Automated Model-Based Localization of Marine Mammals near California

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***Abstract*- In previous work, we developed an algorithm for acoustically tracking singing humpback whales near Hawaii. Pair-wise time-differences in arrival of whale calls as measured by a phase-only correlation process are compared to time-lags predicted by an acoustic propagation model. Differences between measured and modeled time-lags defined an ambiguity surface that identifies the most probable whale location in a horizontal plane around an array. In this work, we describe the application of this technique to a very different environmental scenario involving blue whales off the coast of California. The whale calls are much lower in frequency and the receivers are ocean bottom seismometers. Again the algorithm performs extremely well, providing the capability for real-time, automated monitoring and alert.**

I. INTRODUCTION

Acoustic detection and tracking of marine mammals is of interest to biologists studying whale behavior or censusing [1-4]. In addition, recent stranding incidents have increased interest in being able to detect marine mammals in the vicinity of naval SONAR [5]. Fortunately, the calls of marine mammals are often easily heard underwater [6-9], which makes them good candidates for acoustic localization techniques.

A common technique for passive acoustic localization of marine mammals is that of hyperbolic fixing [10-14]. This is a simple approach; however, its accuracy is limited in environments where refractive and multipath effects are important. To compensate for these effects, we developed a new algorithm for localizing singing whales using acoustic propagation modeling [15]. The new technique uses comparisons between predicted and measured time-differences of arrival (time-lag) between widely spaced receivers to build an ambiguity surface showing the most likely whale position in a horizontal plan view around an array. During acoustic travel time prediction, the acoustic model can account for variations in bathymetry and soundspeed in the waters under observation. The output ambiguity surface also has the nice feature that it inherently provides confidence metrics in the location estimate. The model-based algorithm is fast and does not require user interaction, making it suitable for automated, real-time monitoring applications, and the robustness of the technique is illustrated in its application to an entirely different scenario than for which it was originally designed.

The model-based algorithm was developed using acoustic data from the Pacific Missile Range Facility (PMRF) hydrophone network in the deep waters off the western coast of Kauai. The mammals of interest were humpback whales that are known to congregate near Kauai to breed in winter through spring months after a long migration from North Pacific waters [16]. The algorithm has recently been applied to localizing blue whales migrating along the California coast near the island of San Clemente. Not only are the waters much shallower than Hawaii, but the new species under study has markedly different call characteristics than those of humpback whales. Furthermore, the data under examination is not from hydrophones but rather four bottom-mounted seismometers.

After describing the experiment geometry and 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. EXPERIMENT

The Southern California Offshore Range (SCORE) is a naval training area near the island of San Clemente. In anticipation of future SCORE expansion, surveys of the waters of the nearby Tanner Bank were conducted, which included deployment of four bottom-mounted seismometers in a 3-km square as shown in Fig. 1. The water is relatively shallow at 230 m depth, and average historical soundspeed profiles for the area are known as well.

The seismometers measure velocities on three axes as well as pressure, and eleven days of continuous seismometer data from August 28 to September 7, 2001, sampled at 128 Hz, were made available for analysis. Whale songs were recorded on every instrument and at all times of day. While viewing spectrograms of the data, spectral patterns similar to those associated with blue whales were frequently observed [17]. A typical blue whale call lasts about 20 seconds and has much of its energy at frequencies less than 60 Hz. As an example, Fig. 2 shows a spectrogram from seismometer #1 for a 3-minute segment of data from August 28, 2001; the spectrograms were made using 512-point FFT's with 90% overlap. Alternating type 'A' and type 'B' calls are evident.

When spectrograms from all seismometers 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. It is this difference in arrival times for the same call, called the time-lag, which will be used in the localization process.

