Automated Model-Based Localization of Marine Mammals near Hawaii

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***Abstract*-Acoustic data from the Pacific Missile Range Facility (PMRF) hydrophone network near Hawaii is being used to develop a real-time automated alert and tracking algorithm. The sources of interest are marine mammals, humpback whales in particular, which are regularly seen in the vicinity of the PMRF array. The algorithm under development uses acoustic data from six hydrophones plus an acoustic propagation model to construct an ambiguity surface identifying the most probable whale location in a horizontal plane around the array. It has the further advantage that it can be implemented in real-time and without human interaction, making it suitable for automated alert applications.**

I. INTRODUCTION

Passive acoustic methods of observing marine mammals have been of interest for many years, both in population estimates and behavioral studies [1-4]. The acoustic characteristics of whale songs make them detectable at long ranges (30 km) using hydrophones [4-8]. Unlike radio tagging or visual observations, acoustic methods are unobtrusive; a whale's behavior is unlikely to change because of the observation. Acoustic measurements are also suitable for continuous monitoring applications. They can be obtained at all times of day, in all weather conditions, and at any depth an animal may swim.

When received over an array of hydrophones, a whale song can be used to estimate a singer's position, a valuable tool for learning of whale behavior and migration routes. A common localization technique is that of hyperbolic fixing [4,9-11]. The measured difference in arrival time of a whale call recorded on multiple hydrophone pairs produces intersecting hyperbolic bearing lines indicating the animal's position.

When the hydrophone pairs are very closely spaced as on a typical towed array or vertical line array (VLA), these techniques are no longer practical. Alternative model-based techniques that exploit either the temporal or spatial structure of the received field are then needed. For instance, the arrival times and amplitudes on a single phone can be used to estimate a whale's range [8]. Alternatively, the interphone phase relations on a VLA (representing the arrival angles of the multipath) can also be exploited [12]. Both of these techniques draw on standard techniques from passive SONAR.

Of all the localization techniques demonstrated previously, the most common drawbacks are that they require user interaction and are difficult to implement in real-time. A real-time localization system free of human interaction would be of great benefit both for long-term observations of whale behavior or simply to detect the presence of marine mammals to ensure 'range-safety' in areas of interest. Acoustic data from the Pacific Missile Range Facility (PMRF) hydrophone network off the western coast of Kauai is being used to develop such a real-time automated alert and tracking algorithm. In this application, the mammals of interest are humpback whales (*Megaptera novaeangliae*) which are known to congregate near Kauai to breed in winter through spring months after a long migration from North Pacific waters [13].

The localization algorithm described in this paper is both automated and rapid. In addition, it provides a graphical display of mammal tracks that also conveys the confidence level of those tracks. It uses an acoustic propagation model to account for variations in bathymetry and soundspeed in the waters under observation, thus eliminating the errors from constant soundspeed assumptions inherent to hyperbola fixing techniques. Finally, the confidence metrics provided by the algorithm can also be used to trade-off the probability of detection versus false alarm to suit the particular application.

After describing the available acoustic data set in Section II, the localization technique will be discussed in Section III along with examples of its output. Section IV will describe further possible applications of the algorithm.

II. ACOUSTIC DATA

The Pacific Missile Range Facility is an underwater array of over 100 hydrophones in the waters near Kauai, Hawaii. Personnel at PMRF have implemented a near real-time system for transmitting acoustic data from 6 hydrophones to the Maui High-Performance Computing Center (MHPCC) for analysis. Acoustic data files are posted to MHPCC in 1-minute increments. The hydrophones available for use were spaced 5-20 km apart and are deployed on the sea floor at the locations and depths shown in Fig. 1. Average historical soundspeed profiles for the region are known as well.

