Automated Model-Based Localization of Sperm Whale Clicks

Christopher O. Tiemann, Michael B. Porter
Science Applications International Corporation
10260 Campus Point Dr.
San Diego, CA 92121

Abstract – **In previous work we described an algorithm based on an acoustic propagation model that was used for passive acoustic localization of vocalizing marine mammals. Differences between measured and modeled pair-wise time-differences of arrival were used to define an ambiguity surface that identifies the most probable whale location in a horizontal plane around an array. The algorithm has been successfully applied to humpback whale calls in deep water near Hawaii and blue whale calls in shallow water near California. In this work, we return to Hawaii to track another species of whale, the sperm whale, whose calls are brief, broadband clicks. Acoustic localizations are in close proximity in space and time to aerial observations of sperm whales. We were also able to verify the algorithm's accuracy in a controlled source experiment at the Navy's AUTEC range in the Bahamas. Recordings of sperm whale clicks were broadcast and successfully tracked. The localization accuracy of the model-based technique and traditional hyperbolic techniques is compared.**

I. INTRODUCTION

Efforts to minimize the effects of sound on marine mammals have received increasing attention recently. In just the last two years, at least four federal court orders suspended underwater sound tests of both academic and government institutions, and recent stranding incidents have increased interest in being able to detect marine mammals in the vicinity of naval SONAR [1]. A common mitigation method during acoustic experiments is visual surveillance for mammals during testing. However, passive acoustic detection of marine mammals can also be a powerful tool for identifying when singing whales are within an area of interest. Acoustic methods can find whales that are submerged, at any time of day, in any weather condition, and in an automated fashion.

A common technique for passive acoustic localization of marine mammals is that of hyperbolic fixing [2-6]. This technique uses time-differences of arrival (time-lag) of a whale call heard on a receiver pair to trace out intersecting hyperbolic curves. This technique assumes straight-line, direct-path acoustic propagation between a source (whale) and a receiver. However, in some geometries, such direct paths do not exist; the only acoustic paths between a source and receiver are those that reflect off the sea surface and sea floor. Applying hyperbolic techniques to data from 'indirect' reflected paths can result in localization errors.

We developed a passive acoustic localization technique based on acoustic propagation modeling that can provide increased accuracy over hyperbolic methods in indirect path scenarios, such as in shallow water environments or at long ranges. The model-based technique uses comparisons between predicted and measured time-lags for widely spaced receivers to build an ambiguity surface showing the most likely whale position in a horizontal plan view around an array. The model-based algorithm is fast and does not require user interaction, making it suitable for automated, real-time monitoring applications.

The model-based technique was originally developed for use in locating singing humpback whales in the deep waters near Hawaii using widely spaced bottom-mounted hydrophones of the Navy's Pacific Missile Range Facility (PMRF) [7]. The same algorithm proved to be equally successful in tracking blue whales, animals with markedly different call characteristics, in the shallow waters of the Navy's Southern California Offshore Range (SCORE) [8]. Although some animals were acoustically tracked far outside the receiver array boundaries, it was not possible to verify through other means the animal position.

We were recently given the opportunity to verify the algorithm's accuracy by exercising it against two new data sets as part of the Navy's Marine Mammal Monitoring on Navy Ranges (M3R) program. The goal of M3R is to develop tools for acoustically detecting and tracking marine mammals in Navy test ranges [9]. In analysis of more acoustic data from the PMRF range, this time concurrent with an aerial survey, we were able to track yet another species of marine mammal, the sperm whale, which emits periodic, brief, broadband clicks. Acoustically-derived tracks of sperm whales are in close proximity in space and time to visual observations. Verification of the algorithm against a known source location was made possible using data from a controlled-source experiment at the Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) range in the Bahamas. Simulated sperm whale clicks were broadcast by a target ship, and acoustic localizations match closely with ship position.

II. SPERM WHALE TRACKING AT PMRF

Aerial surveying for marine mammal activity is an accepted means of estimating animal density. However, detection statistics comparing visual and acoustic survey methods are not well defined. This work allowed for both kinds of observation at the Navy's PMRF range, a network of bottom-mounted hydrophones in the waters near Kauai, Hawaii.

