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THESIS

THE DEVELOPMENT OF A KERNEL TO DETECT *ZIPHIUS CAVIROSTRIS* VOCALIZATIONS AND A PERFORMANCE ASSESSMENT OF AN AUTOMATED PASSIVE ACOUSTIC DETECTION SCHEME

by

Jessica Rose Mohamed

September 2008

Thesis Advisor: Ching-Sang Chiu
Thesis Co-Advisor: Christopher W. Miller

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THE DEVELOPMENT OF A KERNEL TO DETECT *ZIPHIUS CAVIROSTRIS* VOCALIZATIONS AND A PERFORMANCE ASSESSMENT OF AN AUTOMATED PASSIVE ACOUSTIC DETECTION SCHEME

Jessica Rose Mohamed
Lieutenant, United States Navy
B.S., United States Naval Academy, 2004

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NAVAL POSTGRADUATE SCHOOL
September 2008

Author: Jessica Rose Mohamed

Approved by: Ching-Sang Chiu
Thesis Advisor

Christopher W. Miller
Thesis Co-Advisor

Mary L. Batteen
Chair, Department of Oceanography

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An ensemble consisting of 150 *Ziphius* cavirostris vocalizations was compiled from acoustic data recorded at two High-frequency Acoustic Recording Package (HARP) locations: the Naval Postgraduate School (NPS)'s Point Sur HARP and Scripps Institution of Oceanography (SIO)'s site H HARP. The ensemble was analyzed via a principal component analysis (PCA). The results of the PCA verified the statistical robustness of the signal and yielded one dominant mode which accounted for 73% of the variance. The dominant mode was used to create a kernel for a matched filter detection scheme. The subsequent detector output was statistically evaluated against a ground truth. The ground truth identified 28,434 *Ziphius* clicks by visually inspecting over 170 minutes of data recorded by NPS's Data Acquisition System (DAS) at the Southern California Offshore Range (SCORE). The inability to visually discriminate a signal embedded in noise created a conservatively biased ground truth estimate which increased the detector's false alarm rate. At an acceptable 0.1% false alarm rate, the detector had an overall 44% probability of detection. A further assessment of the detector's performance divided the data into two categories: cluttered and uncluttered. At a false alarm rate of 0.1%, the probability of detection was 26% and 61%, respectively.

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The completion of this thesis would not have been possible were it not for my co-advisors: Ching-Sang Chiu and Chris Miller. To both, I am extremely grateful and probably owe Chris an infinite number of pop-tarts for imparting upon me as much Matlab knowledge as I could tolerate. Curt Collins, John Joseph, and Tetyana Margolina were instrumental in getting me spun up on this project. Scripps Institution of Oceanography's John Hildebrand, Sean Wiggins, and Erin Oleson were extremely generous in sharing their data and expertise, without which this project would not have been possible. I'd also like to thank John Colosi, CAPT Scott Katz, CDR Rebecca Stone, CDR Beth Sanabia, and LCDR Victoria Taber for both their academic and personal support. My family and friends have been my saving grace throughout this entire process and have graciously heard more about beaked whales and clicks than they ever cared to: especially, the love of my life and soon-to-be husband, Big Ben. And finally, I'd like to specifically thank my Aunt Marian for asking me, oh about 7 years ago, what I knew about Navy SONAR and marine mammals. She had read an article in the newspaper and her question prompted me to pursue this project both in my undergraduate and graduate education. So…Thank you Aunt Marian for the initial motivation!

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I. INTRODUCTION

A. BACKGROUND

In an ongoing legal dispute with the National Resources Defense Council (NRDC), the U.S. District Court for the Central District of California has imposed restrictions which consequently affect the Navy's ability to operate Mid-Frequency Active (MFA) sonar. MFA sonar has been operated for over 60 years and is the primary method to localize submarines (Hastings, 2008). These legal implications impede the combat proficiency and advancement of the U.S. Navy's Pacific Fleet's top priority: anti-submarine warfare (ASW). On January 23, 2007, under Title 16, Section 1371(f) of the U.S. Code, the Deputy Secretary of Defense invoked a two-year National Defense Exemption (NDE) under the Marine Mammal Protection Act (MMPA) which includes 29 mitigation measures. These 29 mitigation measures were developed along with the National Marine Fisheries Service (NMFS) to reduce the potential impacts of MFA sonar on marine mammals through increased aerial monitoring and visual surveying (Federal Register, 2008).

Recent mass stranding incidents involving beaked whales, both temporally and geographically coincident with naval emissions of underwater sound, coupled with these high-profile legal ramifications have increased the need for more effective methods of detection and classification. Cuvier's beaked whales (*Ziphius cavirostris*) are among those of greatest concern with respect to curtailing the potential effects from anthropogenic sound (Zimmer et al., 2005; Cox et al., 2006). Since 1960, more than 40 mass strandings of Cuvier's beaked whales have been reported worldwide (Cox et al., 2006). This species, alone, comprises over 80 percent of all marine mammals involved in stranding incidents (Hildebrand, 2005). Further amplifying the issue, research and knowledge of this species is severely limited. Cuvier's beaked whales are difficult to study and identify via traditional visual surveying techniques due to the nature of their lengthy deep-diving behavioral pattern, typically spending up to 40 minutes beneath the surface of the water for a single dive (Barlow et al., 2006). Cuvier's beaked whales spend less than 3 minutes at the surface between dives, leaving not much time for visual identification (Barlow, 1999). This species has also been observed to surface without any visible blow or splash (Ferguson et al., 2006). In an experiment utilizing acoustic recording tags (DTAGs) attached to a Cuvier's beaked whale, the average depth recorded during a deep diving period was approximately 850m, with vocalizations ceasing when the whale was within 200 meters of the surface (Johnson et al., 2004; Tyack et al., 2006). The accuracy of visual identification is further limited by many additional factors including: sea state, visibility, daylight, and the individual observer's experience level and biases. The development of an automated passive acoustic detector would provide the U.S. Navy with the capacity to observe this species' presence and movement under conditions not appropriate for visual surveys. Furthermore, passive acoustic techniques are more cost-effective, require less underway time, allow for continuous monitoring, and could provide information on seasonal and diurnal population patterns.

