Biomimetic Signal Processing Using the Biosonar Measurement Tool (BMT)

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Abstract. In this paper data recorded on the Biosonar Measurement Tool (BMT) during a target echolocation experiment are used to 1) find ways to separate target echoes from clutter echoes, 2) analyze target returns and 3) find features in target returns that distinguish them from clutter returns. The BMT is an instrumentation package used in dolphin echolocation experiments developed at SPAWARSYSCEN. It can be held by the dolphin using a bite-plate during echolocation experiments and records the movement and echolocation strategy of a target-hunting dolphin without interfering with its motion through the search field. The BMT was developed to record a variety of data from a free-swimming dolphin engaged in a bottom target detection task. These data include the three dimensional location of the dolphin, including its heading, pitch roll and velocity as well as passive acoustic data recorded on three channels. The outgoing dolphin click is recorded on one channel and the resulting echoes are recorded on the two remaining channels. For each outgoing click the BMT records a large number of echoes that come from the entire ensonified field. Given the large number of transmitted clicks and the returned echoes, it is almost impossible to find a target return from the recorded data on the BMT. As a means of separating target echoes from those of clutter, an echo-mapping tool was developed. This tool produces an echomap on which echoes from targets (and other regular objects such as surface buoys, the side of a boat and so on) stack together as tracks, while echoes from clutter are scattered. Once these tracks are identified, the retuned echoes can easily be extracted for further analysis.

INTRODUCTION

Dolphins have an impressive ability to identify underwater targets using their biological sonar (biosonar) system. They can identify objects based on their shape, exterior wall thickness and exterior and interior material compositions. A variety of reasons contribute to this uncanny ability. From a purely sonar point of view, there are at least two reasons that enable the dolphins to identify underwater targets with such success. One of these reasons is that dolphins can inspect objects by emitting trains or sequence of impulsive sound known as clicks whose frequency content and amplitude as well as inter-click separation can be adaptively controlled. The other reason is that the dolphin sonar operates on a highly mobile platform. They can move around the object of interest, ensonify it at different angles and obtain different "look" directions in much the same way as humans visually inspect objects at different angles. The dolphin clicks are approximately 50-100 μs long with peak frequencies typically ranging between 30-150 kHz and fractional bandwidth between 10%-90% of peak frequency [1,2]. Although the outgoing clicks are brief, echoes reflected from objects can be several milliseconds long rich with information about the object's shape, orientation and composition. The inter-click separation as well as the click amplitude and frequency content can be adjusted depending on the range to and the type of object being interrogated. However, of the three major subsystems that make up the echolocation system, namely reception, transmission and signal processing, despite their impressive performance, the dolphin's reception and transmission subsystems are quite mediocre compared to its signal processing capabilities [3]. It is how dolphins process, integrate and direct sonar functions that gives them the unsurpassed ability to identify underwater objects.

It is the overall performance of the dolphin sonar that has been the subject of extensive research. The objective of many researchers has been to learn how dolphins solve the classification problem and to construct analogous, biomimetic mechanisms. The SPAWAR Systems Center, San Diego (SSCSD) has conducted experiments with dolphins since the 1960's. In these experiments SSCSD researchers have addressed the characteristics of echolocation clicks, mechanisms of click production and echo reception and the adaptive production of clicks relative to the echolocation task performed. To investigate the echolocation strategies of a target-hunting dolphin during a target detection and identification experiment, the team at SSCSD has developed the Biosonar Measurement Tool (BMT) and the Instrumented Mine Simulator (IMS) [4]. The BMT is an instrument that can be held by the dolphin using a bite-plate during an echolocation experiment (see Figure (1)). It records the movement and echolocation strategy of a target-hunting dolphin without interfering with its motion through the search field. The BMT can record a variety of data from a free-swimming dolphin engaged in a bottom target detection task. These data include the three dimensional location of the dolphin, including its heading, pitch roll and velocity as well as passive acoustic data recorded on three channels. The outgoing dolphin click is recorded on one channel and the resulting echoes are recorded on the two remaining channels. The IMS is an instrument that records echolocation clicks at a mine simulator.

