Passive Detection and Localization of Transient Signals from Marine Mammals using Widely Spaced Bottom Mounted Hydrophones in Open Ocean Environments

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***Abstract*:** One objective of the Marine Mammal Monitoring on Navy Ranges project is to use existing Navy undersea range infrastructure to develop a toolset for passive detection and localization of marine mammals. The Office of Naval Research funded the M3R project as part of the Navy's effort to determine the effects of acoustic emissions on marine mammals and threatened/ endangered species. A necessary first step in this effort is the creation of a baseline of behavior which requires long-term monitoring of marine mammals. Such monitoring, in turn, requires the ability to detect and localize the animals. This paper will present algorithms for passive detection and localization of transient signals developed as part of the M3R toolset. It will also present results of the application of these tools to detection and tracking of various toothed whales at the Atlantic Undersea Test and Evaluation Center (AUTEC), Andros Island, Bahamas.

1.0 Introduction

Navy undersea ranges such as the Atlantic Undersea Test and Evaluation Center (AUTEC) use arrays of widely spaced bottom mounted hydrophones to acoustically track undersea and surface vehicles. Traditionally, the vehicles are equipped with acoustic pingers that emit known identification signals at known repetition rates. Increasingly, range instrumentation infrastructure (figure 1) is being applied to non-traditional tracking problems. The Marine Mammal Monitoring on Navy Undersea Ranges (M3R) program has developed a set of signal processing tools to detect and track marine mammals using Navy range facilities [1]. Under the M3R program, algorithms were developed to automatically detect and track two classes of whale vocalizations -- clicks and whistles. Both of these classes of signals are transient in nature. The tool set was recently tested at AUTEC over a two-week period. Over five hundred square nautical miles of ocean were simultaneously monitored via 68 broad-band hydrophones. Several species of toothed whales where automatically detected and tracked in real-time. The positional accuracy of the M3R tracking tools was confirmed by visual sightings by a surface craft and by manual analysis of the hydrophone data.

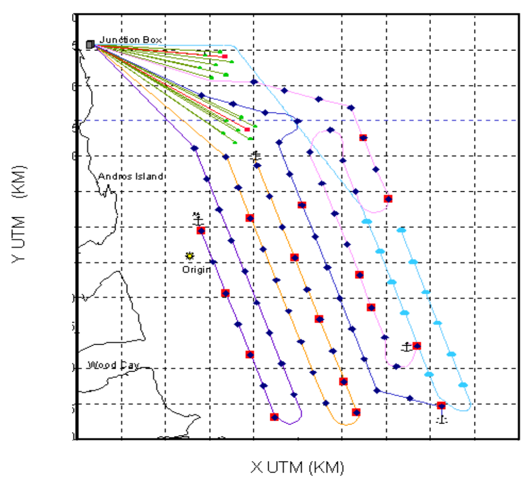


Figure 1: AUTEC has sixty eight, broad-band bottom mounted hydrophones with a 2 NMi baseline.

2.0 Discussion

Visual sightings [2] and aural analysis of hydrophone recordings [3] indicate that many species of toothed whales are present at AUTEC. The most commonly seen and heard are sperm whales, dolphins and short finned pilot whales, all of which are present nearly year round. Consequently, the M3R tools were developed to detect and track these common species. For purposes of algorithm development, the vocalizations produced by the whales were characterized as clicks and whistles. Clicks are, in general, any impulsive, broad-band signal. However, sperm whale clicks were of particular interest. Sperm whale clicks are very distinct, have high source level, and occur in regular patterns [4] or "click trains" (figure 2). Whistles were more broadly defined as any narrowband event that sweeps in frequency over time (figure 3).