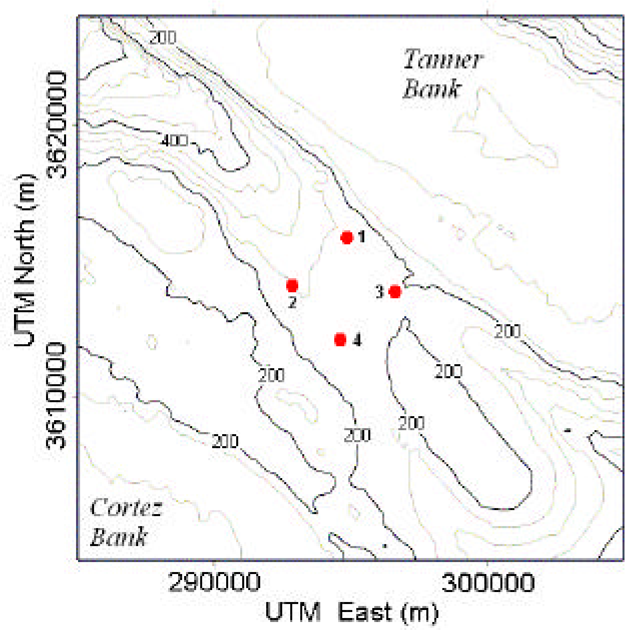

Fig. 1. Bathymetry contours (m) and seismometer locations (1-4) near the Southern California Offshore Range (SCORE) by San Clemente Island. Axes are for UTM Zone 11.

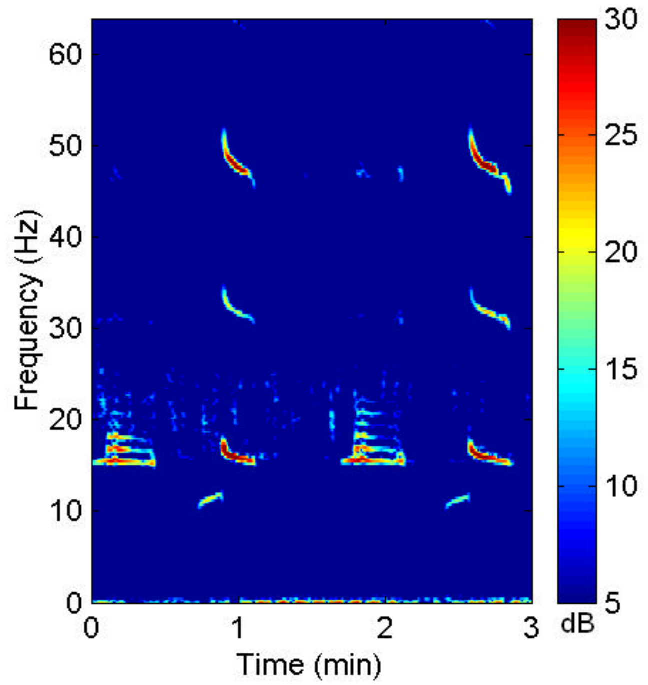

Fig. 2. Spectrogram of data from seismometer #1 starting at time 11:36 on 08/28/01. Spectral amplitude is in dB. Alternating type 'A' and 'B' blue whale calls are evident here and throughout the dataset.

III. LOCALIZATION ALGORITHM

A singing whale is localized through the construction of an ambiguity surface, or probabilistic indicator of the source location made through the comparison of measured time-lags ('data') to predicted time-lags ('replicas'). There are three main components of the localization algorithm: 1) cross correlation to calculate time-lags, 2) replica generation, and 3) ambiguity surface construction, which takes input from the other two modules. Because each of these modules is distinct, alternative methods of performing each can be tested to find the best processing solution. This was the case when measuring time-lags through a correlation process.

A. Phase-only Correlation

Measuring time-offsets between whale call arrivals at different receivers 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 in the time domain or frequency domain is open to debate [11,13]. In our previous work at PMRF, more consistent pair-wise time-lag measurements were made using spectral pattern correlation rather than waveform correlation, perhaps because the unique spectral structure of the humpback whale call remains obvious even in the presence of interferers. Both spectral and waveform correlation techniques were applied to the SCORE dataset, with time-lag results being approximately equal in quality. However, a third correlation technique provided time-lag measurements as good or better than the others with a calculation time shorter than the spectral correlation method. That method is called phase-only correlation, and the results to follow are a result of its use.