A 7-hour aerial survey over the PMRF range was conducted on March 10, 2002, by Dr. Joseph Mobley in efforts for the North Pacific Acoustic Laboratory (NPAL) experiment. Acoustic data from 24 hydrophones of the PMRF range were collected for several overlapping hours on the same day. The aerial survey reported both humpback whales and sperm whales in the waters near Kauai, and calls typical of each were heard in the acoustic data. Data from eight hydrophones were extracted for closer analysis, and their locations on a bathymetry map of the range are shown in Fig. 1.

Their high signal-to-noise ratio makes sperm whale clicks easy to identify in a timeseries of acoustic data [10]. However, their uniform nature and periodicity make it difficult to associate arrival times for the same click on multiple receivers. Cross-correlation tools previously used in conjunction with the model-based localization were not suitable for the click-association task, so we developed tools that do so by exploiting the periodic nature of the sperm whale clicks. For any given timeseries of acoustic data, timestamps of click arrivals are found using an amplitude threshold to search for brief, loud events. Next, a search for periodic occurrences is conducted by measuring the time difference between any given click and the next several clicks that follow it. Should only one sperm whale be vocalizing, it is easy to detect a periodic pattern of clicks, all of which are then associated with the same individual. When multiple animals are clicking, the assumption that any two clicks are periodic calls from one animal is used to hypothesize when the next click event should occur. If no click is seen at the expected time, the two original clicks are associated with different animals and the search for periodic events repeats with a different pair of clicks. Fig. 2 shows an example of a waveform recorded on hydrophone 501. Dots above the waveform indicate times of click events, and all clicks from the same individual have matching colors. Three click trains have been identified in this example; the ‘red’ and ‘blue’ click trains could be from the same individual as they do not overlap in time.

After timestamps for click trains seen on all receivers have been assigned to individuals, they must then be matched across receivers. The result is a table of arrival times for any single event as observed at several receivers. Given the distance between receivers, the acoustic travel time from a whale to a receiver can be longer than the inter-click interval. Thus, there could be two or more options when trying to align a given click with clicks seen at another receiver. Fortunately, the small differences in inter-click intervals provide enough clues to align click trains unambiguously.

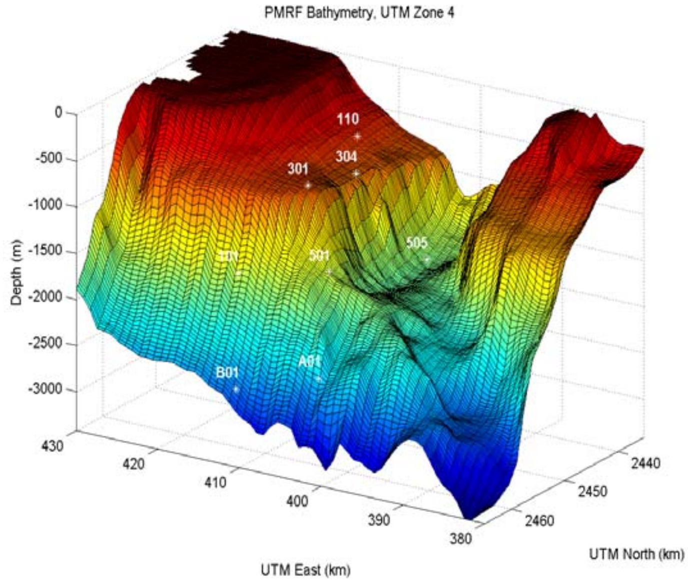

Fig. 1. Bathymetry at PMRF with hydrophone positions labeled. Coordinates are for UTM Zone 4.

Following click association, the differences in arrival times, or time-lags, are calculated for all combinations of receiver pairs and for all events. These time-lags are then passed to the model-based localization algorithm for use in estimating whale position at the time of each click. An acoustic model (BELLHOP ray/beam model) predicts the acoustic travel time from a hypothesized source at several locations around the array to each receiver. The differences between predicted travel times are the predicted time-lags. A comparison between predicted time-lag and measured time-lag generates a likelihood score that an animal was at a particular hypothesized source location. These likelihood scores can then be assembled to make an ambiguity surface, or visual representation of likely whale position. Surfaces from several receiver pairs are added to make an overall surface like that shown in Fig. 3. It represents a planview of waters within the PMRF array, and location estimates common to all receivers overlap to form a peak indicating the most likely origination point for one click.