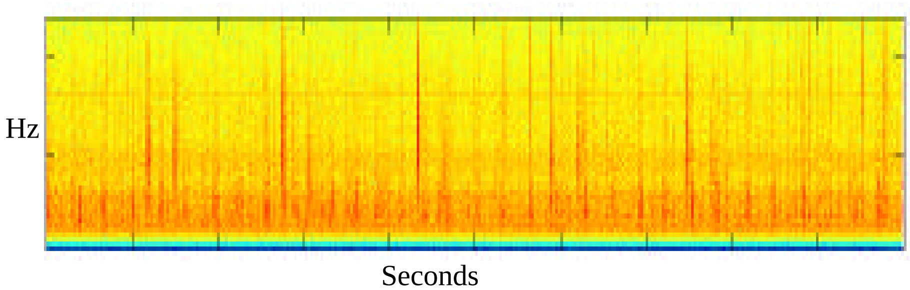


Figure 2: Spectrogram showing sperm whale clicks from several individuals

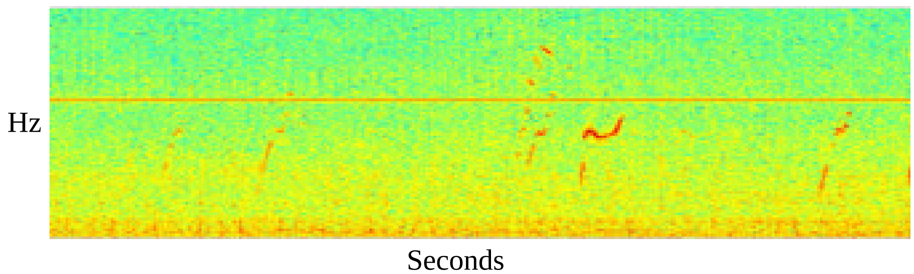


Figure 3: Spectrogram showing a sequence of whistles probably from a short finned pilot whale

There are three distinct parts to the whale localization problem. First the vocalizations or whale calls must be automatically detected. In order to determine the position of the animal in three dimensions, a given call must be detected on a minimum of four hydrophones. The second part of the problem is the association of the detections received on various hydrophones with each other. That is, one must be able to determine that the call received on hydrophone A at time t_A is the same signal that was received by hydrophone B at time t_B. Finally, associated sets of arrival times are input into a multilateration algorithm to solve for position. A three-dimensional hyperbolic positioning model [5] is used to determine the vocalizing animal's location in X, Y, and Z as well as the time of emission of the call.

M3R employs a real-time frequency domain energy detector for whale call detection. A spectrogram of the incoming acoustic data from each of the hydrophones is formed using 512-point fast Fourier transforms (FFT) with a rectangular window and fifty percent overlap. The resultant spectrogram has a frequency resolution of approximately 51 Hz and a time resolution of approximately 9.8 ms. Each time-frequency bin of the spectrogram is compared to a time varying threshold, $D(f,t)$. The threshold is set to be m dB above the (time) average power within frequency bin f. The output of the detector, $Q_i(f,t)$, for each hydrophone, is a binary valued "detection spectrogram" which contains a 1 in each time-frequency bin that exceeded $D(f,t)$ and a 0 everywhere else (figure 4). The detection spectrogram indicates, in real-time, the presence of whale vocalizations as well as providing information on their frequency content. As evident in figures 2 and 3, the signal structure of (sperm whale) clicks is very different from the signal structure of whistles. Therefore, separate detection association algorithms were developed for each signal type.

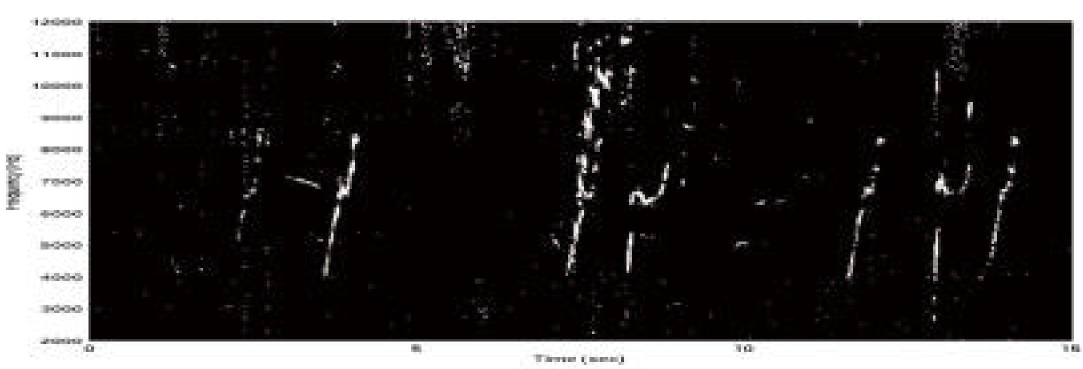


Figure 4: Detection spectrogram, $Q(f,t)$, of whistles. Threshold was set 6-dB above the average spectral power.

A series of clicks from a single sperm whale exhibits nearly the same inter-click interval on all receiving hydrophones. Calls from each additional animal exhibit their own unique pattern. In fact, inter-click interval patterns were found to be an effective means of both differentiating between individual whales and associating patterns of detections among hydrophones [6]. In the first step of the M3R click association algorithm the time-frequency detection spectra from all hydrophones were reduced to binary "click maps". Click maps contain a 1 for time indices where broad band events occurred in the detection spectrum and 0 for all other times (figure 5). Conceptually, the next step is to cross correlate the click maps from several hydrophones with a master hydrophone to find the difference in time of arrival between each hydrophone and the master. However, care must be taken in implementing the cross correlation in order to properly associate each click detection among the hydrophones. Figure 6a shows an example of a click map from a single hydrophone containing clicks from two individuals. Figure 6b shows the click map from a second hydrophone over the same time period. The question is which clicks in figure 6b belong to which individual?