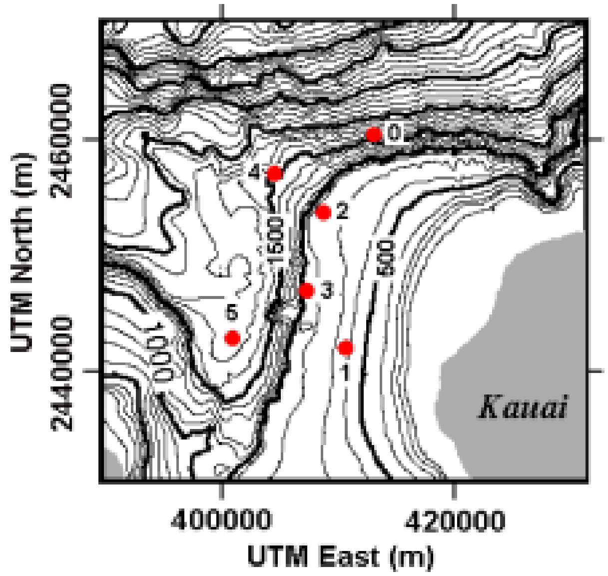

Fig. 1. Bathymetry contours (m) and hydrophone locations (0-5) at the Pacific Missile Range Facility. Axes are for UTM Zone 4.

Two days of continuous acoustic data from March 22-23, 2001, from the 6 hydrophones sampled at 20 kHz were made available for analysis and algorithm development. Data were low-pass filtered and downsampled to 2000 Hz to isolate the frequency band most used by the marine mammals of interest. Whale songs were heard on every hydrophone and at all times of day. In many cases, the sounds of multiple marine mammals could be heard simultaneously. While viewing spectrograms of the acoustic data, spectral patterns similar to those associated with humpback whales [14-15] were frequently observed. While it was not practical to listen to every channel of the entire data set, spectrograms could be examined quickly to confirm that all recordings contained the patterns expected of whale songs.

When spectrograms from all hydrophones for the same time segment were viewed concurrently, similar spectral patterns could be recognized in two or more spectrograms, but offset in time. In such cases, the same whale call is being recorded on multiple receivers, but the time of arrival at the receiver varies according to range from the singer. As an example, Fig. 2 shows spectrograms from hydrophones 2 and 4 for a 20-s segment of data from March 22, 2001; the spectrograms were made using 512-point FFT's with 90% overlap. A call pattern can be seen repeated on hydrophone 4 approximately 3.5 seconds after the same pattern on hydrophone 2. It is this difference in arrival times for the same call, called the time-lag, which will be used in the localization process.

III. LOCALIZATION ALGORITHM

The localization algorithm consists of two main components: spectral pattern correlation to calculate time-lags and ambiguity surface construction to generate a location estimate. Both will be described here along with comparisons to typical alternative techniques.

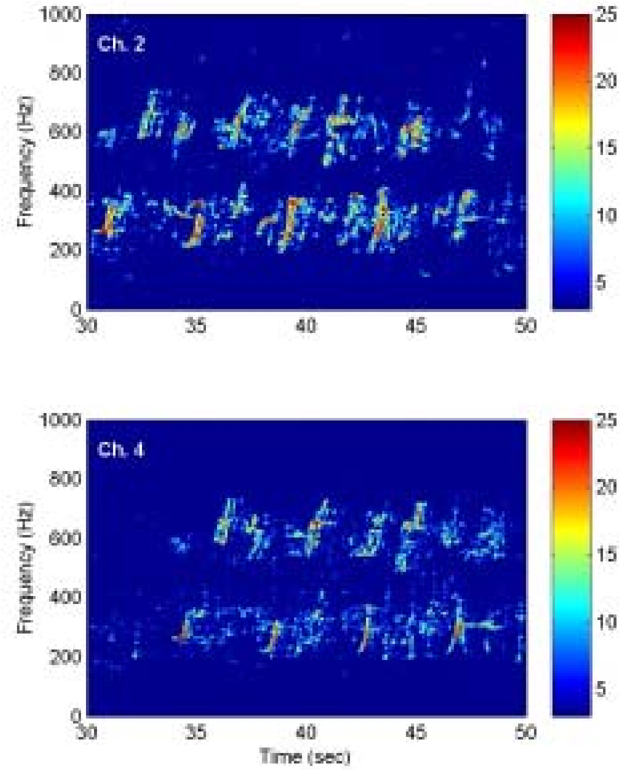

Fig. 2. Spectrograms of acoustic data from hydrophones 2 (top) and 4 (bottom) starting at time 20:16:30 on 3/22/01. Spectral amplitude is in dB. A 3.5 s time-lag for spectral transients is apparent between the two spectrograms.