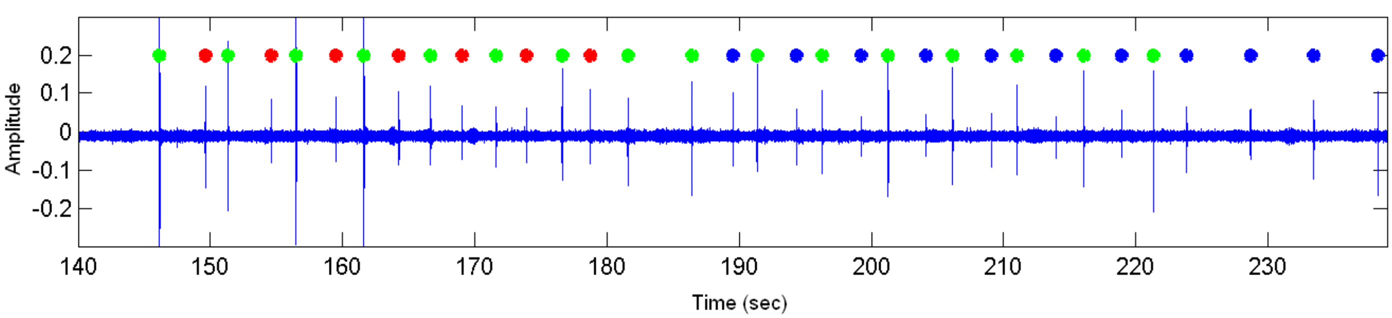

Fig. 2. Timeseries recorded on hydrophone 501 of PMRF at 03/10/02 11:54. Dots over waveform indicate times of sperm whale clicks. The periodic clicks are automatically grouped into click trains with members indicated by dot color.

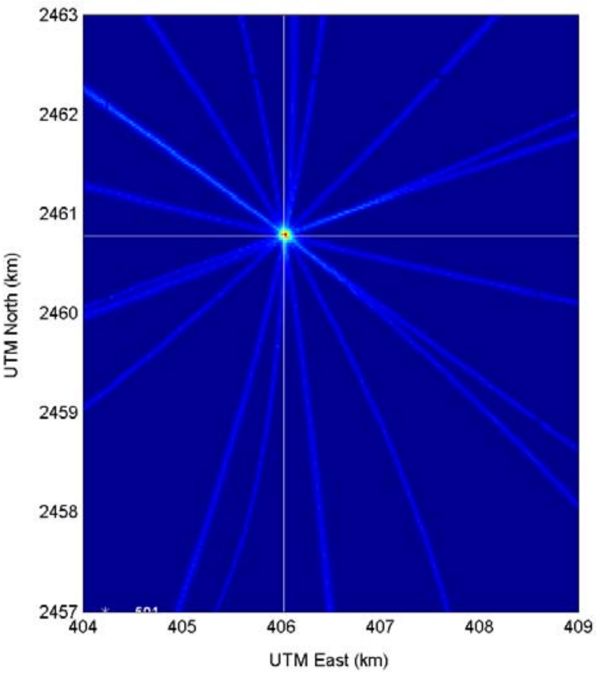

Fig. 3: Plan view of waters within the PMRF array. Axes are for UTM Zone 4. Ambiguity surface from model-based localization shows single sperm whale position estimate with bright peak and crosshair. Data is from 03/10/02 11:52.