In phase-only correlation, a 30-second window of simultaneous time series data is extracted from two receivers, and the amplitude and phase of their frequency components are determined via an FFT. Next, their frequency spectra are whitened by normalizing all amplitude values to the same constant, but phase information is maintained unaltered. Correlation is performed through complex multiplication of the whitened spectra, and a correlation function is made by an inverse FFT on the resulting product. The location of the correlation function peak determines the time-lag between the two receivers, and the peak correlation score provides a confidence level of the measurement. Additionally, one can define which frequencies will contribute to the correlation by zeroing amplitudes for frequency bins outside those bands of interest prior to taking the product of the two spectra.

Time-lags between all combinations of receiver pairs are measured for each time window of interest. Although the correlator returns a time-lag measurement for every time window examined, only those measurements with high correlation scores are passed to the next module of the localization process. Fig. 3 shows an example of pair-wise time-lags provided by the phase-only correlator after analysis of 2.5 days of data from seismometers #1 and #4; those time-lags with high associated correlation scores are shown here and are used in the localization examples to follow. In this figure, slowly varying time-lag measurements indicate a noise source is changing bearing relative to the receiver pair. By setting thresholds on the correlation score, only the most confident of the time-lag measurements are used during ambiguity surface construction, thus minimizing incorrect localizations and freeing the correlation output from human examination.

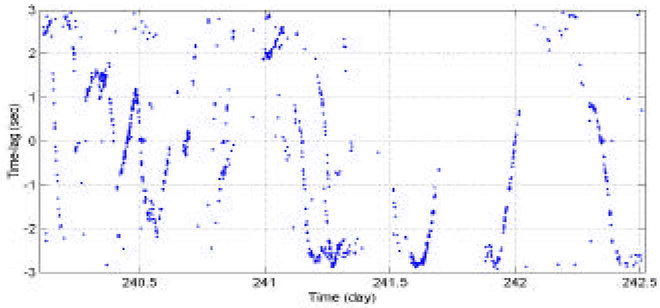

Fig. 3. Time-lags measured by the phase-only correlator between seismometers #1 and #4 during August 28-30, 2001. Slowly varying time-lags indicate a source changing bearing relative to the receivers.

B. Replica Generation

Another input needed for ambiguity surface construction is the replica. Here, replicas are predictions of the time-lags that would be measured by every receiver pair combination from a hypothesized source at every location within a grid of candidate positions around the array. Time-lags are predicted by first calculating the acoustic travel time from every hypothesized source to every receiver, then taking the difference in travel times between receiver pairs. Simulated sources are spaced 200 m apart in a 20-km square grid around the array.

The acoustic propagation model BELLHOP was used to calculate the acoustic travel times as it can account for depth-dependent soundspeed profiles and range-dependent bathymetry. Note that soundspeed profiles are range-independent, and a shallow source depth at 35 m was assumed. The water depth along a line between every source and receiver is extracted from a bathymetry grid of the area and is used in the modeling process, thus allowing multipath arrivals from bottom-reflected acoustic paths to be included in the travel time calculation.

As an aid in visualizing the acoustic model output, Fig. 4 shows the predicted acoustic ray paths from a hypothesized whale northwest of the array to seismometers #1 and #4. The curvature of the acoustic rays is due to the downward refracting effects of the soundspeed profile used in the modeling. Note how the paths from the whale to receiver #1 include both a direct (non-reflecting) path and a bottom-surface-reflecting path. In some long-range cases, there may be no direct ray path between source and receiver, as is the case in this example between the whale and receiver #4. The accounting of bottom reflections is one advantage of the model-based localization method over traditional hyperbolic techniques which assume a direct path between source and receiver even when none exist.

Each modeled ray path has an associated travel time, and for every source/receiver combination, an average of all the predicted travel times, weighted by the predicted amplitude of each arrival, is used as the single value of predicted travel time. Taking the differences between travel times completes the replica calculation. The replicas need only be calculated once, provided the receiver positions or environment do not change.