In this paper data recorded on the BMT during an echolocation experiment are used to 1) find ways to separate target echoes from clutter echoes, 2) analyze target returns and 3) find features in target returns that distinguish them from clutter returns. This paper is organized as follows: in Section II the experimental setup is described, in Section III results of the data analysis are discussed followed by summary in Section IV.

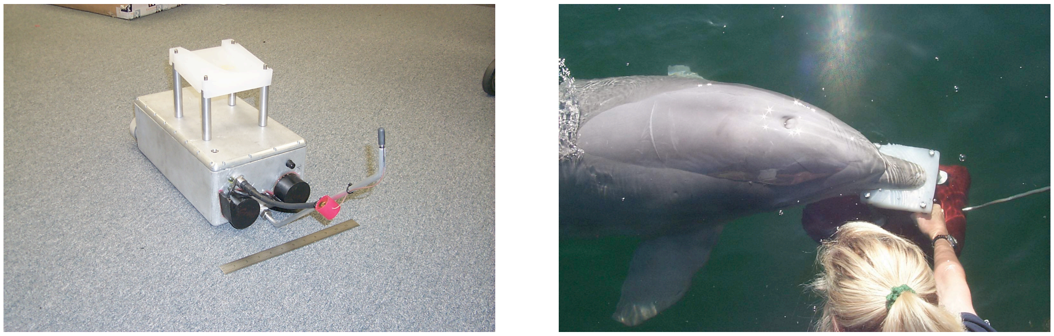

Figure 1. The picture on the left shows the BMT and the one on the right shows a trainer putting the bite-plate attached to the BMT to the mouth of a subject dolphin.

Figure 2. The left picture shows the target used in the trail discussed in this paper. It is composed of a sphere attached to a cylindrical post with a rectangular base. The figure on the right shows the dolphin search path, as it interrogates the target, issues a positive whistle and returns to the workboat. The red dots indicate transmission of the clicks.

EXPERIMENT SETUP

The experimental design used to investigate dolphin echolocation strategies during target detection and identification is dubbed "hide and seek" [4]. During these experiments one of two dolphin subjects is taken out to a pre-configured location. A trail consists of positioning the workboat 20 to 60 meters from one of the surface swim floats. A swim float marks either a positive station (i.e. it has a mine simulator within 3 to 30 meters located nearby) or a negative station (i.e. a mine simulator is not located nearby). The dolphin is trained to station on the port side of the workboat and take the BMT into its mouth during the start of the trial. The dolphin is trained to swim towards the surface float while conducting an acoustic search for the bottom targets. It reports positive "target present" by whistling at the end of the search. An assistant listens to the response with a hydrophone and headset and a bridge signal is provided to the dolphin if the response is correct. The dolphin returns to the workboat immediately after issuing the positive whistle response. The positive whistle response is also recorded by the acoustic sensors on the BMT. If the dolphin does not find a target, it is required to swim to and around the surface float before returning to the workboat. Typical trials range in time anywhere between several seconds to 90 seconds.

In the trial of interest to this paper a target (shown in left panel of Figure 2) was placed near the surface swim float on the bottom and a dolphin subject named Flip was used to echolocate the target. The right panel in Figure 2 shows the dolphin search path as it interrogates the target. The red dots along the swim path of the dolphin show the transmissions of clicks. Note that the frequency of click transmission increases as the dolphin gets near the target, located at approximately 10 meters below the surface. After the dolphin issues a whistle, reporting that a target is present, he turns around and swims back up towards the workboat. He continues to click during his return path, presumably to echolocate the boat. During this trial, which lasted a little over 40 seconds, over 1100 clicks were transmitted. The transmitted clicks and the associated echoes were recorded on the BMT. These data will be analyzed in the next section.