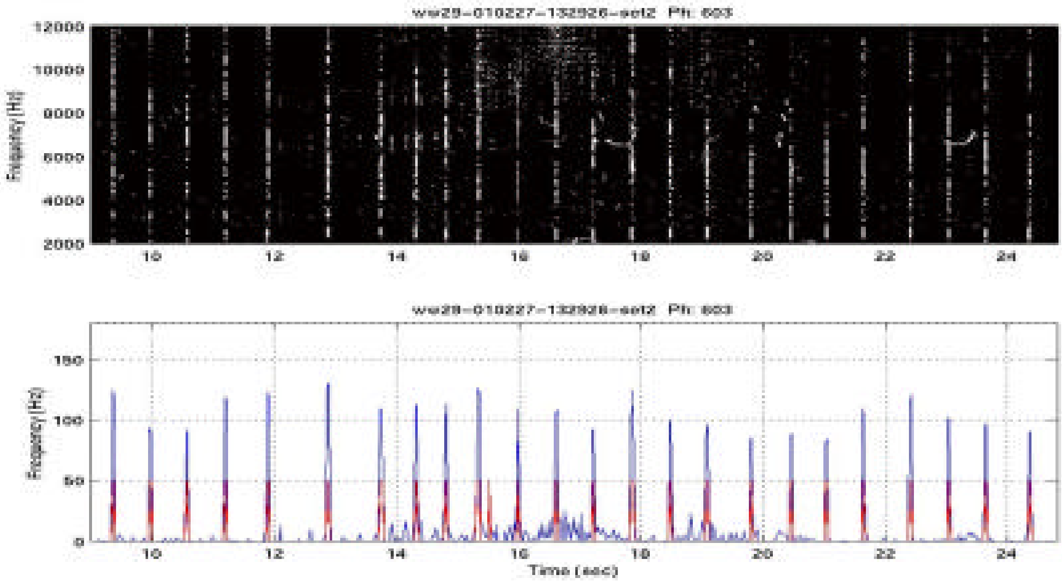


Figure 5: Click maps are formed by summing the detection spectrum (above) along frequency then thresholding the sums. The red curve indicates the click map for this data.

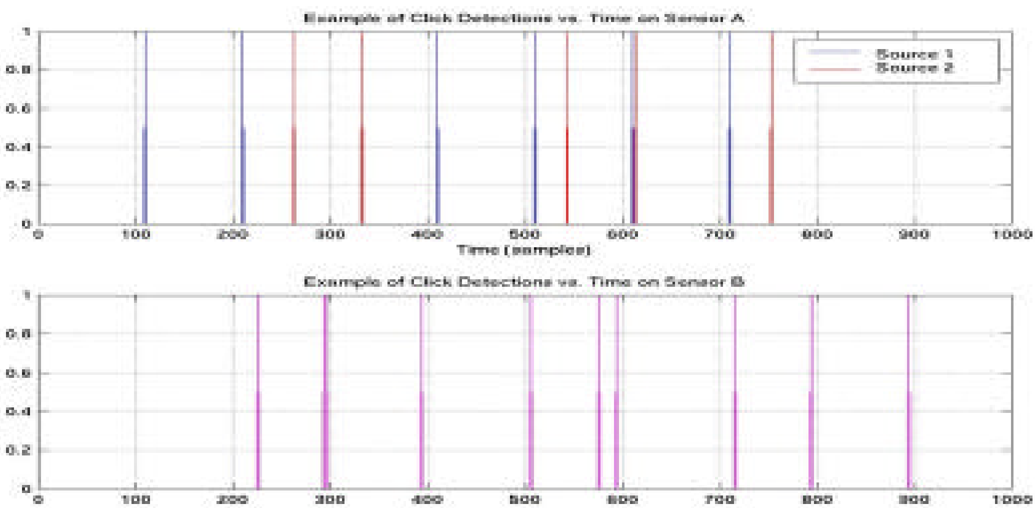


Figure 6: Click maps for two hydrophones containing clicks from two individuals. It is not evident which clicks received by hydrophone B are associated with Source 1 or Source 2.

