder detection with direct and reflected arrivals. Because the summit of the seamount is relatively flat and broad, the seafloor reflection can be used to estimate the range to the vessel. In particular, the difference in arrival time between the direct and seafloor-reflected arrival is a function of the range of the vessel from the hydrophone. We refer to direct-reflected time differences as DRTDs.

For each echosounder detection, a DRTD was established by extracting a sample that included 3 ms before the detection and 20 ms after. The sample was bandpass filtered using a 6th order Butterworth filter with a 10 kHz band centered on the signal's peak frequency. The envelope of the filtered sample was calculated by taking the absolute value of the Hilbert transform. The auto-correlation function was applied to the envelope. The first peak in the auto-correlation function always corresponds to zero lag, and the second peak occurs when the direct arrival overlaps with the reflected arrival. That is, the lag of the secondary peak of the auto-correlation function of the envelope corresponds to the DRTD. For each echosounder detection, DRTDs were obtained in this way and are henceforth referred to as the *measured* DRTDs.

An echosounder *event* was defined as a slowly-varying group of DRTDs that persisted for more than 30 s; each event corresponds to the presence of a boat using an echosounder continuously for 30 s or more. Echosounder events were extracted by applying a clustering method to DRTDs against direct arrival times. The clustering method used a distance criterion which grouped DRTDs if they their values were within 3 ms of each other and if they occurred within 10 s of each other. Echosounder events lasting less than a half a minute were discarded.

To estimate errors in measured DRTDs, a third degree polynomial regression model was fit to the DRTDs of each echosounder event. The differences between the polynomial fit and the DRTDs for each event were used to estimate the standard deviation of the measured DRTDs. Error bars in the DRTD measurements were defined as two standard deviations of the measured DRTDs. Figure 2 shows an example of an echosounder event with corresponding polynomial fit.

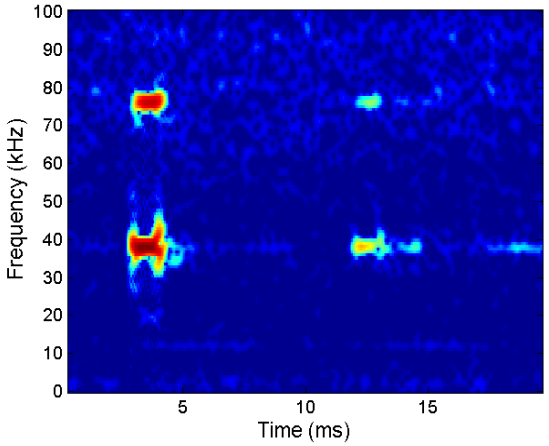


Figure 1. Spectrogram of a typical echosounder detection with peak frequency at 38 kHz, the first overtone at 76 kHz, and a seafloor reflection about 10 ms after the direct arrival.

A sound speed profile calculated from conductivity, temperature, and depth (CTD) measurements taken in the area during hydrophone deployment was used to model difference in arrival times between seafloor reflected and direct as a function of range. We used the ray tracing software Bellhop [5] and assumed a surface vessel and flat seafloor. DRTDs were calculated for ranges that varied from 0 m to 2 km with 1 m spacing. Figure 3 shows the modeled DRTDs as a function of range.

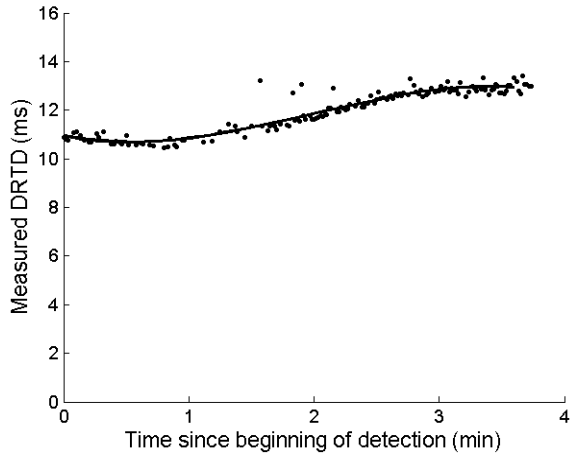


Figure 2. All measured DRTDs for an echosounder event extracted at 01:55 GMT on October 11, 2005. The line is a third degree polynomial fit with standard deviation 0.288 ms.