DATA ANALYSIS AND RESULTS

For every transmitted click the BMT records tens and tens of echoes from features in the ensonified field. Figure 3 shows a sample of these echoes. As it can be seen in Figure 3, it is impossible to be able to tell whether these echoes belong to the target or

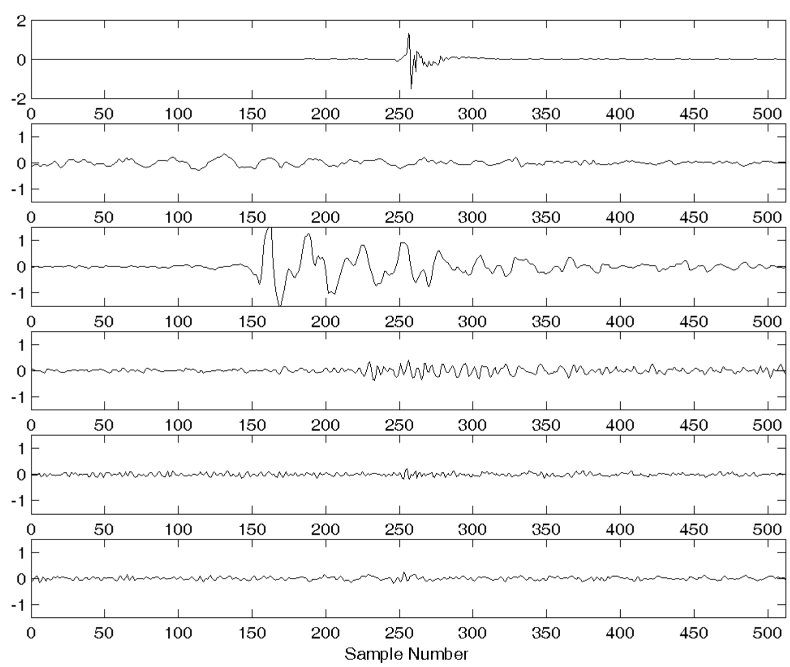

Figure 3. The top panel shows a typical dolphin click. The bottom five panels show echoes from various features in the ensonified field.

clutter.

To be able to group echoes, we plotted the time for each transmitted click along the vertical axis and the corresponding time for the returned echoes along the horizontal axis. The time for the returned echoes is measured from the time that the corresponding click was transmitted. This plot, which we refer to as the echomap, is shown in Figure 4, where each point represents the location of the peak of an echo time series.

The remarkable feature of the above plot is the appearance of tracks, which correspond to echoes that consistently line up regardless of the location of the dolphin. The echoes from the target are shown in red. Note that as the dolphin approaches the target, the time separation between the clicks and the echoes decreases. At the end of the track the dolphin whistles, indicating that he has found the target. The vertical track, which crosses the target track, corresponds to echoes from the ocean surface. Observe that after the dolphin makes the positive identification and is on its way toward the surface, the time separation between the clicks and the surface echoes decreases, indicating that the dolphin is approaching the surface. The other tracks on the echomap cannot be identified easily, as they may correspond to echoes from the surface floats, the workboat or discarded objects on the ocean bottom. Nevertheless, the echomap provides the means to be able to divide the received echoes into at least two groups: those that appear on tracks and those that do not.

Once a point or a series of points are selected for further analysis, their corresponding echo time series can be extracted. Figure 5 shows ten randomly selected returned echo time series along each of the three colored tracks shown on the top left panel. The top right panel shows echoes along the red track, the bottom left panel shows echoes along the magenta track and the bottom right panel shows echoes along the blue track. The echoes along the blue and the red tracks are those of the target. They exhibit the two dominant returns from the front and the back of the target, as is typical of returned echoes from curved shells. The echoes along the magenta track belong to an unknown target. The echo time series for points that do not lie along a track exhibit completely different characteristics. A few echo time series representing these points are shown in Figure 3.

Before analyzing the received echoes, it is useful to look at the transmitted clicks since differences in the received echoes cannot be fully explained without accounting for their corresponding transmitted clicks. Figure 6 shows a correlation matrix of all transmitted clicks, where each click was correlated with every other click. As can be seen in Figure 6, the early clicks (<370) are highly correlated. This is the period of time when the dolphin is in the process of searching and identifying the target. The gap at around click number 370 occurs when he stops clicking and issues a whistle, announcing that he has identified the target. Although the dolphin keeps clicking until he returns to the boat, his later clicks, particularly those above 800, do not correlate well with his earlier clicks when he was searching for the target.