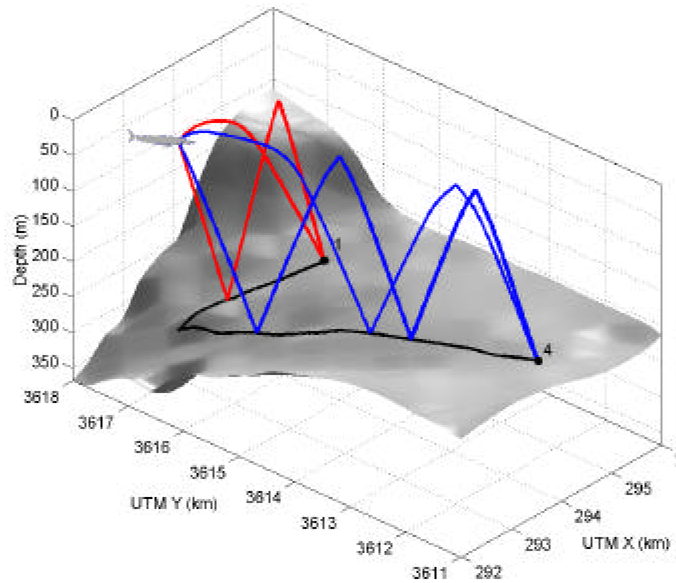

Fig. 4. Predicted acoustic ray paths between a hypothesized whale and seismometers #1 and #4. Whale not drawn to scale. The range-dependent acoustic model allows for both direct and reflected ray paths to be included in the travel time calculation.

C. Ambiguity Surface Construction

The time-lag data and replica are used as inputs to construct an ambiguity surface that will provide the location estimate for the whale. For each candidate latitude-longitude coordinate in the search grid around the array, the predicted time-lags that would be seen between a pair of hydrophones are compared to the measured time-lag to determine the likelihood that the source is at a particular grid location. The likelihood score is then scaled according to the acoustic transmission loss predicted by BELLHOP, minimizing the likelihood of a detection at long range from the array. Likelihood scores from one receiver pair are then assembled on a two-dimensional plan view of the area around the array, completing one ambiguity surface. Ambiguity surfaces from several receiver pair combinations are then summed to make an overall surface where source location estimates common to many receiver pairs stack to form a peak. The ambiguity surface peak is declared the best estimate of source position.

D. Localization Examples

A sample of ambiguity surfaces showing blue whale localizations appears in Fig. 5. Each surface represents a 20-km square plan view around the seismometer array, and bright peaks and crosshairs indicate a likely whale location. The three surfaces of Fig. 5 show successive localizations over 13 minutes of August 28, 2001, and the peak location can be seen to move to the southwest over time. When ambiguity surfaces from many consecutive time windows are viewed in order, one can watch a localization peak rise and fall as the whale pauses between calls.

Repeated localizations like in this example can be used to follow the motion of a single target as it moves around the array. When the location estimates from many consecutive