B. THESIS OBJECTIVES

There are two primary objectives for this thesis. The first objective is to develop a kernel for the vocalizations of Cuvier's beaked whales. This will be achieved by conducting a principal component analysis (PCA) upon an ensemble of extracted *Ziphius* clicks. The kernel will then be used in an automated passive acoustic matched filter detection scheme.

The second objective of this thesis is to assess the performance of the automated passive acoustic detector. This will be achieved by first creating a ground truth count of *Ziphius* vocalizations. Then, Receiver Operating Characteristic (ROC) curves portraying the detector's performance will be constructed via a statistical comparison of the ground truth to the detector output.

C. OUTLINE

The remainder of this thesis consists of three chapters. Chapter II describes the methods used to achieve the two primary objectives. To create the kernel, a principal component analysis was conducted upon an ensemble comprised of 150 randomly selected Cuvier's beaked whale vocalizations. To assess the detector's performance, a ground truth was created by visually reviewing 174.8 minutes of the Naval Postgraduate School (NPS)'s Data Acquisition System (DAS) recordings for the Southern California Offshore Range (SCORE) and identifying 28,434 occurrences of a *Ziphius* click. Chapter III contains the ROC curves and a discussion of the automated passive acoustic detector's performance relative to the ground truth. Chapter IV presents the conclusions of this thesis.

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II. METHODOLOGY

A. KERNEL DEVELOPMENT

1. Signal Characterization

A characterization of the *Ziphius* signal, derived via recent research results, initiated the kernel developmental process. Although some odontocetes, toothed whales, produce clicks and whistles during vocalization, Cuvier's beaked whales are known only to click (Hildebrand, 2005). Recent research suggest the clicks of Cuvier's beaked whales exhibit a unique spectral and temporal structure that differs significantly from the recordings of other non-ziphid toothed whales. A unique signal is favorable for automated acoustic monitoring.

In September of 2003, research conducted by attaching a digital acoustic recording tag (DTAG) directly to a whale reported a click duration of 175 µs with an interclick interval (ICI) of 0.4 seconds. The spectrum swept upwards from 30 to 48 kHz (Johnson et al., 2004). One year later, NATO Undersea Research Center (NURC) and Woods Hole Oceanographic Institution (WHOI) collaborated in a concentrated attempt to build upon the sparse knowledge of Cuvier's beaked whales. Their research found a click duration of 200 µs and an average ICI of 0.4 seconds. The spectrum was frequency modulated (FM) and swept upwards from 35 to 45 kHz (Zimmer et al., 2005). However, it should be noted that both of these studies used acoustic recording devices with a cutoff frequency of 48 kHz; and hence, no information is provided for the higher frequency limit of click energy. Consequently, the click durations are shortened and the bandwidths are narrowed.

On September 26, 2005, further research by NURC, utilizing a towed array, reinforced and expanded upon the DTAG *Ziphius* signal characterization. This recording method was able to capture the entire bandwidth of the signal. A Passive Acoustic Monitoring (PAM) system with a bandwidth of 96 kHz was activated after a visual sighting of two Cuvier's beaked whales initiating a deep dive. The PAM recordings depicted an upswept energy range of 16 to 60 kHz with a center frequency of 40 kHz. The click duration was approximately 300 µs with an average ICI of 0.38 s (Pavan et al., 2006). These results mark the first time a sub-surface detection device was able to verify characteristic features of the DTAG recordings. The increase in the signal's duration and bandwidth is explained by the increased bandwidth of the recording method.

Additional DTAG research indicates significant differences in signal characteristics between Cuvier's beaked whales and other toothed whales. The *Ziphius* signal was characterized by an upswept FM pulse, an average click duration of 200 to 300 µs, and an ICI of 0.4 s (Tyack et al., 2006). Overall, recent research indicates a unique signal structure that is favorable for automated acoustic detection.

2. Ensemble Creation

Designed specifically to monitor marine mammals, the High-frequency Acoustic Recording Package (HARP) was developed by the Scripps Institute of Oceanography (SIO). The HARP, which is capable of a 200 kHz sampling rate and nearly 2 TB of data storage per instrument deployment, is ideal for recording *Ziphius*'s higher frequency clicks over long periods of time. For recordings made at a sampling rate of 200 kHz, 55 days of continuous recording is possible (Wiggins and Hildebrand, 2007). To study the signals of Cuvier's beaked whales, long-term, broad-band, underwater acoustic data recorded via a HARP, was obtained from two different locations with known *Ziphius* activity: Point Sur and San Nicolas basin. The NPS Point Sur HARP is moored at: 36 17.95′ N, 122 23.63′ W, approximately 40 km off the central coast of California at a water depth of 1390 meters. Acoustic data recorded during the NPS Point Sur HARP's second deployment, which spanned from 24JAN07 until 17JUL07, comprised one half of the data that was used in the ensemble creation. SIO provided data, spanning from 22AUG07 to 24AUG07, from their Site H HARP, located just east of the San Nicholas Basin at a depth of 1013 meters.

To evaluate the statistical robustness of the signal, two ensembles were randomly extracted from the HARP data sets: one a compilation of *Ziphius* clicks, the second a compilation of ambient noise segments. The click ensemble will be used to generate a kernel which contains the statistically dominant characteristics of the signal. The noise ensemble will duplicate the statistical analyses performed on the click ensemble to ensure that the ambient noise is not correlated. Triton software, courtesy of Wiggins (personal communication), was used to visually inspect the data and extract 150 random vocalizations, following the qualitative characterizations of the *Ziphius* click from previous research. The total ensemble of clicks consisted of 75 samples from each HARP location. An example of one click extraction from each location is shown in Figure 1. The 100 sample ensemble of random ambient noise segments consisted of 50 noise segments from each HARP dataset.