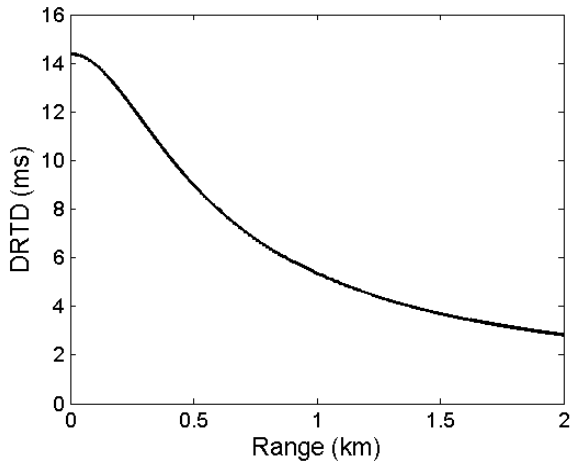


Figure 3. Modeled DRTD as a function of range for a surface vessel, flat seafloor with 400 m depth, and a hydrophone 11 m off the seafloor. CTD measurements taken on the seamount during hydrophone deployment were used to calculate the sound speed profile used in the model.

For each measured DRTD, the range of the vessel was estimated by finding the range r that minimizes

$$\left(DRTD_{\text{meas}} - DRTD_{\text{model}}(r)\right)^2$$

where $DRTD_{\text{meas}}$ is the measured DRTD and $DRTD_{\text{model}}(r)$ is the modeled DRTD for range r. To determine error bars for the estimated ranges, the DRTDs were recalculated for seafloor depth between 395 and 405 m, hydrophone height off of the seafloor between 10.5 and 11.5 m. Errors due to uncertainty in sound speed profile were not considered since they are small compared with errors due to uncertainly in seafloor and hydrophone depths. For each range the difference between the minimum and the maximum possible DRTDs approximated uncertainty curves for the modeled DRTDs. Error bars for measured DRTDs were projected onto the DRTD model curves and then onto range to give error bars for the range estimates. Figure 4 illustrates this approach.

5 RESULTS

Six months of data took 1 month to process on a 2.8 MHz Pentium IV desktop PC. Processing resulted in over 400 thousand detections, 30 thousand of which were classified as echsounders. Clustering these detections resulted in 145 echosounder events. The detected echosounder events lasted an average of 2.8 minutes, with the shortest lasting half a minute (which corresponds to the cutoff defining an echosounder event) and the longest lasting five minutes (which is the longest possible recorded event due to the duty cycle). No attempt to link events between duty cycles was made. All detected echosounder ping durations were between 2 and 3 ms. By far the most commonly extracted echosounder events (140 of 145 events) had detections with 50 kHz peak frequency. These are probably commercially available fish finders which commonly operate at dual frequencies of 50 and 200 kHz (Garmin's FishFinder 340C or the Lowrance X59, for example). The other five echosounder events had a peak frequency of 38 kHz. Four of these were recorded within the first 5 days of the record. Since 38 kHz is a frequency used by fisheries research split-beam echosounders (the Simrad EK60, for example), these first four 38 kHz events probably came from the echosounder aboard the vessel that deployed the hydrophone. Note that echosounder pulses above 100 kHz could not be detected with the HARP because of the 200 kHz sampling rate.

The furthest range at which an echosounder event was detected was 828 m; the nearest was nearly

directly above the hydrophone. Error bars for DRTD measurements were 0.65 ms on average and ranged between 0.08 ms to 1.08 ms. These translated to errors bars for range estimates from 52 m to 310 m. As expected, errors generally increased with range. Figure 5 shows the range estimates for the event in Figure 2.