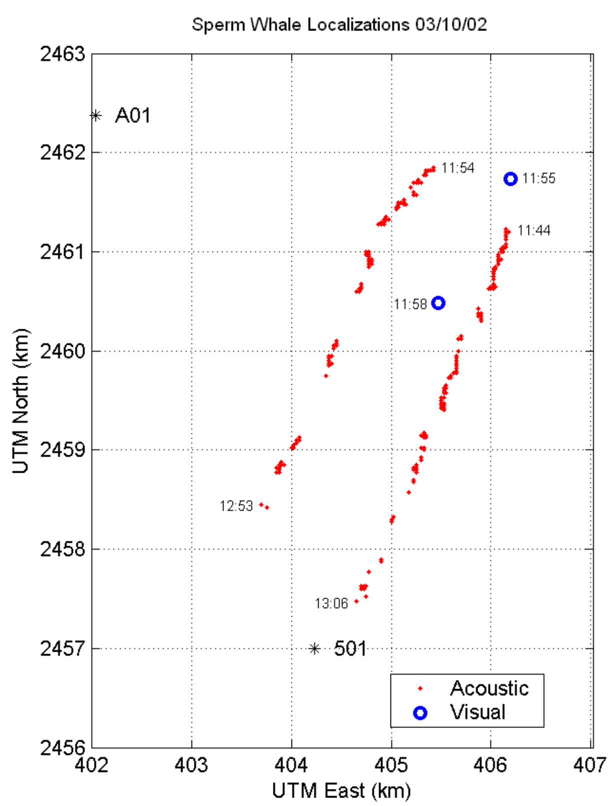

Fig. 4: Planview of waters within the PMRF array with hydrophone positions indicated (A01, 501). Axes are for UTM Zone 4. Points indicate sperm whale location estimates from many consecutive click events tracking two whales on parallel course south. Acoustic data from 03/10/02 11:44-13:06 with timestamps noted by some data points. Sperm whale locations from concurrent aerial survey shown by circles.

An ambiguity surface like that of Fig. 3 was made for every click event detected over 1.3 hours of data. The resulting whale location estimates were then plotted together on the single planview of Fig. 4. Two sperm whales were concurrently tracked along parallel paths heading south through the PMRF range. The times of these tracks coincide with an aerial survey in the immediate area which noted two surfaced sperm whales in close proximity to the acoustically derived locations. Note that while the two closest hydrophone locations are visible in Fig. 4, other hydrophones contributing to this track were over 6 km away.

III. ALGORITHM VALIDATION AT AUTEC

Previously, all demonstrations of source localization with the model-based algorithm used marine mammal calls as noise sources. The resulting tracks of whale motion were reasonable, but there was no way to confirm the localizations or estimate errors. A controlled-source experiment at AUTEC provided the data necessary to validate the algorithm and compare its output to the more traditional hyperbolic fixing method.

Acoustic data from 31 bottom-mounted broadband hydrophones of the AUTEC range were recorded for several hours on July 20 and 21, 2002. During these recordings, a towed source moving through the range transmitted a variety of signals: LFM sweeps, simulated pilot whale and humpback whale calls, and a recorded sperm whale click. Tow-ship position was noted from GPS, and XBTs provided environmental data for the acoustic modeling component of the localization algorithm. Bathymetry under the experiment area was relatively flat at about 1800 m depth as shown by the map of Fig. 5. Positions of hydrophones used in the analysis to follow are shown as well.

The AUTEC experiment was being conducted as a test of the M3R toolset for marine mammal tracking as developed by Naval Undersea Warfare Center (NUWC). Therefore, in addition to the acoustic data set, NUWC also provided output from its M3R tools. M3R output includes results from its own click detection and association tools, times of arrival information, and the resulting hyperbolic fixing localizations. To demonstrate integration with existing M3R tools, we used the M3R time of arrival information to calculate receiver pair time-lags which were then passed to the model-based localization algorithm. Model-based localizations were compared to M3R localizations and GPS positions to determine accuracy.

A recorded sperm whale click was repeatedly broadcast for over an hour on July 21, 2002, as the tow-ship moved northwest through the range. M3R output for that hour included click time of arrival information for the following hydrophones near the ship path: 44, 49, 50, 51, 57. All of these hydrophones are within the direct-path radius of the source; acoustic paths without reflections existed between the source and all receivers. Predicted time-lags were calculated with the acoustic model and compared to the measured time-lags provided by M3R.