A. Spectrogram Correlation

Measuring time-offsets between whale call arrivals at different hydrophones is a critical step in the localization algorithm. The standard method for determining time-lags between two whale calls is through cross correlation, but whether the correlation should be performed on the original waveforms or their spectrograms is open to debate. Spectrogram correlations are commonly used in whale localization efforts, perhaps because the signal structure remains obvious even in the presence of interferers [4,10,11]. However, waveforms containing whale calls have been successfully used in both matched-filter [9] and cross correlation [10] processes. Proponents of waveform approaches argue that the resulting estimates of time-lag are more precise. However, when waveform correlations were attempted between hydrophone pairs of the PMRF data set, the resulting time-lag estimates were scattered, even over short time periods with relatively obvious time-lags. The poor quality of the waveform correlations is assumed to be due to the large number of interferers, often other distant animals singing simultaneous songs. Better results were obtained using pair-wise spectral shape correlations following an example described in [16]. Spectrograms from two hydrophones were digitized, i.e. converted to two levels of intensity (on or off) based on a data-adaptive threshold. As the two digitized spectrograms are shifted past each other, correlation is done very quickly by performing a logical AND operation on the overlapping region. Summing the overlapping pixels provides a correlation score whose maximum determines the time-lag between channels as well as providing a confidence level of the measurement.

An example of cross correlator output is shown in Fig. 3, where results from both waveform correlation (Fig. 3a) and digitized spectral correlation (Fig. 3b) are presented for comparison. Data are from hydrophones 2 and 4 for minute 20:16 on March 22, 2001; this time segment includes the data shown in Fig. 2. A time window 10 seconds long extracts data subsets to use with each correlation, and the window advances in 1-second increments through the entire minute, calculating a time-lag and correlation score at each step. (Note that correlation scores indicate relative correlation strength among time steps and should not be compared between the two techniques.) While the waveform correlation's time-lag estimates are quite variable over the minute, the spectral correlation process correctly extracts the interchannel time-lag of 3.5 seconds during periods when the whale is singing. Furthermore, the spectral correlator score drops significantly when the animal stops singing (20-25 s). By setting thresholds on this correlation score, only the most confident of the time-lag estimates are passed to the localization process, thus freeing the correlation output from human examination.

B. Ambiguity Surface Construction

After calculating time-lags for all possible hydrophone pair combinations, those with high spectral correlation scores (over about 40% of maximum possible score) were then used in the localization process. The traditional technique of plotting intersecting hyperbolic trajectories of possible source positions based on time-lags did not provide precise estimates of whale positions in this case. The assumption of a constant soundspeed in this technique is invalid as a sound's vertical distance traveled must be accounted for in the travel time calculation. The mean soundspeed from source to hydrophone could vary from 1300 m/s to 1520 m/s depending upon range and depth of the receiver.

A more effective localization display is provided by constructing an ambiguity surface, or a probabilistic indicator of the source location. The first step in doing so is to predict the direct path travel times from a grid of possible source positions within a 30 km square area to every hydrophone. The acoustic propagation model BELLHOP was used to calculate the travel times as it can correctly account for depth-dependent soundspeeds and varying receiver depths; a 500-Hz source at 10-m depth was assumed. Fig. 4 shows both the average soundspeed profile used in the acoustic ray trace calculations and the resulting direct acoustic ray paths between the shallow source and hydrophone #0 at several ranges. The receiver depth was varied and acoustic travel times versus range were recalculated for every hydrophone.