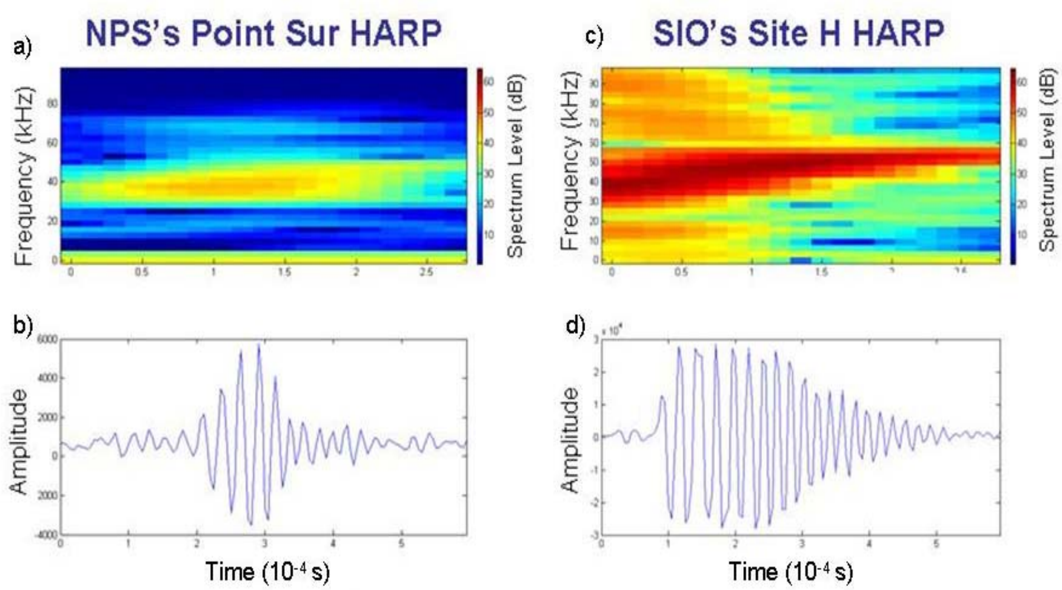

Figure 1. Two examples of *Ziphius* clicks extracted from HARP data: a) Spectrogram of a click extracted from NPS's Point Sur HARP with click energy upsweeping from 35 to 50 kHz. b) Time series of a click corresponding to the spectrogram above it. c) Spectrogram of a click extracted from SIO's Site H HARP with click energy upsweeping from 35 to 50 kHz. (d) Time series of a click corresponding to the spectrogram above it

Although both ensembles were created solely from HARP data, the subsequent analyses had to account for the bandwidth and sampling frequency differences between a HARP and a SCORE hydrophone in order to produce results that would be applicable for data from either acoustic recording method. A SCORE hydrophone has a band-pass filter installed which limits the frequency response to a bandwidth of 8-40 kHz. At the time of the data collection, the sampling rate of the SCORE hydrophone was set at 80 kHz; whereas, the HARP was set at 200 kHz. To ensure consistency between recording methods, the ensembles were processed into two distinct sub-sets.

In order make the ensembles applicable to a SCORE hydrophone, the first step was to decrease the sampling rate from 200 kHz to 80 kHz. To ensure the bandwidth was consistent with a SCORE hydrophone, a band-pass filter with pass bands of 15-40 kHz and was applied to the ensemble. Fifteen kHz was used as the lower pass band to eliminate noise that existed at frequencies lower than the *Ziphius* signal. The sampling rate of the ensembles was then increased to a sampling frequency of 1 MHz, to increase the resolution and decrease the potential for correlation quantization errors. For clarity, this first sub-set will be referred to as the ensembles that were band-pass filtered between 15-40 kHz.

The ensembles were also processed for applicability to HARP data in a second sub-set. Both ensembles were band passed between15-60 kHz to eliminate noise at frequencies lower than the *Ziphius* signal. The higher pass band of 60 kHz allows for the inclusion of more high-frequency click energy. As in the first sub-set, the sampling frequency was increased for the click and noise segment ensembles to a rate of 1MHz. This second sub-set will be referred to as the ensembles that were band-pass filtered between 15-60 kHz.

3. Quantitative Signal Evaluation

A correlation analysis was performed on both sub-sets of ensembles to assess the statistical robustness of the *Ziphius* signal and evaluate the feasibility for the development of an automated detector. First, the 150 samples of both click ensembles were demeaned, normalized, and aligned via circular shifting. For both sub-sets of click ensembles, the click to click cross-correlation results indicated a statistically high level of correlation among the samples. Figure 2 depicts the values for the 150 click to click cross-correlations for the click ensemble that was band-pass filtered between 15-40 kHz. These results indicate that the signal is statistically robust. A cross-correlation was also performed on each sub-set's ensemble of random noise segments to ensure that the noise was not correlated. For both of the sub-set's noise segment ensembles, the noise to noise cross-correlation results indicated a statistically low level of correlation among the samples.