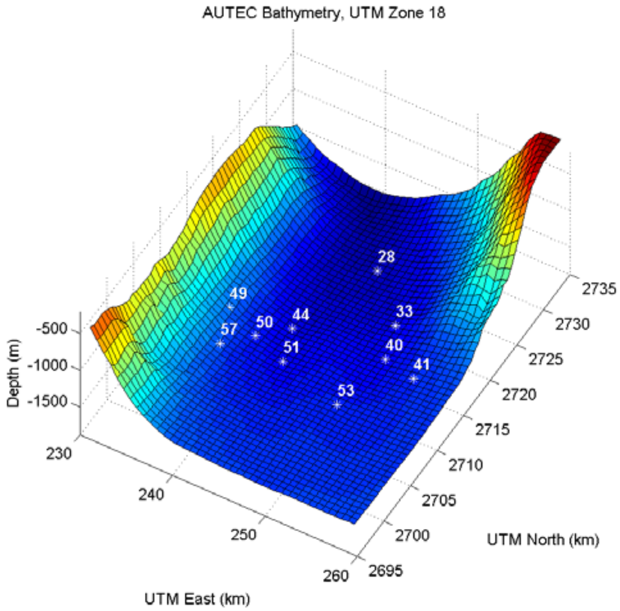

Fig. 5: Bathymetry at AUTEC with hydrophone positions labeled. Coordinates are for UTM Zone 18. The box of hydrophones (44, 49, 50, 51, 57) were used for direct-path localization while the others were used for long-range, indirect-path localization.

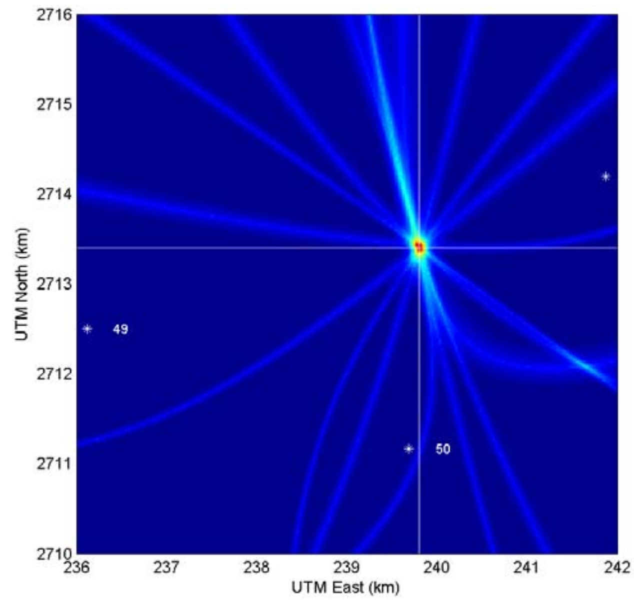

Figure 6: Plan view of waters within the AUTEC array with hydrophone positions labeled. Axes are for UTM zone 18. Ambiguity surface from model-based localization shows single click position estimate with bright peak and crosshair. Data is from 07/21/02 18:27.

An ambiguity surface like that of Fig. 6 was generated for each click, and source location estimates extracted from each surface.

Model-based source location estimates from 2814 click broadcasts are shown in Fig. 7 along with hydrophone positions. A smooth, consistent track that follows the source as it moves northwest is seen. The same localization data was then overlaid on a plot of known ship position and localizations from M3R tools as shown in Fig. 8. (Note that UTM coordinates of Fig. 7 have been converted to latitude/longitude coordinates for easy comparison to GPS positions.)

In Fig. 8, both model-based and hyperbolic localizations consistently overlap. The model-based localizations appear quantized because of the 20 m search grid used when hypothesizing source locations during the