The M3R click association algorithm uses the notion of a “scanning sieve” [7] to match detection patterns between hydrophones. The sequence of click detections (i.e. click map) within the scanning sieve on the master channel is compared to the clicks maps from surrounding hydrophones (“scanned” signals). The scanning sieve time window always starts on a click detection, and is moved across the scanned signal one click detection at a time. That is, the resultant correlation value at any time delay represents the number of matches between the master channel pattern starting a specific click and the scanned channel pattern starting at a specific click. The delay of the maximum correlation value represents the difference in time of arrival where the first clicks in the scanning sieve and the scanned signal were best aligned. The output of the scanning sieve process are sets of time difference of arrival (TDOA) for each click detection received on the master channel (figure 7). The TDOA data from each hydrophone are then histogrammed to estimate the number of separable sources (figure 8). Only detections associated with significant populations are used (figure 9). These associated TDOA sets are then sent to the AUTEC multilateration tracking algorithm which calculates 3D position.

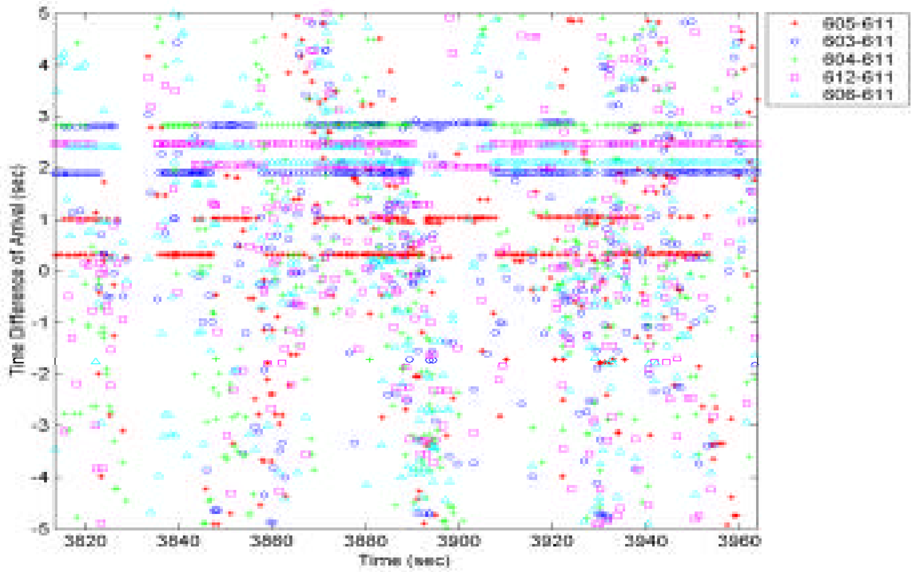


Figure 7: Preliminary output of the M3R click association algorithm showing the estimated TDOA between the scanning sieve, hydrophone 611, and five additional hydrophones.

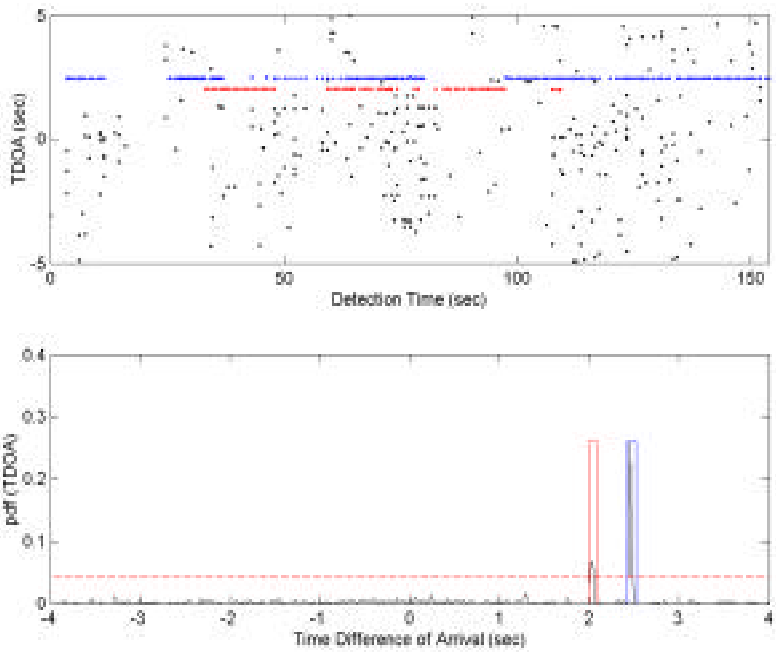


Figure 8: Above is the output of the click association algorithm for hydrophone 612 (indicated in purple in figure 7). Two separate times of arrival are evident indicating the presence of 2 whales. A histogram of the TDOA data shows two significant populations.