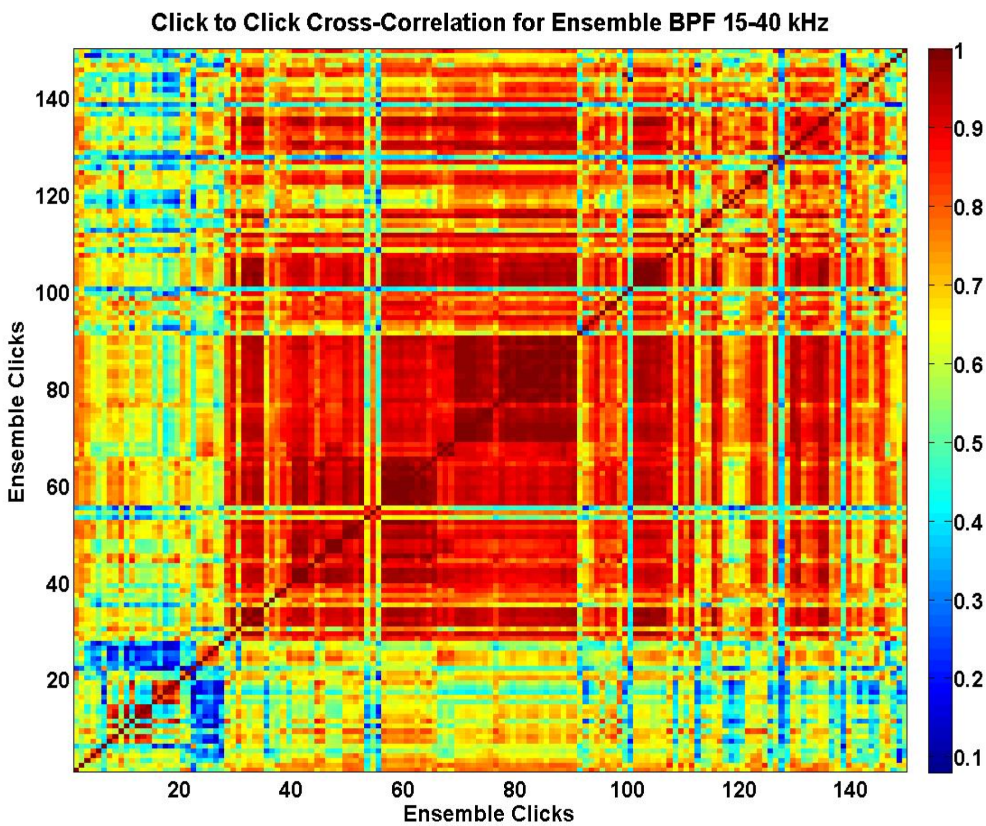

Figure 2. Click to click cross-correlation results for the click ensemble that was band-pass filtered between 15-40 kHz: The correlation values range from 0 to 1, with a value of 1 indicating a perfect correlation.

4. Principal Component Analysis

Once the signal was determined to be quantitatively robust, both sub-sets of click ensembles were analyzed via a principal component analysis (PCA) to further evaluate the potential for a matched filter detection scheme. The goal of the PCA is to isolate the desired signal from the noise. A PCA is a useful statistical technique that was invented in 1901 by Karl Pearson. PCA is defined as an orthogonal linear transformation that converts data into a new coordinate system such that the greatest variance of the data comes to lie on the first coordinate, often referred to as the principal component (Shaw, 2003). The second variance ranking lies on the second coordinate, the third variance ranking lies on the third coordinate, and so on. This method of decompressing the data makes it possible to retain the characteristics of the signal that contribute most to its variance by keeping the components with the highest variance and ignoring the components with the least amount of variance.

Mathematically, the principal component can be obtained by solving the following eigenvalue-eigenvector equation:

$$\mathbf{A}\,\mathbf{A}^{\mathbf{T}}\ \underline{v}_i = \mathbf{L}^{\mathbf{2}}{}_i\ \underline{v}_i \qquad (1)$$

where, **A** is a data matrix with 150 columns, and each column contains one realization of a realigned click from the ensemble. $\mathbf{A}\,\mathbf{A}^{\mathbf{T}}$ is the data covariance matrix. $\mathbf{L}^{\mathbf{2}}{}_i$ is the eigenvalue which is the variance resolved by the *ith* component, $\underline{v}_i$.

The PCA was performed via a Matlab routine to yield the components and the associated variances. For the click ensemble that was band-pass filtered between 15-40 kHz, the PCA's first component contained 73% of the variance. The remaining components all had values of less than 6% and correspond to noise including multipath contamination. The results of this PCA indicate that there is only one dominant component. The results of the PCA for the first sub-set are shown in Figure 3.

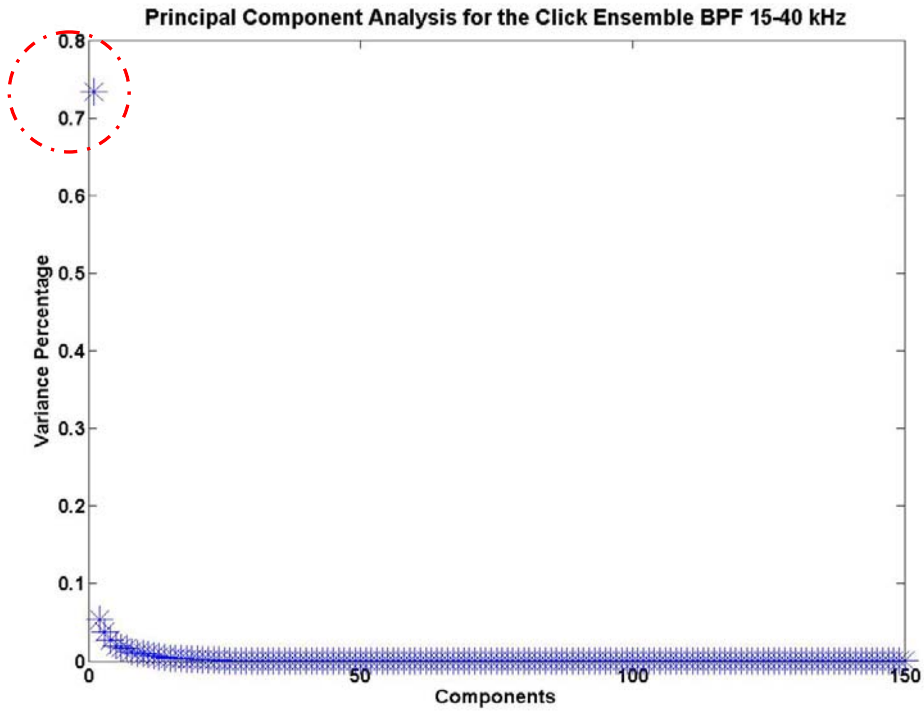

Figure 3. Principal component analysis results for the click ensemble that was band-pass filtered between 15-40 kHz: The dominant component is emphasized with a red circle and contains 73% of the variance.