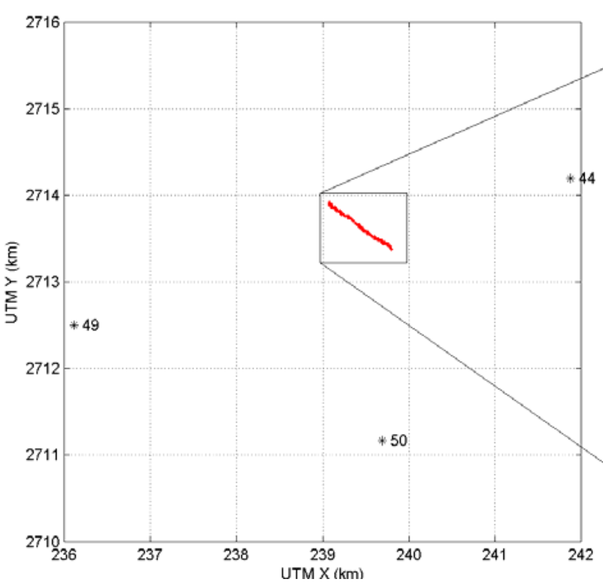

Fig. 7. Planview of waters within the AUTEC array with hydrophone positions indicated (44, 49, 50). Axes are for UTM Zone 18. Points indicate model-based click location estimates from 07/21/02 18:27–19:16 which follow a controlled source towed northwest through the range.

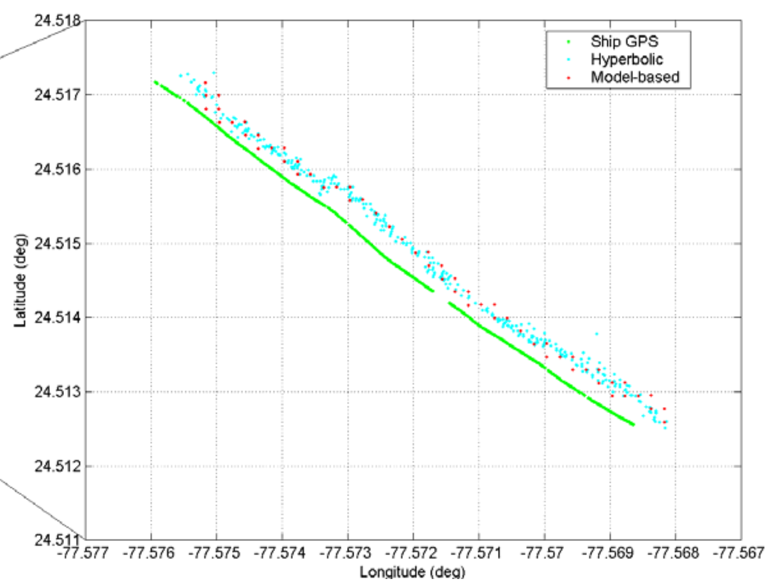

Fig. 8. A zoom of the boxed area in Fig. 7. Points show tow ship GPS (green), M3R localizations (blue), and model-based localizations (red). Localization methods agree well when localizing with direct acoustic paths. Offset of ship path and acoustic localization is due to separation between GPS antenna and towed source.

acoustic modeling stage. As a result, many click events can localize in the same search bin and thus will appear as just one localization point. Both localization methods routinely place the source about 50 m away from the ship GPS position. This is a reasonable horizontal offset given the distance between the ship's GPS antenna and towed source. Conclusions drawn from Fig. 8 are that both localization techniques can correctly localize a source equally well in geometries where direct acoustic paths exist between a source and all receivers. Performance for long-range localizations was compared next.

IV. INDIRECT-PATH LOCALIZATION AT AUTEC

The benefits of model-based localization should be most evident when trying to locate a source in geometries where the direct-path assumption of hyperbolic fixing is invalid. This will often be the case at long ranges or in shallow water where the only acoustic paths between source and receiver are those that reflect off the sea surface and sea floor. Before validating the long-range capability of the model-based algorithm, it was first necessary to determine the direct-path radius of the AUTEC range, or how far away from the source direct paths exist.

The acoustic model BELLHOP was used to predict acoustic paths from a source at 55 m depth in a range-independent environment similar to that of the AUTEC range. These acoustic paths are shown in Fig. 9. Refractive effects from a downward refracting soundspeed are evident, as are reflections off the seafloor 8-10 km away from the source. From this figure, one can assume that 10 km is the direct-path radius as that is the maximum range of the first seafloor reflection.