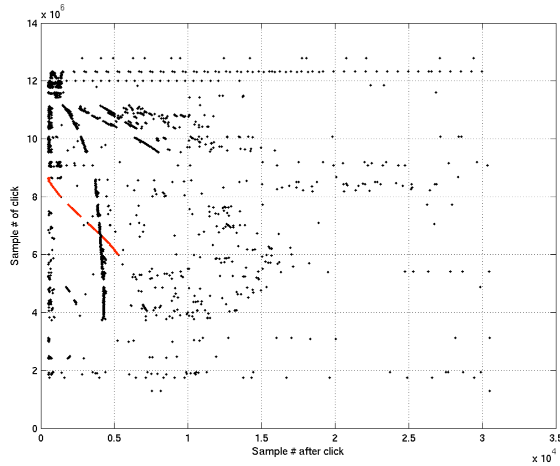

Figure 4. This figure is a plot of the time of received echoes, shown in terms of sample number along the horizontal axis, versus the corresponding outgoing clicks along the vertical axis. The time along the horizontal axis is measured from the time that the corresponding click was transmitted, i.e. all clicks lie along the vertical axis.

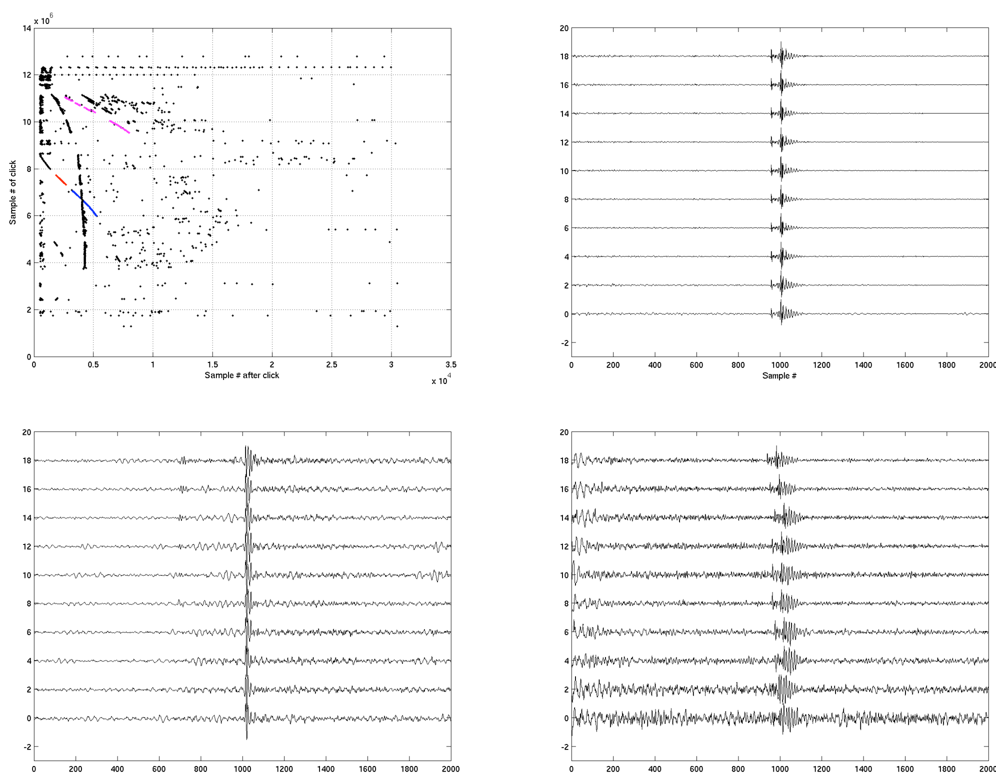

Figure 5. The echo time series corresponding to ten randomly selected points along the colored tracks shown in the top left panel. The top right panel shows the time series for points along the red track, the bottom left and bottom right panels show the same for points along the magenta and blue tracks, respectively.

This suggests that dolphins may use different types of clicks depending on the type of task they have to perform.