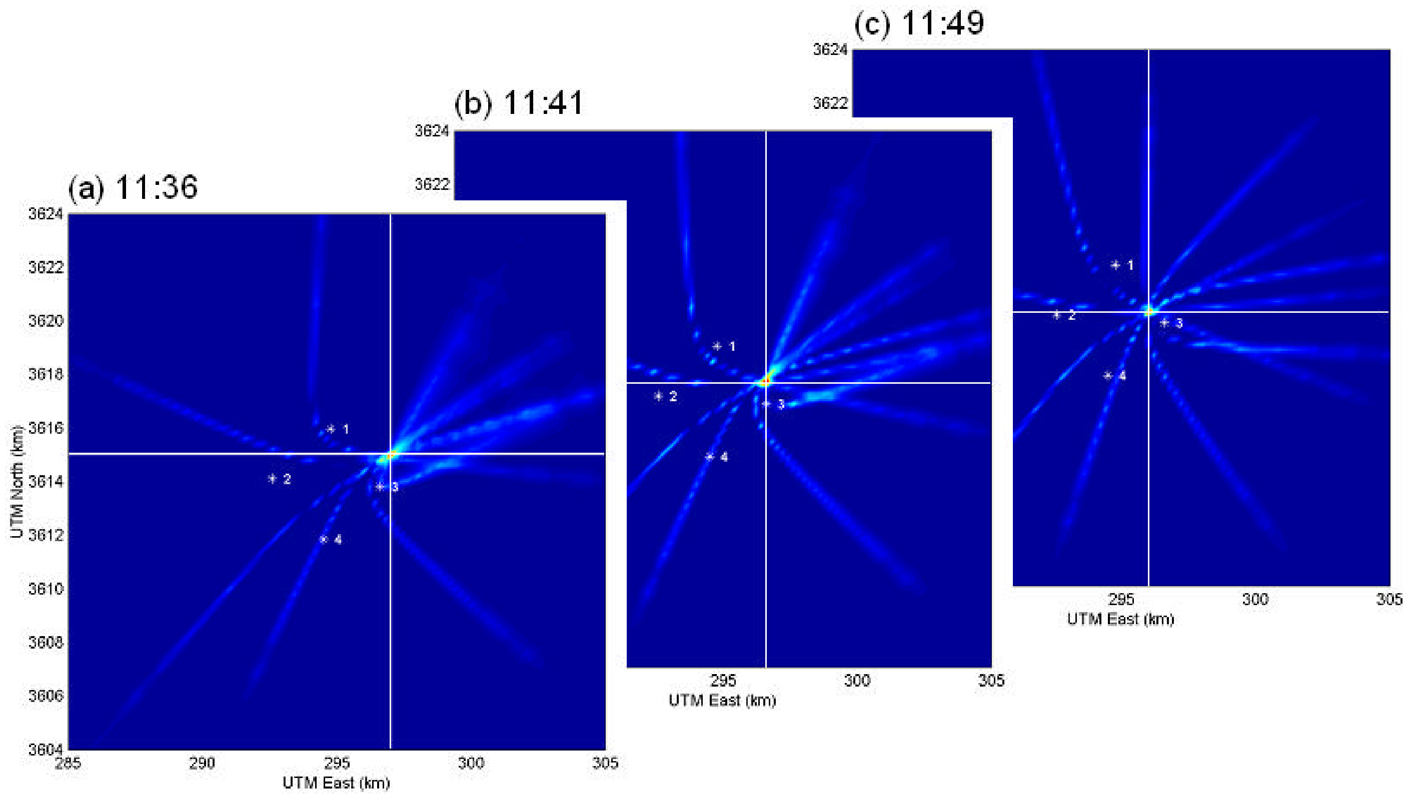

Fig. 5. Plan views of the waters around the array with seismometer positions (1-4) indicated. Axes are for UTM Zone 11. Ambiguity surfaces from model-based localizations indicate blue whale position estimates with bright peaks and crosshairs. Data are from August 28, 2001 at the following times: (a) 11:36 (b) 11:41 (c) 11:49. The location estimate can be seen to move to the southwest in successive frames.

times are viewed together in a plan view, the track of a whale's course can be seen. Fig. 6 shows examples of such whale tracking over several-hour windows on two different days. While tracking of the source is expected to be reliable within the array, the reasonable localizations several kilometers outside of the array are very encouraging. Because the correlation score thresholds limit the contributions from the correlator, the tracks maintain a fairly tight focus and outlying points are minimized. The tracks are also expected to break up at long range as shown because the chances of having a high correlation score decrease with range from the receivers.