Next, for each candidate latitude-longitude coordinate on the ambiguity surface, the predicted time-lag that would be seen between all pairs of hydrophones is then compared to the

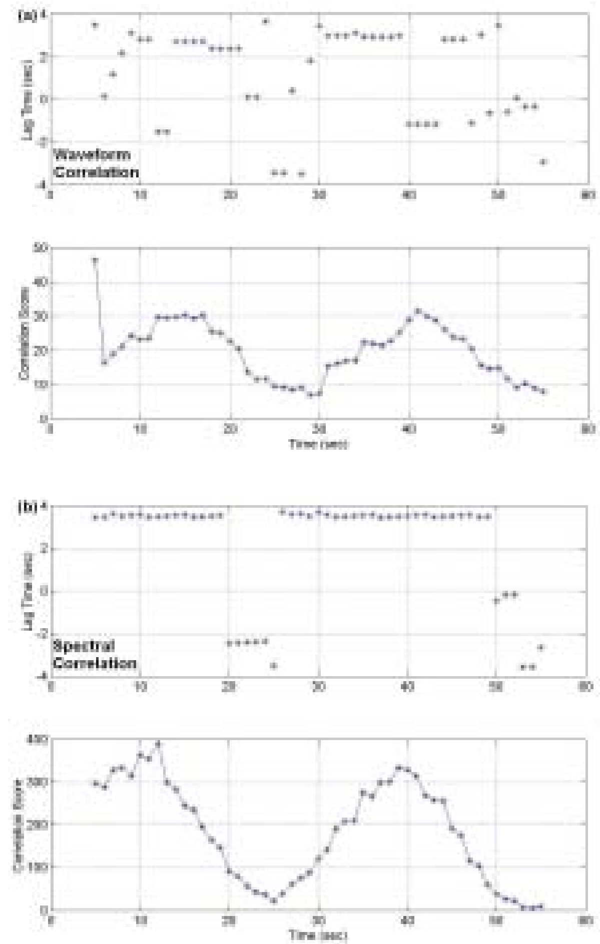

Fig. 3. Time-lags and correlation scores output by the cross correlator using waveforms (a) and digitized spectra (b). Cross correlations use data from hydrophones 2 and 4 for minute 20:16 on 3/22/01. The 3.5 s time-lag estimate from the spectral correlation agrees with that visually observed in Fig. 2.

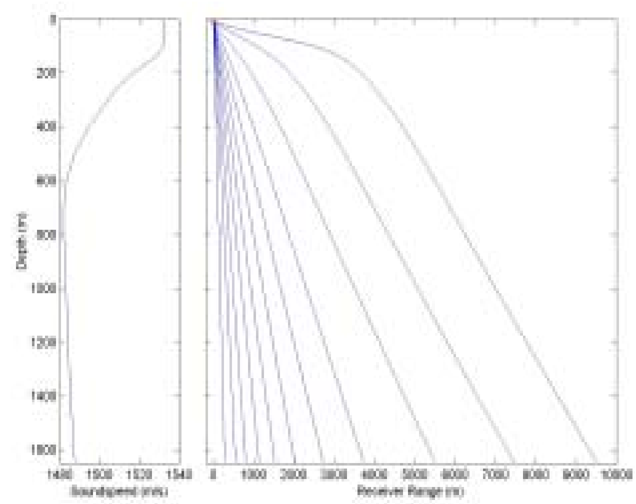

Fig. 4. Average soundspeed profile and predicted direct acoustic ray paths between a 10-m source and hydrophone #0 (1638 m depth) at several ranges. The predicted mean acoustic soundspeed varies with range from the receiver.

measured time-lag to determine the likelihood that the source is at that particular coordinate. A likelihood score is then scaled according to the acoustic transmission loss predicted by BELLHOP, logarithmically over a 30 dB range. For example, sounds from a distant source location will be attenuated, so the probability of a source localization at that far range is reduced. After a likelihood score is calculated for every hypothesized source position, the unitless scores are assembled on a two-dimensional plan view of the area around the array, completing the ambiguity surface. Each receiver pair generates its own ambiguity surface, and those with high likelihoods are summed to make an overall ambiguity surface. Source location estimates common to many receiver pairs stack to form a peak indicating the best estimate of source position.