Acoustic data from the same times as the previous short-range validation, but for hydrophones at distances beyond the direct-path radius, were examined. The hope was to compare short- and long-range localization by using data only from indirect acoustic paths to locate the same click events. Unfortunately, clicks could not be heard on any receiver beyond the direct-path radius; attenuation from the bottom reflection may have been too great. However, 4-second LFM sweeps (3-12 kHz) broadcast earlier in the experiment could be heard at ranges over 10 km, despite the bottom reflection. Therefore, hydrophones far to the north and east (28, 33, 40, 41, 53) were used to demonstrate indirect-path localization of a sweep.

Because M3R tools are typically applied to data from hydrophones close to the source, automatically generated M3R arrival time output and localization did not exist for the hydrophones selected for long-range use. Arrival times at the far hydrophones of an LFM sweep at 07/21/02 16:42 were manually noted instead. The sweep was then localized using both the model-based and hyperbolic fixing techniques.

Hyperbolic fixing relies on the intersection of hyperbolic curves defined by pair-wise time-lags to identify a source location. The technique assumes a straightline acoustic path between source and receiver

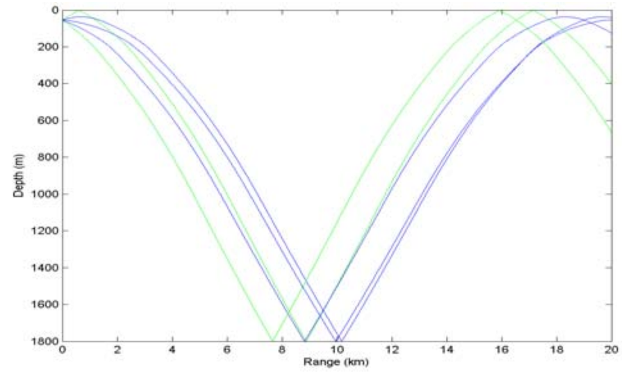

Fig. 9. Predicted acoustic ray paths from a 55 m deep source propagating in the AUTEC environment. The direct-path radius, or maximum range of non-reflected paths, is about 10 km.

through a medium with a constant soundspeed, independent in both range and depth. When all these approximations are valid, the hyperbolic curves will intersect at a single point that is the estimate of source position. Fig. 10 shows the resulting hyperbolic curves when using data from the hydrophones indicated. A closer view of the area around the intersections (Fig. 11) shows that the many curves do not converge on a single solution; there are several candidate intersection points distributed over a few hundred meters.

The same time-lag information used for hyperbolic fixing was then provided to the model-based localization algorithm to compare indirect-path localization accuracy. An ambiguity surface was constructed and is shown in Fig. 12. Note that Fig. 12 is showing the same 2 km^2 zoom planview as Fig. 11, but recall that all contributing hydrophones were over 10 km away. The peak of the ambiguity surface and best estimate of source location is indicated by the crosshair. The location estimate is within 50 m of the ship GPS antenna, the same offset seen earlier in Fig. 8.

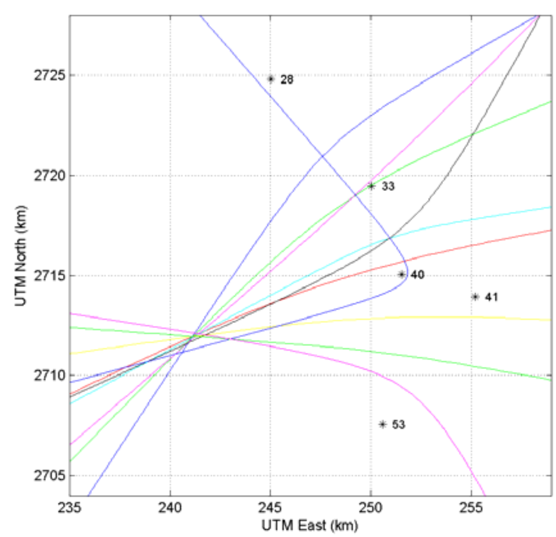

Fig. 10. Planview of the waters within the AUTEC array with hydrophone positions indicated. Axes are for UTM Zone 18. Curves from long-range hyperbolic fixing intersect at several possible source positions. Acoustic data is from an LFM sweep at 07/21/02 16:42.