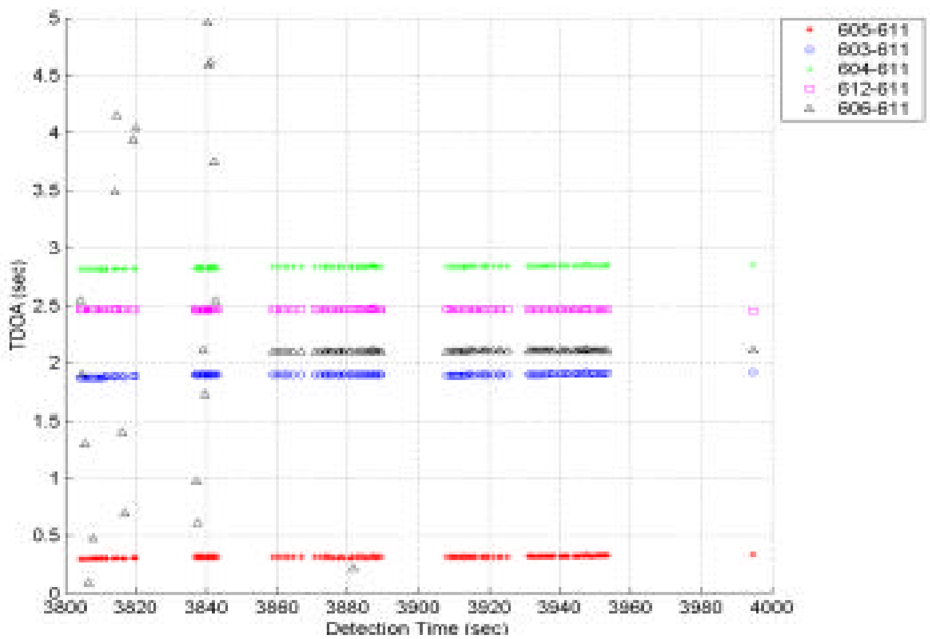


Figure 9: Final output of the click association algorithm for calls from a single sperm whale. The points indicate the TDOA at which the algorithm found the best matches between the scanning sieve and the clicks maps of hydrophones 605, 603, 604, 612 and 606 relative to master hydrophone, 611. Notice the minimal scatter of the TDOA points.

Whistle vocalizations do not typically follow known repetition patterns. An individual can emit a single short whistle or groups of sweeps that last several seconds or both. However, the time-frequency characteristics of the calls in whatever sequence they may occur remain the same on all receiving hydrophones. To determine the TDOA of signals among the hydrophones, the detection spectrograms $Q(f,t)$ of the available hydrophones are cross-correlated against a master channel, M [8]. The cross correlation $C_i(t,\tau)$ between the i-th channel and the master channel is calculated over a time window of approximately 6 to 10 seconds. That time window is then advanced by one half its duration and $C_i(t,\tau)$ is updated.

$$C_i(t,\tau) = \Sigma\ \Sigma\ Q_M(f,t)Q_i(f,t+\tau)$$

The time delay associated with the peak of the correlation functions indicates the TDOA for a signal relative to the master hydrophone (figure 10a). If whistles from multiple whales are present within a cross correlation time window, multiple correlation peaks will be evident (figure 10b). Note that if both clicks and whistles are present at the same time, sperm whale clicks will dominate the detection spectra. Correlation peaks due to whistle signals will be obscured. Therefore, for practical purposes, broad-band click events should be removed from the detection spectra prior cross correlation.

While cross correlation of detection spectra indicates times of signal arrival and the presence of multiple whales, it does not associate the time delays of the correlation peaks with an individual across the hydrophone channels. However, as mentioned early, the sequence of whistles from an individual is the same on all receiving hydrophones. Figure 11 shows the time differences of arrival relative to a master hydrophone of the correlation peaks for five hydrophones. Notice that there are two distinct patterns of detections versus time along specific time delays. Matching these patterns along time delays associates the TDOA's among the hydrophones with an individual whale. Associated sets of TDOA can then be the sent to the multilateration tracking algorithm which calculates 3D position.