In order to demonstrate the strengths of model-based localization and ambiguity surface visualization, spectral correlator time-lag estimates from three instances were used with both the model-based technique and standard hyperbolic fixing, and results from both techniques are shown together in Fig. 5. Each frame of Fig. 5 represents a 30-km square area of ocean around the PMRF array, with hydrophone positions labeled. Only time-lag estimates with high correlation scores

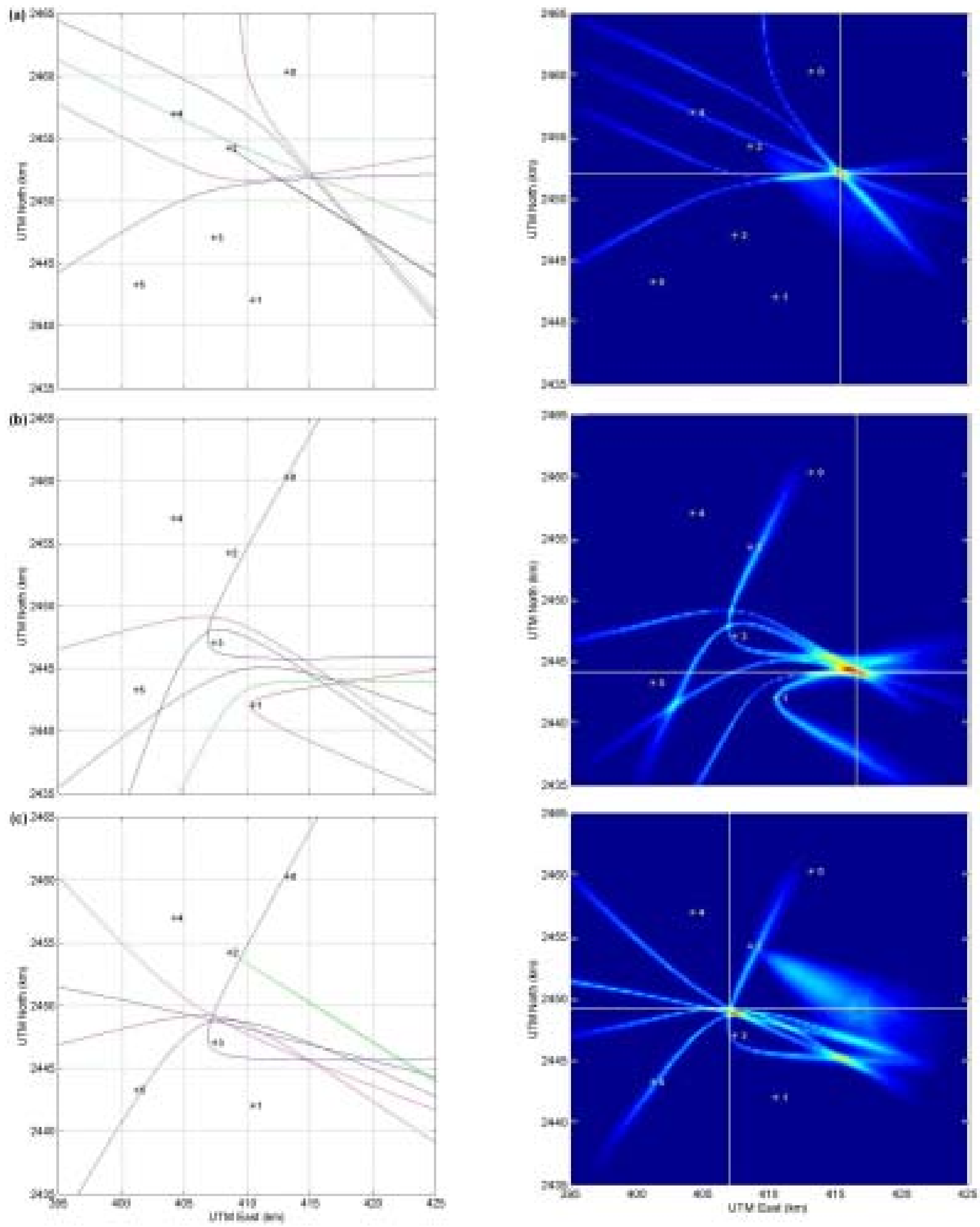

Fig. 5. Planviews of the waters around the PMRF array with hydrophone positions (0-5) indicated. Axes are for UTM Zone 4. Curves from hyperbolic fixing (left) intersect at several possible whale positions. Ambiguity surfaces from model-based localizations (right) indicate whale position estimates with bright peaks and crosshairs. Data from the following times were used to create the figure pairs: (a) 3/22/01 20:16 (b) 3/23/01 00:00 (c) 3/23/01 13:00

were used in the localizations. On the ambiguity surfaces, areas of peak intensity represent the whale position estimates and are marked with crosshairs, while hyperbolic fixing relies on the intersection of several curves to identify a singer's location. The constant soundspeed assumption used in hyperbolic fixing can prevent curves from intersecting at a single common point, and the lack of a confidence indication requires one to judge which intersections will contribute to an average location estimate. Note that ambiguity surfaces still reveal patterns resembling hyperbolas; however, the curves have effectively been thickened and stacked in such a way that one can easily identify the most probable source locations. Also note how curves on the ambiguity surfaces fade with range indicating the reduced likelihood of a long-range source localization. Furthermore, should distant pairs of hydrophones localize confidently on two separate animals, two separate ambiguity surface peaks would be seen.

The analysis described here was applied to many short time segments throughout the two days of acoustic data. In every case, a source was confidently localized by the contribution of four or more receiver pairs. The acoustic data from those times were then played back to verify the presence of a marine mammal. Furthermore, when ambiguity surfaces are made for several consecutive time segments, one can see a peak rise and fall as the whale pauses between calls.

IV. CONCLUSION AND FUTURE IMPLEMENTATION