The second sub-set, which was band-pass filtered between 15 and 60 kHz, also produces only one dominant component. The first component of the second subset's PCA contains 66% of the variance. The remaining components correspond to noise including multipath contamination. Both PCAs indicate that the first component can be used as a kernel in a matched-filter detection scheme. The first components of each subset's PCA were extracted to be used as kernels, shown in Figure 4. The first subset's kernel is noticeably shorter in duration than that of the second sub-set. This is because it was created from a click ensemble with a narrower bandwidth, 15-40 kHz vice 15-60 kHz; and therefore, some of the higher frequency click energy was excluded. The variance of the first sub-set's kernel is also higher, 73% in comparison to 66% of the second sub-set's kernel. This is because the first sub-set was created from a narrower bandwidth; therefore, there was less in-band noise.

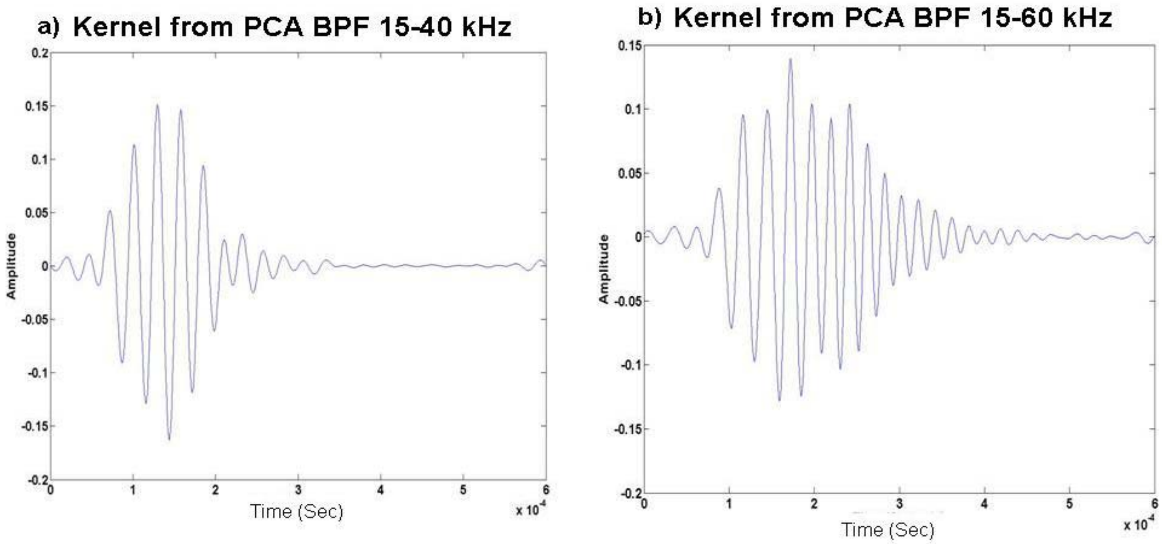

Figure 4. Kernels developed for use in a matched-filter detection scheme: a) Kernel created from the PCA of the click ensemble that was band-pass filtered between 15-40 kHz can be used as a kernel with SCORE hydrophone data. b) Kernel created from the PCA of the click ensemble that was band-pass filtered between 15-60 kHz can be used as a kernel with HARP data.

This thesis does not utilize or assess the kernel created from the second sub-set of data that was band-pass filtered between 15-60 kHz. Follow-on research would be valuable in assessing the performance of this kernel in a matched-filter detection scheme for comparison to the performance of the first sub-set's kernel. From this point forward, all references to a kernel are with respect to the first sub-set of data that was band-pass filtered between 15-40 kHz.

One final analysis was performed to further investigate the robustness of the *Ziphius* click and evaluate the performance of the kernel on the click ensemble: a cross-correlation of the kernel to the entire click ensemble. This cross-correlation is shown in Figure 5. The majority of the clicks within the ensemble are highly correlated to the kernel. The cross-correlation of the kernel to click 51 produces a high correlation value with only one dominant arrival and represents minimal multipath effects. However, it should be noted that a few of the clicks have a lower cross-correlation coefficient. For example, click 98 is not as highly correlated to the kernel. This particular cross-correlation example clearly indicates multiple peaks which can be attributed to multipath effects. The normalization of the signal in the presence of multipath arrivals is responsible for decreasing the correlation coefficient. Without normalization, the peak correlation value for this particular example would be consistent with the higher values of the other cases. Overall, the results of the kernel to click ensemble cross-correlation are further evidence that the *Ziphius* click is a robust signal, and signifies that a kernel can feasibly be used in a matched-filter detection scheme.

A cross-correlation of the kernel to the noise segment ensemble was also performed. All of the noise segments were poorly correlated to the kernel. This is an expected result and verifies that the high correlation coefficients of the kernel to click ensemble are not a coincidence.