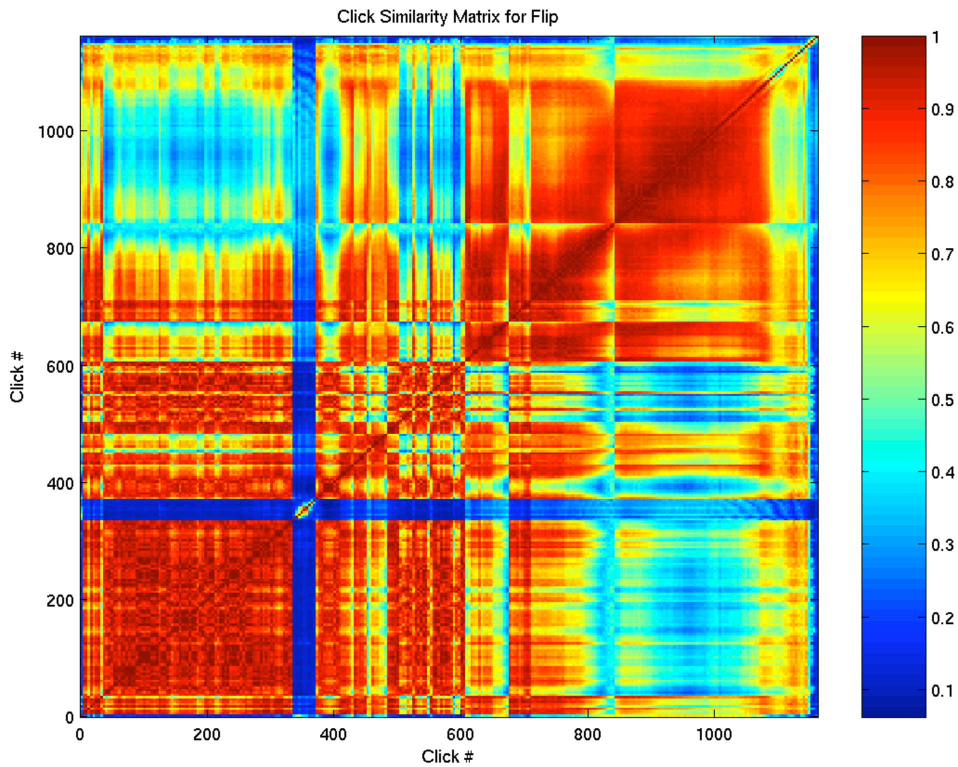

Figure 6. The correlation matrix for the transmitted clicks shows that earlier clicks (<370) are highly correlated. The later clicks, particularly those >800 do not correlate well with the earlier clicks.

As a way to quantitatively study the differences between received echoes we correlated the echoes from the target with all other echoes. An experimental time series echo model was constructed by averaging 31 consecutive returns from the target. This corresponds to the middle of the red track in Figure 4. We also correlated the envelope of the averaged time series and a boxcar model with all received echoes. The boxcar model represents the grossest features of the time series envelope, namely the two dominant peaks. The top left panel in Figure 7 shows the three experimental models used. The remaining three panels in Figure 7 show color-coded echomaps of the correlation between each experimental model and all the received echoes. The color in each echomap represents the amplitude of the correlation, with red representing large values and blue representing small values. The purpose of plotting these color-coded echomaps is to see the distribution of correlation on the echomap.