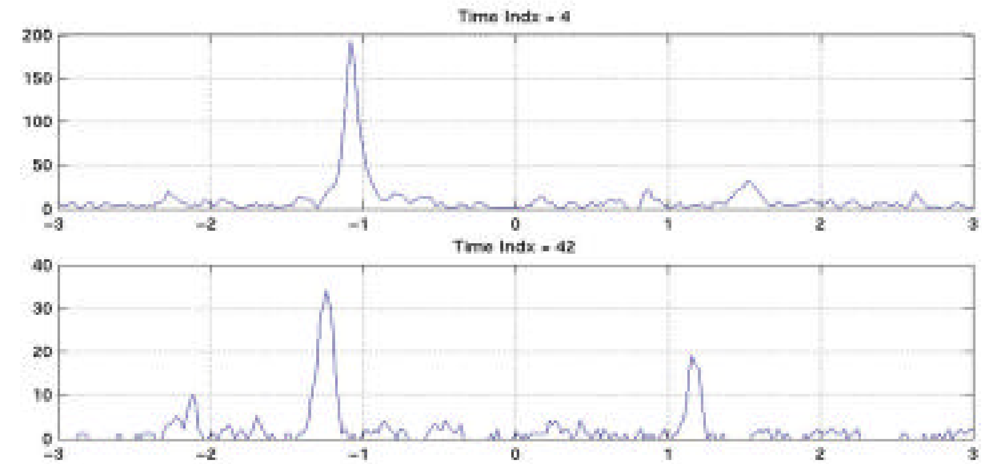


Figure 10:
a) Results of cross correlation indicating the TDOA of the signal from one whale.

b) Cross correlation results indicating the TDOA's of signals from two whales.

Figure 11: TDOA data resulting from cross correlations of five hydrophones against a master hydrophone. Two individual whales show two distinct patterns (indicated by purple and green boxes) of detections versus time along specific TDOA's.

3.0 Recent Results

The M3R toolset was demonstrated at AUTEC as part of a joint experiment with researchers from Woods Hole Oceanographic Institution (WHOI). The WHOI team was testing a new whale tagging system [9]. The M3R algorithms were used with sixty-eight of the AUTEC hydrophones to monitor over 500 sq. NMi. When marine mammals were localized, their positions were relayed to the tagging vessel, which then endeavored to maneuver close enough to place a tag.

The detection, association and tracking algorithms described in Section 2.0 were implemented to run in real-time for arrays of five to seven hydrophones. Given that there were 68 hydrophones to monitor, other display tools were used to broadly locate whales before applying the high resolution positioning algorithm. The Circle display is a Matlab program that shows the number of detections on each hydrophone by drawing a circle around the respective hydrophone. The number of detections per minute is mapped to the color of the circle. Figure 12 shows an example of the Circle display while two groups of whales were on the range. The bright circles around Hydrophone 85 were caused by a single clicking sperm whale. The bright circles around Hydrophone 53 were caused by a group of pilot whales just off the range (hydrophones 47, 48, 54 and 55 were not monitored). The WHOI team successfully tagged two of the pilot whales shortly after this picture was taken.

The strip chart program displays the detection spectrogram from a particular hydrophone in real-time. The program reads the detection data from a server process allowing the user to run multiple charts on multiple computers simultaneously. During the AUTEC tests this display was quite handy for monitoring phones over a wide area. At various times, both broad sperm whales clicks, and pilot whale clicks and whistles were evident (figure 13).

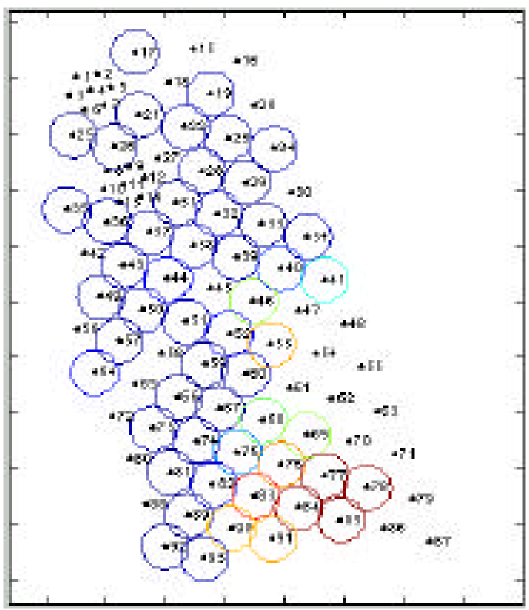


Figure 12: Circle detection count display. maps color of the circle around a hydrophone to the number of detection per minute.