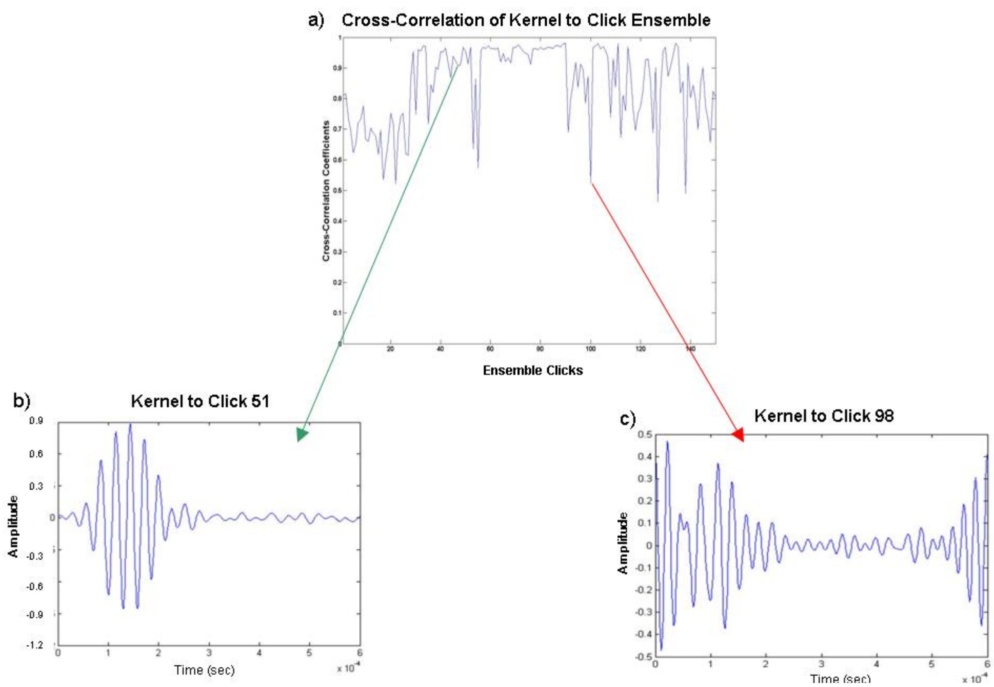

Figure 5. Cross-Correlation of the Kernel to the Click Ensemble: a) A majority of the correlation coefficients indicate that the kernel is highly correlated to the clicks of the ensemble. b) Click 51 is highly correlated to the kernel. c) Click 98 is poorly correlated to the kernel.

B. AUTOMATED MATCHED FILTER DETECTOR SCHEME

The statistically dominant first component produced via the PCA can be used as a kernel in a matched filter detection scheme. The kernel was cross-correlated with acoustic data obtained from NPS's Data Acquisition System (DAS) recordings at SCORE, using a matched filter detector designed by Chris Miller (personal communication) of NPS's Ocean Acoustic Laboratory (OAL). The SCORE data that was fed into this detector came from a hydrophone at a depth of 1,497 meters and located at 32 50.62′ N, 119 5.26′ W in the San Nicolas Basin.

The automated passive acoustic matched-filter detection schematic is portrayed in Figure 6. The first step in Miller's detector was to cross-correlate the kernel with the SCORE data. Then, the output of this first box was peak picked above a given threshold. The final box of Miller's detector utilized a rank-ordered culling system with a culling window of +/- 390 μs. The culling window size of +/- 390 μs was selected because it is exactly twice the length of the kernel. This step removes a majority of the multipath effects as well as the side lobes that were introduced by the correlation and the sinusoidal nature of the detector kernel. Removing the side lobes by culling the data cleans up the output and significantly reduces the number of false alarms.

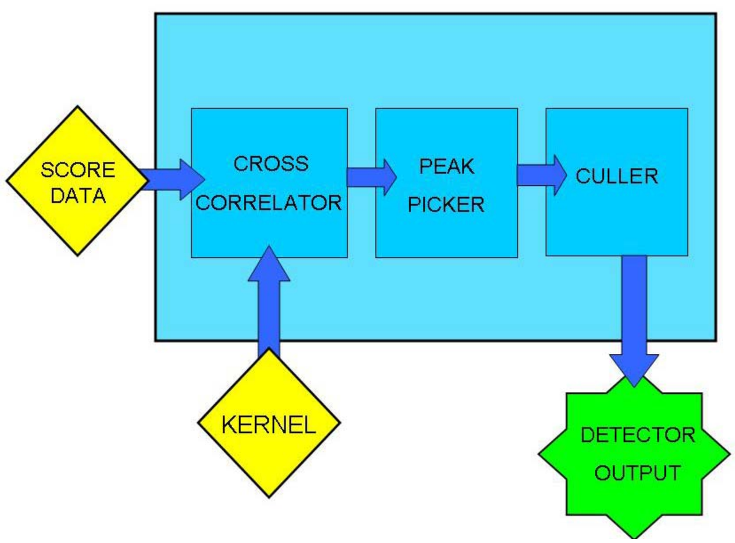

Figure 6. Automated passive acoustic matched filter detection schematic: The design and development of the detector are courtesy of Miller (personal communication).

C. GROUND TRUTH CREATION

1. Selection Criteria

To evaluate the performance of the detector, the detector output must be compared to an assumed ground truth. The ground truth was created by visually inspecting SCORE data and annotating each instance of an observed *Ziphius* click. 174.8 minutes of acoustic data recorded on 23FEB08 by a SCORE hydrophone was reviewed in the ground truth creation process. The duration of a *Ziphius* signal is less than 400 μs; therefore, the time scale used to visually review the SCORE data was divided into 12,800 smaller segments, each with a length of 0.82 s. The final log of presumably positive *Ziphius* vocalizations was then used to statistically analyze the automated detector's performance via probabilistic means comparing hits, false alarms, and misses at varying threshold levels.

The ground truth creation proved to be the most arduous and time-consuming aspect of this research. Even at a decreased time scale, the certainty of the ground truth remained dependant upon discernment. An initial ground truth was deliberately discarded; because, as the ground truth creation process progressed, the experience level and the signal discrimination improved and unacceptable inconsistencies became inherent.

The successive ground truth creation process incorporated specific criteria to alleviate subjectivity. The first criterion mandated that a click selected for inclusion in the ground truth must have continuous energy between 22.5 and 35 kHz. This standard was adopted under the notion of continuous eye integration, meaning the eye has the ability to visually connect miniscule gaps within the click energy of the spectrogram. If the first condition was not met, the second criterion directed ground truth inclusion if a click was part of a distinctive click train, consisting of regular, repeated clicks with a constant ICI. Figure 7 exemplifies an instance in which the energy criterion was not met; however, a distinctive click train was present. Thus, the clicks not spanning 22.5 to 35 kHz were still included in the ground truth having met the second criterion. The energy criterion is visibly enhanced with the overlaying of two solid black lines on the spectrogram. The dashed blue lines on the spectrogram and the blue stars on the time series indicate identified clicks. The final criterion established that only one click would be selected in the case of a cluster. A cluster consisted of multiple clicks that were visually indistinguishable from one another at the prescribed time scale. These subjective criteria allowed for the creation of a more objective ground truth. In total, 28,434 clicks were identified in the 174.8 minutes of data that was reviewed.