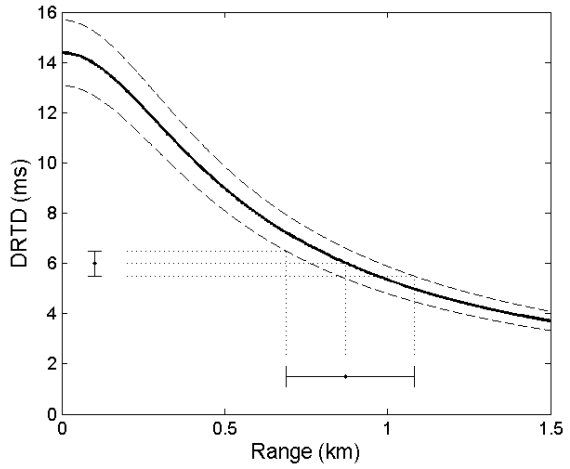


Figure 4. Modeled DRTD as a function of range (as in Figure 3) with uncertainty curves from errors in seafloor and hydrophone depth. Errors bars in measured DRTD are projected onto these curves and then onto range to give error bars for range estimates.

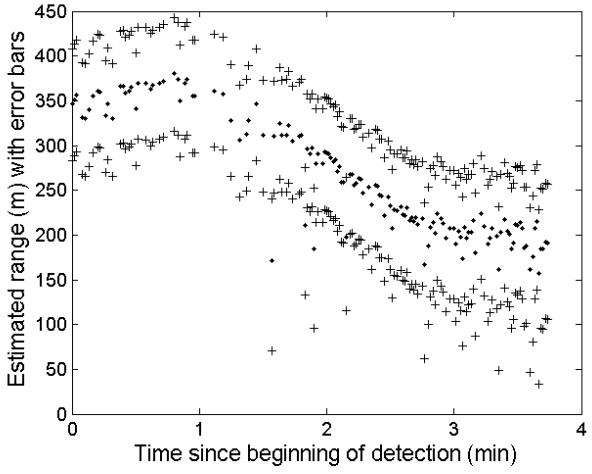


Figure 5. Range estimates (dots) with error bars (pluses) for the event from Figure 2.

6 CONCLUDING REMARKS

The number of extracted echosounder events is certainly an underestimate of the number of actual events. Extractions can be improved by using a more optimal detector and by using improved clustering techniques (many echosounder detections were discarded during the clustering phase). Nevertheless, the results presented here illustrate the potential of using passive acoustic monitoring for remote marine environments. For example, with some improvements (especially in the detection and clustering methods) these methods could be used to estimate fishing effort in an area.

The CTD data were invaluable in helping to reduce uncertainties in sound speed profile, which can become especially troublesome at long ranges [6]. However, large uncertainties in seafloor and hydrophone depth resulted in large uncertainties in range estimates. We highly recommend that these depths be established as carefully as possible during hydrophone deployments. Running a transect over the hydrophone while recording ship position via GPS and using an echosounder might be a good approach to this and could provide a valuable ground-truth dataset. A single hydrophone provides enough data to establish range only, but data from an additional hydrophone would also provide bearing estimates. Moreover, data from three hydrophones would give an exact position estimate (i.e. it would resolve the left/right ambiguity of a 2 hydrophone system).

There are several limitations to the methods presented here. Most obviously, they can only be applied to vessels using echosounders. Moreover, the high-frequency echosounder pulses can attenuate quite rapidly as they propagate. Deeper water and higher bottom-loss will result in weaker bottom-reflections, hence the range at which the methods can be applied are reduced. Another problem involves multiple vessels. Two vessels at similar range (but possibly different bearing) have the same DRTDs and cannot be separated using the methods presented here. It may be possible to improve our methods to separate the vessels if (1) the echosounders use different frequencies or (2) the vessel ranges change relative to one another fast enough that the plot of DRTDs vs time (as in Figure 2) shows two clearly independent tracks (that intersect only when the vessels are at the same range). This problem would be eliminated by using multiple hydrophones.

7 ACKNOWLEGEMENTS

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