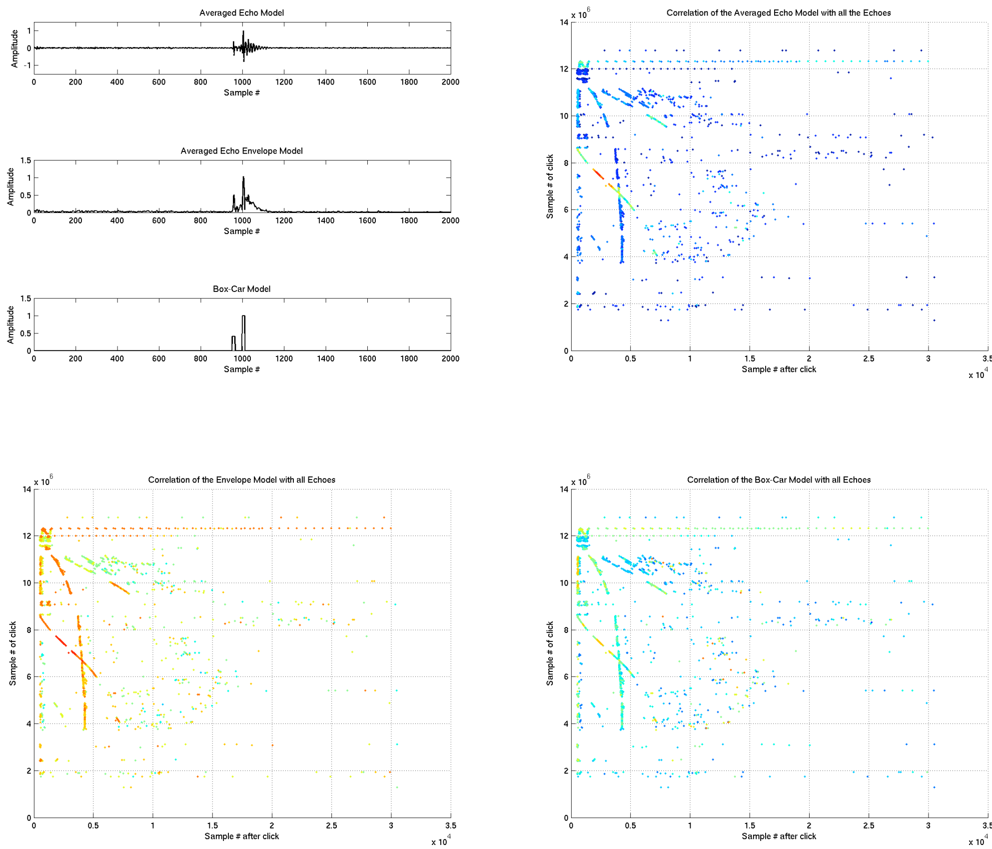

Figure 7. The top left panel in this figure shows the three experimental target echo models: the top panel shows the averaged time series model, the middle one shows the envelope of the averaged time series and the bottom one shows the boxcar model, which has the grossest features of the envelope model, namely the two dominant peaks. The other three panels show color-coded echomaps, which display the distribution of high (red) and low (blue) correlation of the three echo models with all the received echoes. The top right panel is a color-coded echomap showing the distribution of correlation of the averaged time series model with all the other received echoes. The bottom left and bottom right panels show the same for the envelope and box-car models, respectively.

As is evident from the top right panel in Figure 7, the average time series model correlates well with points on the echomap, which belong to echoes from the target (the red track in Figure 4). This is to be expected, since this model was constructed by averaging 31 time series selected from points along the same track. However, observe that this model does not correlate well with echoes that are not located on the target track. Therefore, a threshold correlation value can be found to separate echoes belonging to the target track from the rest of the echoes.

The envelope model can separate echoes that are located on tracks from the rest of the echoes (scattered echoes). The boxcar model shows a slightly better performance. However, to be able to compare the performance of these models quantitatively, the echoes on the echomap were divided into two major groups: those that lie on tracks and those that do not. The ones that lie on tracks were divided into five subgroups color-coded in red, blue, green, magenta and yellow. The red and the blue subgroups represent the target echoes. The experimental models were correlated with the echoes from each group and the color-coded correlations were plotted in Figure 8.