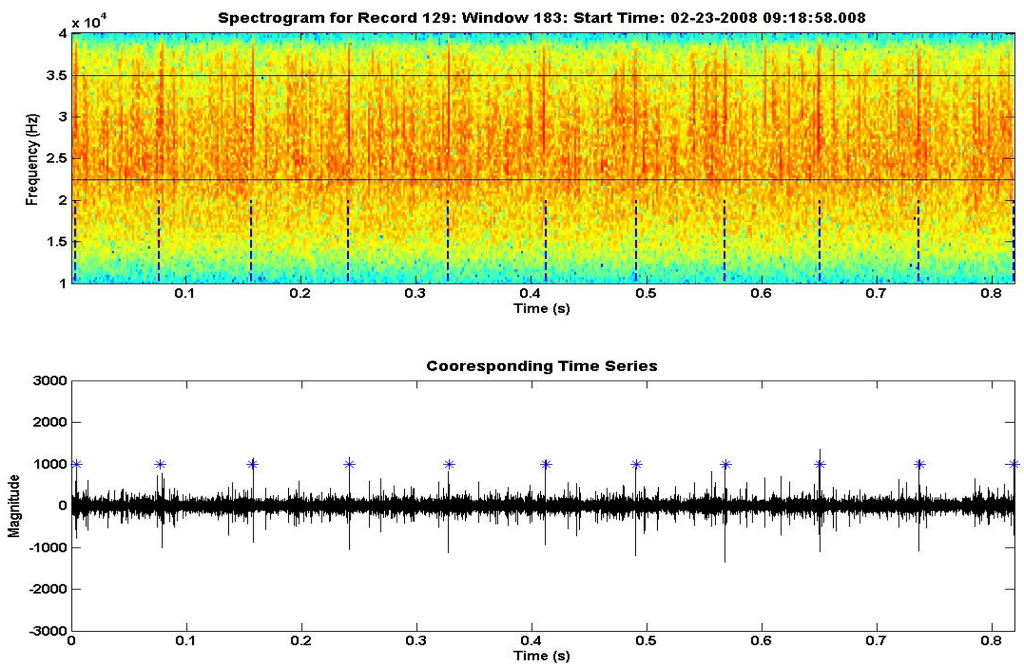

Figure 7. Ground truth creation example: The upper panel is a spectrogram, and within it the energy criterion is exemplified by the solid black lines spanning 22.5 - 35 kHz. The lower panel is the corresponding time series of the SCORE data. The click energy does not span the entire width of the energy criterion; however, there is a distinctive click train. The dashed blue lines on the upper panel and corresponding blue stars on the lower panel represent the identification of a click utilizing the second criterion, which directs the selection of a click if it is part of distinct click train. This is also an example of a time period where the *Ziphius* click was able to be distinguished among competing signals. Time periods such as this were designated as “clutter” for the subsequent statistical analysis.

2. Statistical Analysis Exclusions

The eventual detector output was biased with respect to the ground truth creation. The acoustic signatures of other marine mammals occur approximately within the same frequency range as that of a Cuvier's beaked whale. Figure 8 (National Resources Council, 2003) depicts these overlapping frequency ranges of vocalizations. Visual surveys conducted from July 2006 to April 2007 identified several of these species of marine mammals with overlapping vocalization frequencies in the SCORE. In addition to Cuvier's beaked whales: Risso's dolphins, Pacific white-sided dolphins, Sperm whales, Orcas, Baird's beaked whales, False killer whales, and Humpback whales have all been found in the SCORE (Hildebrand, 2007).