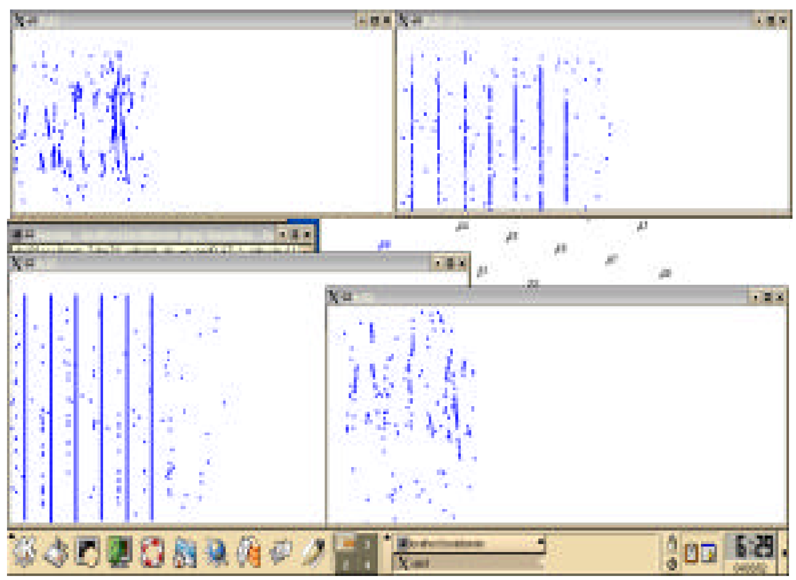
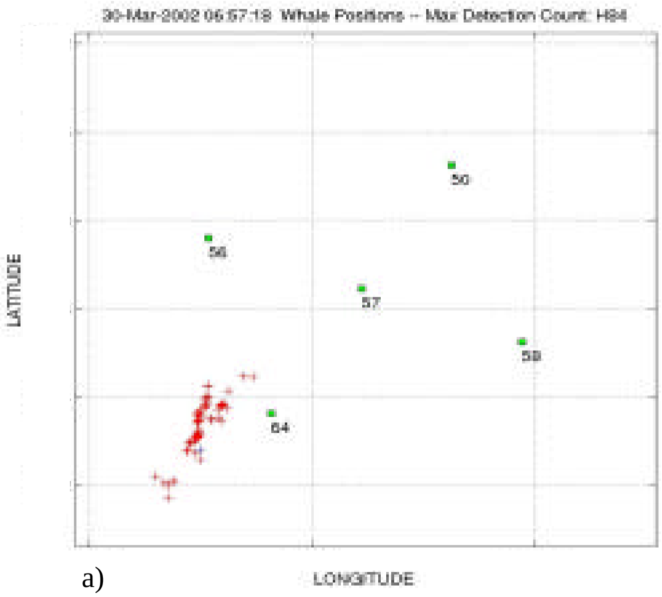


Figure 13: Strip chart displays scroll horizontally to display detection spectra for a given hydrophone in real-time. The top right and lower left charts show sperm whale clicks while the top left and lower right show whistles.

Both the click association and whistle association algorithms worked well during the exercise. Vocalizing whales were heard on range almost everyday. At different times, individuals and/or groups of sperm whales, short finned pilot whales, roughed toothed dolphins, melon headed whales and even a beaked whale were all detected and tracked by the M3R algorithms. The track positions produced by M3R were confirmed by GPS readings and visual observations from the tagging vessel, as well as by manual monitoring of the hydrophones. Figures 14a-b show an example of real-time X-Y position and depth plots for a group of two or three sperm whales. The depth plot indicates that these whales were likely performing deep feeding dives. On some dives monitored during the test, sperm whales were tracked at depths of 1000 to 1200 m. Figure 14c shows the depth track for a single sperm whale that was performing shallow, near-surface dives. Figure 15 shows the real-time X-Y position plot for a group of whistlers, which were later