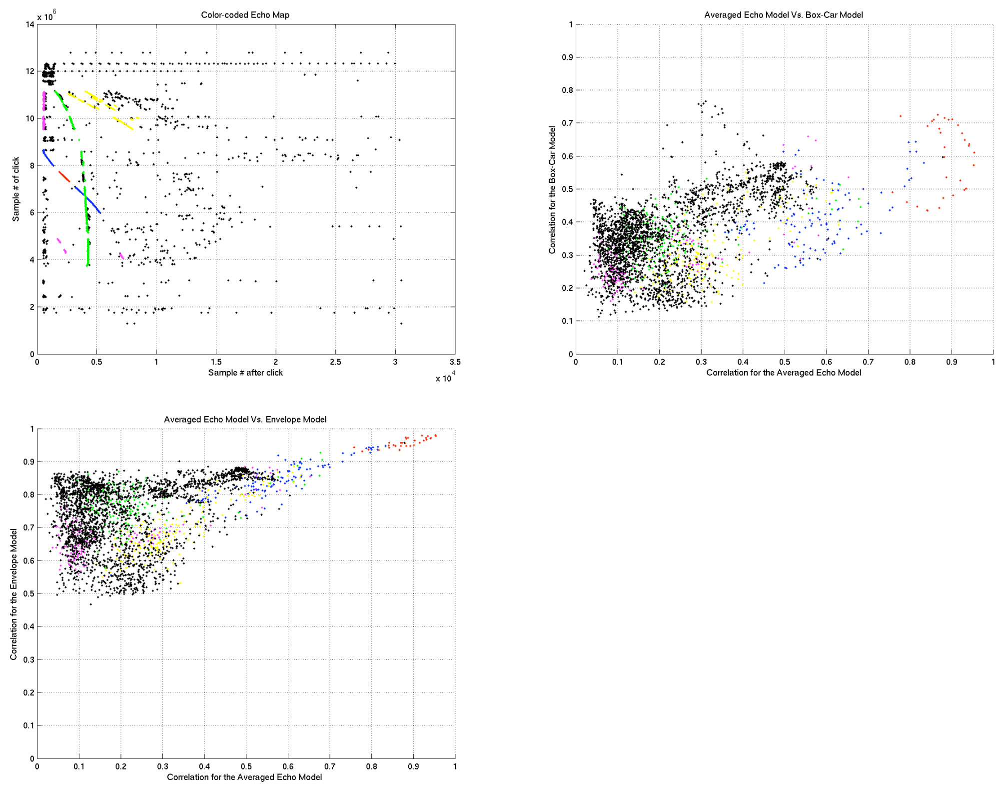

Figure 8. A quantitative comparison of the performance of the experimental echo models using feature space plots. The top left panel shows the division of the echoes in the echomap into six groups, each designated by a different color. The top right panel shows a feature space plot of the box-car model correlation versus the averaged time series model correlation. The bottom left panel shows the same type of plot for the envelope model. The feature space plots have the same color convention as the color-coded echomap.

The top right and bottom left panels in Figure 8 are feature space plots comparing the performances of the three experimental echo models. The top right panels compare the performance of the averaged time series model with that of the boxcar model. Observe that the averaged time series model is able to separate echoes located on the target track (red and blue) from the rest of the echoes very well. The correlation values for echoes located on the target track and the rest of the echoes are well apart and a threshold correlation value of about 0.6 can separate them. The boxcar model cannot separate the target echoes as well and a relatively high threshold correlation value of approximately 0.8 is required to do this. Hence, its performance is not as good as the averaged time series model. The bottom left panel in Figure 8 compares the performance of the envelope model with that of the averaged time series model. Note that the envelope model correlates well with both the target and non-target echoes, as all the correlations have values larger than 0.5. It does separate the target echoes from the rest of the echoes, but a large threshold correlation value of almost 0.9 is required to do this. Therefore, the envelope model has the worst performance of the above three models.

Correlation techniques provide one way of comparing target echoes with non-targets echoes. Pattern recognition techniques can also be employed to discriminate targets and non-targets by looking at the time-frequency response of each class. Figure 9 shows a series of spectrograms selected from points along the target track, where time is along the horizontal axis and frequency is along the vertical axis. The two strong arrivals, due to scattering from the front and the back of the target, are clearly visible. Note that the second arrival is stronger and spans over a wider band of frequency. The two arrivals and the ensuing ringing give the time-frequency response of the target a unique L shape, which is not present in the time-frequency response of the non-target echoes shown in Figure 10. Based on the differences between the two sets of time-frequency responses, in principle it is possible to design a pattern recognition-based classifier to discriminate the target echoes from those of non-targets.