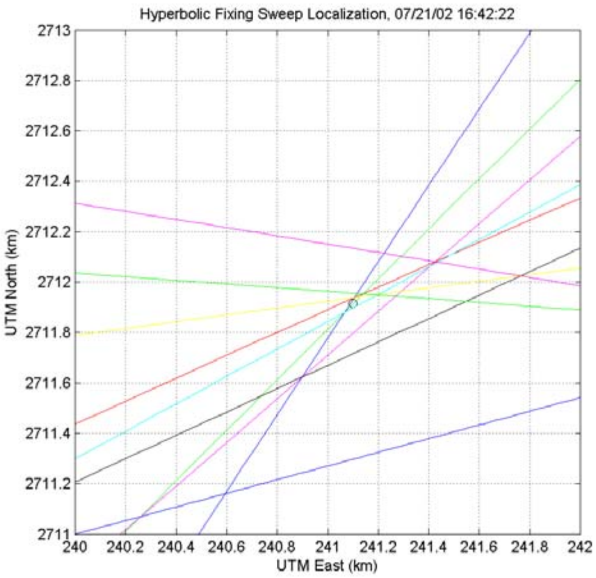

Fig. 11. A zoom of the intersection area of Fig. 10. Hyperbolic curves do not intersect at a single location estimate. Ship GPS location is shown by the circle.

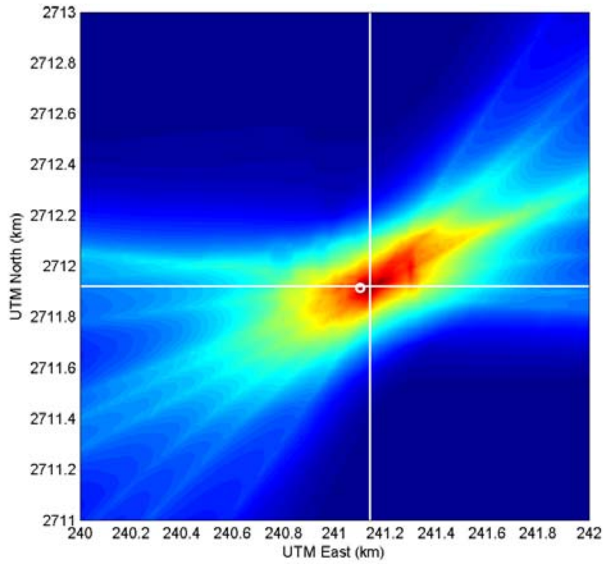

Fig. 12. Planview of the same area within the AUTEC array as that of Fig. 11. Axes are for UTM Zone 18. Ambiguity surface from model-based localization shows sweep position estimate with bright peak and crosshair. Ship GPS location is shown by the circle. Acoustic data is from an LFM sweep at 07/21/02 16:42 recorded on hydrophones over 10 km away.

V. CONCLUSIONS

Passive acoustic localization has the potential to be a valuable tool in marine mammal mitigation efforts, and one goal of this research was to validate acoustic localization methods. Against a controlled source of known position, the model-based localization algorithm performed well in accurately tracking a target moving over a sparse array of passive acoustic receivers. The opportunity to compare acoustic tracking versus visual observations of live animals is also beneficial in that it can provide insight into comparing detection statistics of both.

Traditional hyperbolic fixing and new model-based localization techniques were shown to be equivalent when tracking sources within the direct-path radius of receivers. Either technique should be satisfactory at tracking marine mammals within heavily instrumented ranges such as AUTEC. However, with their added accuracy in indirect-path environments, model-based localization tools should be considered for extending coverage areas farther beyond array boundaries or in areas with sparse receiver coverage.

This work also resulted in additional advances of the model-based localization algorithm. It was tested against yet another species of marine mammal (sperm whale) and on another Navy range (AUTEC) with success. Click association tools were added to the algorithm if needed for sperm whale localizations, as well as the ability to integrate with existing M3R tools. Also added was the ability to track multiple clicking targets simultaneously. Lastly, the algorithm achieved its longest-range localization yet, using five widely-spaced hydrophones with a 17 km baseline, all over 10 km away from the source.

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