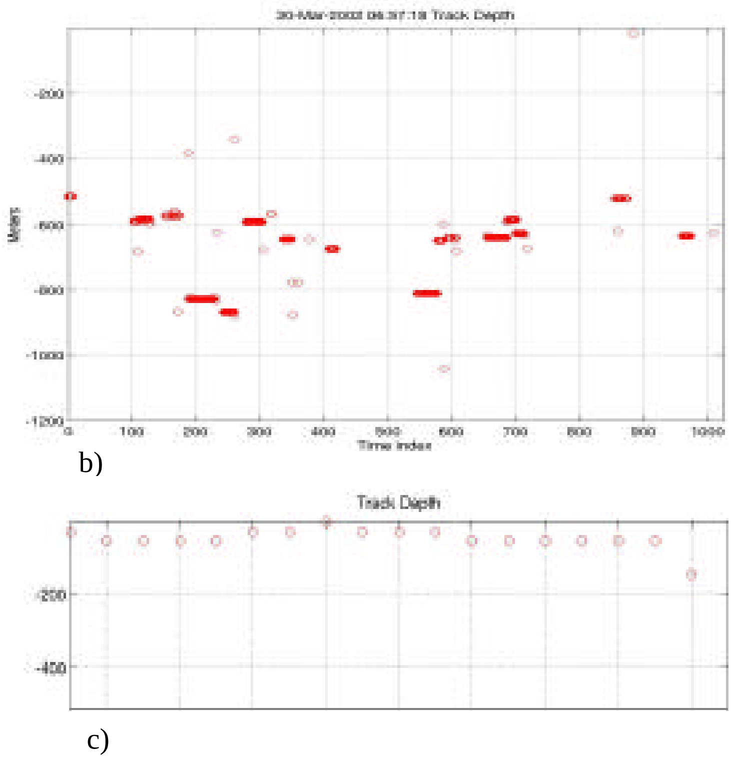


Figure 14: Examples of position and depth plots for sperm whales. a) Real-time X-Y display for a group of 2 or 3 individuals. b) The depth plot for that group. c) A depth plot showing the shallow dives of a single sperm whale.

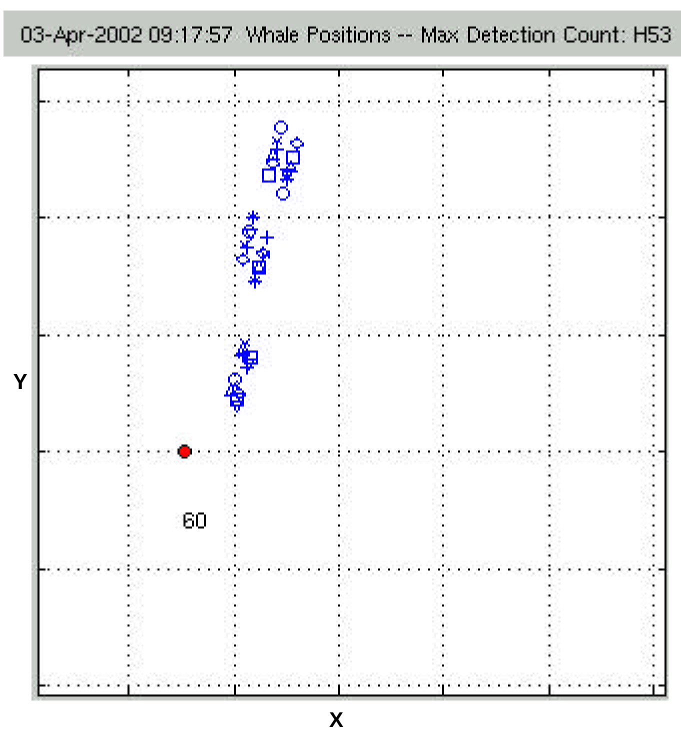


Figure 15: A real-time X-Y position plot for multiple whistlers. The icon shapes indicate the individuals that the M3R tools were able to identify. This group was observed by researchers aboard the WHOI whale tagging vessel. The group consisted of more than twenty roughed toothed dolphins and melon headed whales.

4.0 Summary

The M3R project has developed algorithms for the passive detection and tracking of marine mammals using widely spaced, bottom-mounted hydrophones characteristic of Navy undersea tracking ranges. While these algorithms have been implemented and tested for deployment at the AUTEC, they are applicable to any fixed or portable range that uses multilateration tracking algorithms. Potential ranges with the hardware to support the M3R system include the Pacific Missile Range Facility, the Southern California Offshore Acoustic Range, and any of the Navy's various portable systems.

The M3R algorithms have been designed to work in a highly channelized multi-processor hardware environment, and the software architecture has been developed to be fully network compatible. Signal detection, and detection-association algorithms for two primary types of whale calls, whistles and clicks, have been developed. These algorithms are specifically designed to be used with widely spaced sensors, and assume that the marine mammals vocalize repetitively with sufficient source levels to be detected on multiple hydrophones.

The M3R algorithms, for both clicks and whistles, have been successfully demonstrated resulting in real time 3D tracking of several species of toothed whales including sperm whales, rough toothed dolphins, melon headed whales and pilot whales. The M3R tool set allows automated collection of data previously unavailable for the long-term monitoring of marine mammal bioacoustics within their natural environment. This opportunity has been created with minimal investment in infrastructure by providing Navy ranges as a dual-use asset. Research applications of the M3R system include the ability to remotely estimate marine mammal abundance, assessment of bioacoustic behavioral baselines, and evaluation of the impact of anthropogenic noise compared to those baselines.

Acknowledgement

We would like to acknowledge our sponsor, Dr. Robert Gisiner, at the Office of Naval Research, for funding this project. We would also like to thank the AUTEC personnel, especially Thomas Szlyk, for access to their considerable infrastructure and ongoing support. In addition, we would like to thank the NUWC Division Newport ILIR program manager, Richard Philips, for supporting the initiative to create a baseline sperm whale bioacoustic characterization in the Tongue of the Ocean (TOTO).

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