SUMMARY

In this paper data recorded on the BMT were used to analyze the outgoing dolphin clicks and returned echoes during a dolphin echolocation experiment. To accomplish the main objective of the paper, which is to find ways to distinguish target echoes from those of clutter, the peaks of the returned echoes as a function of time and click number were mapped on to what is referred to as the echomaps. After analyzing the returned echoes further, it was verified that on an echomap echoes from regular objects (planar, curved, etc.) appear as tracks and those from irregular objects (rough surfaces, rocks, etc.) appear as scattered points. This property of the echomap was used to divide echoes from the ensonified field into separate categories of target, target-like, clutter-like and clutter. The time series for three target echo models were correlated with the echoes from each one of the above categories. The three target echo models consisted of an experimental echo time series, obtained from averaging 30 echoes from the target, a boxcar model, which consisted of two rectangular pulses collocated at the two prominent returns of the experimental echo time series and the envelope of the experimental echo time series. Various techniques, including feature space plots were used to determine how well each one of the above models could separate target echoes from clutter echoes. It was shown, perhaps not surprisingly, that the experimental echo model had the best performance followed by the boxcar model. Finally, spectrogram matching using pattern recognition techniques is proposed as a potentially more robust method for discriminating target echoes from non-target echoes.

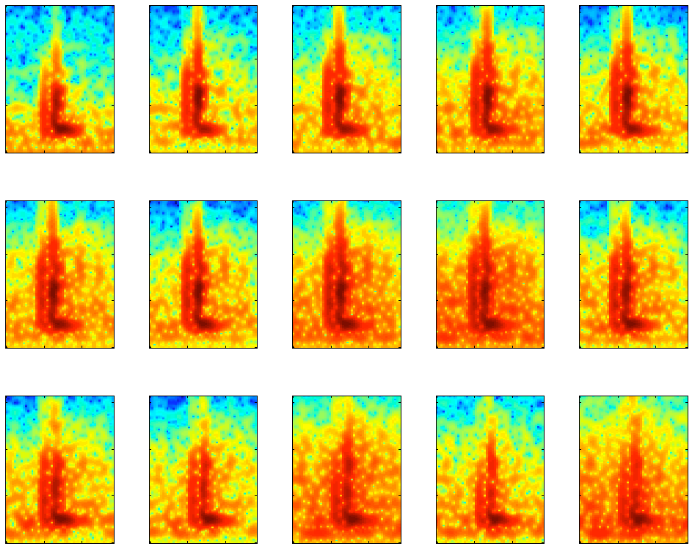

Figure 9. The spectrograms for echoes selected from the target track. The horizontal axis represents time and the vertical axis represents frequency.

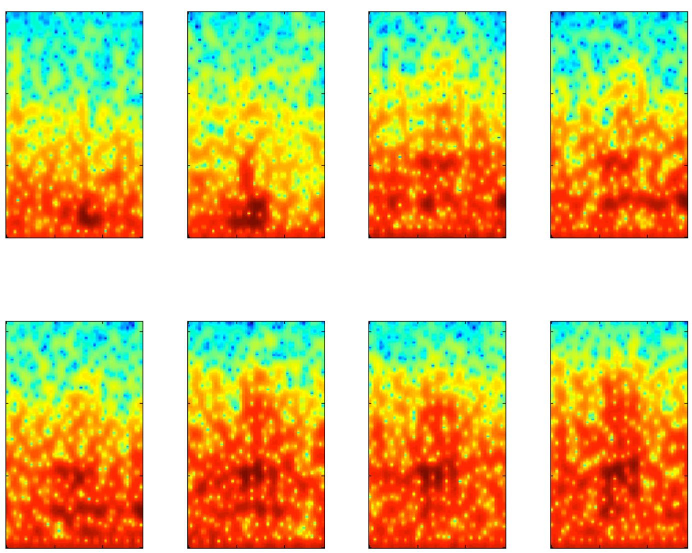

Figure 10. The spectrograms for echoes selected randomly from scattered points on the echomap.

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