Acoustic data from the Navy's PMRF array has been used to develop a real-time method for localizing marine mammals. The algorithm is novel in its use of an acoustic propagation model to construct an ambiguity surface identifying the most likely whale location in a horizontal plane around the array.

Now that algorithm development is complete, the machinery exists to implement it in a near real-time monitoring system at the MHPCC. The algorithm could run continuously, examining each new data set from PMRF immediately as it becomes available. After pre-calculating acoustic travel times and predicted time lags, the remaining computation is relatively simple and could be completed within the data update period (perhaps one minute). Alerts could be automatically generated and emailed, complete with graphic location estimates and some measure of confidence, whenever a whale is localized within the search area of interest. Setting high thresholds on both correlation and ambiguity surface scores minimizes the chances of false alarms. The same alerts could also launch real-time tracking algorithms or flag time periods of interest for later analysis.

While real-time localizations would be a useful tool for those wishing to study, or avoid, marine mammals, the same localization data viewed over long, continuous time periods could give valuable clues to marine mammal behavior. Travel routes may become apparent, and "conversations" between alternating singers might be observed.

The algorithm could also be considered modular in that the correlation process is independent of the ambiguity surface construction. Should waveform cross correlations ever offer advantages over the spectrogram correlations described above, it would be easy to substitute that step in the process. Visualization modules are also under development that will hopefully create maps of whale paths or time-lapse movies of estimated position.

Although the algorithm was originally planned to take advantage of the existing PMRF facility to track marine mammals, it is readily portable to other arrays of interest and should work well localizing any transient audible target. The effect of extensive shipping traffic or constant noise sources on the localization algorithm has not yet been examined, but provided some transient sounds are detectable over a background, the algorithm has a reasonable chance of success.

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