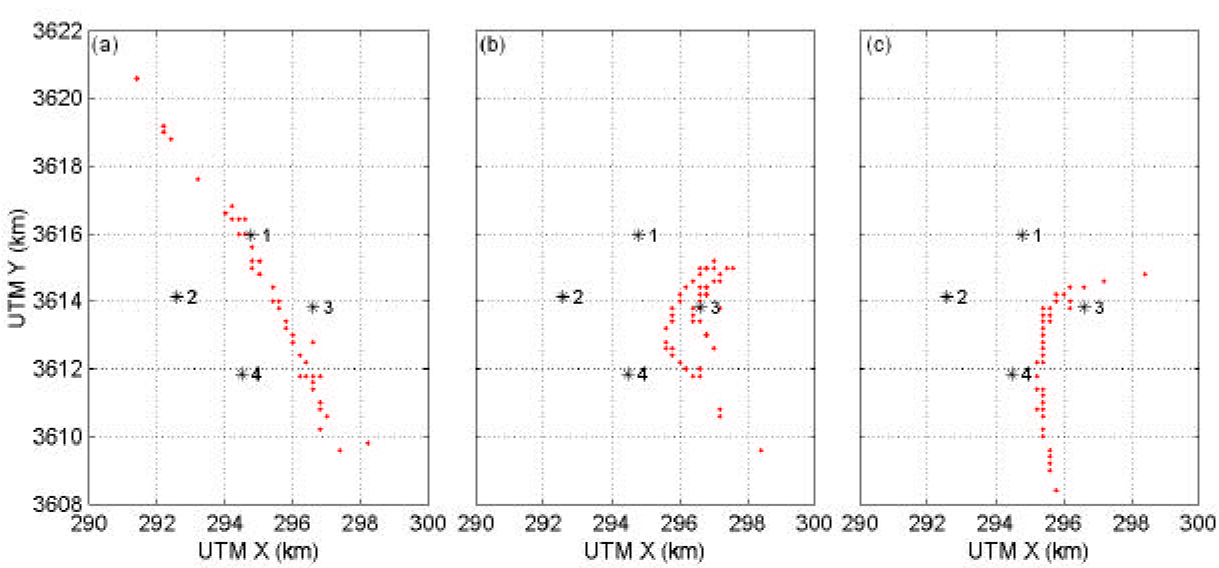

Fig. 6. Plan views of the waters around the array with seismometer positions (1-4) indicated. Axes are for UTM Zone 11. Points indicate location estimates from many consecutive time windows, allowing tracking of a whale's path. Data are from the following time windows: (a) 08/28/01 02:52-04:52 (b) 08/28/01 09:33-13:50 (c) 08/29/01 02:55-04:50.

IV. CONCLUSION AND FUTURE IMPLEMENTATION

An algorithm originally developed for passively tracking humpback whales within the Navy's PMRF test range near Hawaii is also suitable for monitoring blue whale behavior along the California coast. The algorithm is novel in its use of a range-dependent acoustic propagation model and construction of an ambiguity surface to show probable whale locations in a horizontal plane around a widely spaced array. Successfully applying the algorithm to the new California environment and mammals of interest demonstrates its robustness and portability, as little modification was made to the localization process. The modular design of the algorithm is a benefit in that different processing schemes can be easily substituted and evaluated, such as when the phase-only correlator replaced the original spectrogram correlator for this analysis.

The model-based localization technique is suitable for use in an automated, real-time monitoring system. All of the tracking results presented above were made without user-interaction, and calculation time is small once the replicas have been generated. An automated system could continuously monitor a range for mammal activity, generate alerts, launch tracking routines, and flag times of interest for later study; high thresholds on correlation scores can prevent false alarms. Such tools can assist those studying whale behavior as well as those interested in mammal mitigation issues.

There is also room for further algorithm advancement. The largest assumption made by the algorithm is that of a constant source depth, but the ability to profile dive behavior is an interesting goal for behavior studies. More sophisticated use of multipath arrival times, both measured and simulated, may provide the solution to resolving depth. Because this work used seismometers, there may be a way to exploit the three-axis nature of the seismometer data to get further directionality clues. Lastly, applying the algorithm to other ranges and species to further test its robustness is yet another goal, as is confirming acoustic localization estimates with other means such as visual surveys.

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