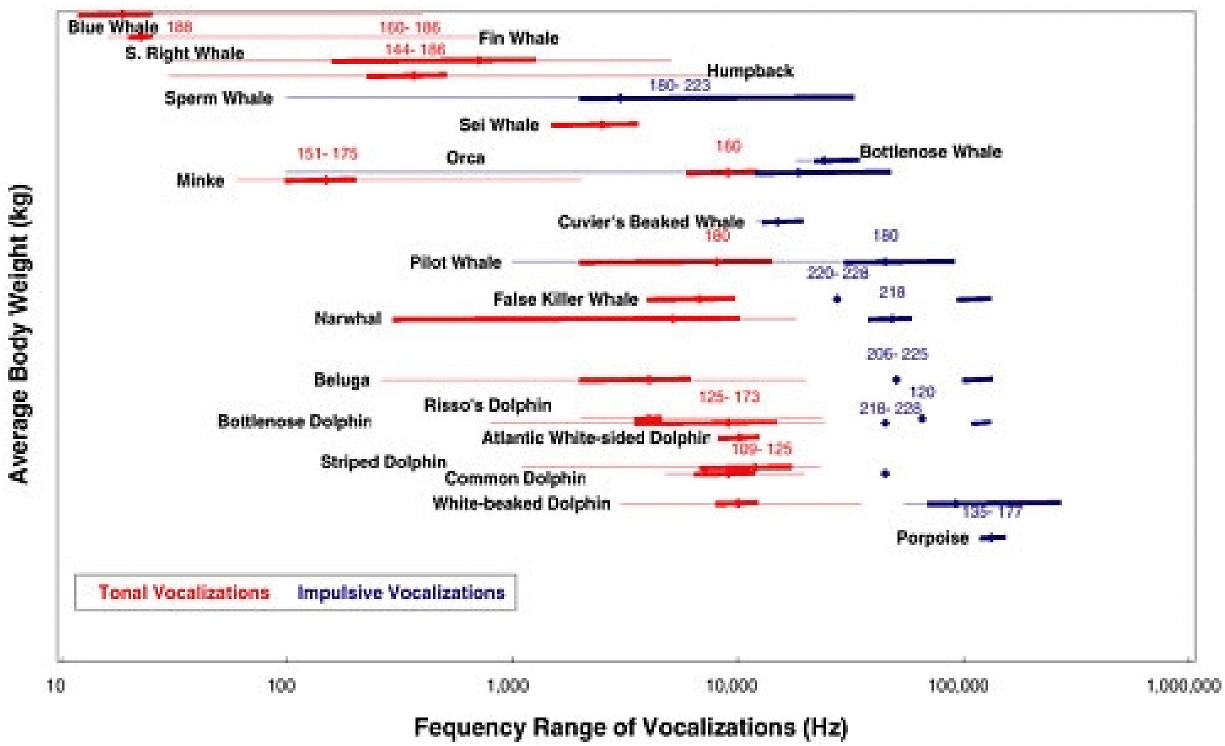

Figure 8. Representative vocalizations of marine mammals (National Resources Council, 2003): Tonal vocalizations are plotted in red; impulsive vocalizations are plotted in blue. The thicker lines represent frequencies near maximum energy and the thinner lines indicate the total range of frequencies. The numbers above the line indicate measured source levels in dB re µPA at 1m.

The overlapping frequency ranges of other marine mammals and Cuvier's vocalizations create uncertainty within the ground truth. To diminish this uncertainty, the time periods containing such indiscriminant signals were purposefully excluded from the subsequent statistical analysis. Similarly, time periods in which the data recordings were interrupted and/or turned off were also eliminated. Figure 9 is an example of a time period that was deliberately removed from the ground truth due to its indistinguishable clutter. A total of 28.89 minutes were selected to be excluded from the statistical analysis.

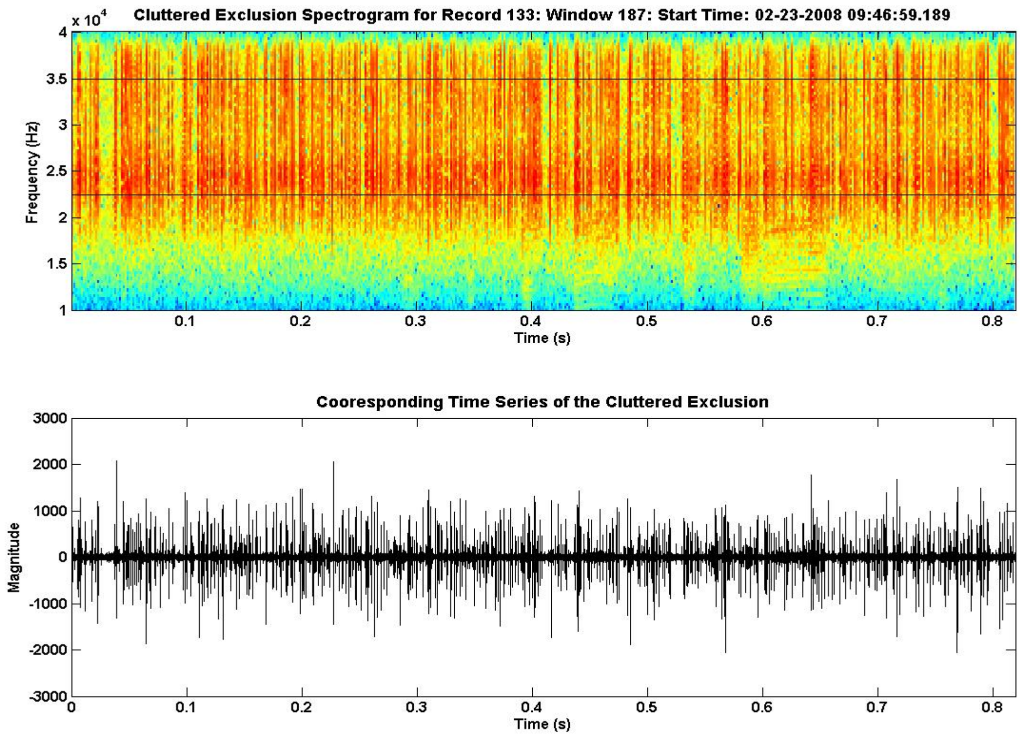

Figure 9. Ground truth exclusion due to indistinguishable clutter: The upper panel is a spectrogram and the lower panel is the corresponding time series for the data that was reviewed to create the ground truth. This is an example where the signal was indistinguishable due to the presence of other marine mammals' vocalizations. Time periods such as these were excluded from the statistical analysis because the *Ziphius* signal could not be visually distinguished from amongst the clutter.

3. Clutter Categories

To further remove uncertainty from the remaining ground truth, a sub-category consisting of un-excluded clutter was created. This category consists of time periods wherein significant clutter was present; however it differs from the previously discussed excluded clutter because in this instance the *Ziphius* signal remained discernable. By distinguishing the cluttered time periods from the non-cluttered time-periods, two distinct sets of statistics were able to be generated for the detector performance analysis. Figure 7 is an example where competing signals were present; yet, the *Ziphius* signal was still able to be distinguished among the clutter. A total of 20.83 minutes were designated as un-excluded clutter.

4. Interclick Interval

During the creation of the ground truth, an unexpected observation was made with respect to the ICI. Previous research has cited an ICI of approximately 0.4 s for Cuvier's beaked whales (Johnson et al, 2004, Zimmer et al, 2005, Pavan et al., 2006, Tyack et al, 2006). The data inspected to create the ground truth consistently displayed *Ziphius* vocalizations with a discernable ICI of approximately 0.05 s. A possible explanation for this striking difference could be that these are different animals vocalizing intermittently. It is also possible that these are not Cuvier's beaked whales. However, the average 0.05 s to 0.1 s ICI appears to be regular and is repeated constantly throughout the dataset. Figure 10 depicts one of these time periods within the ground truth with a distinctive and regular ICI. This particular example has an ICI of 0.05 s which is not an uncommon observation. The order of magnitude difference between the referenced literature and these observations was unexpected. Further exploration of the ICI dynamics is tangential and beyond the scope of this research.

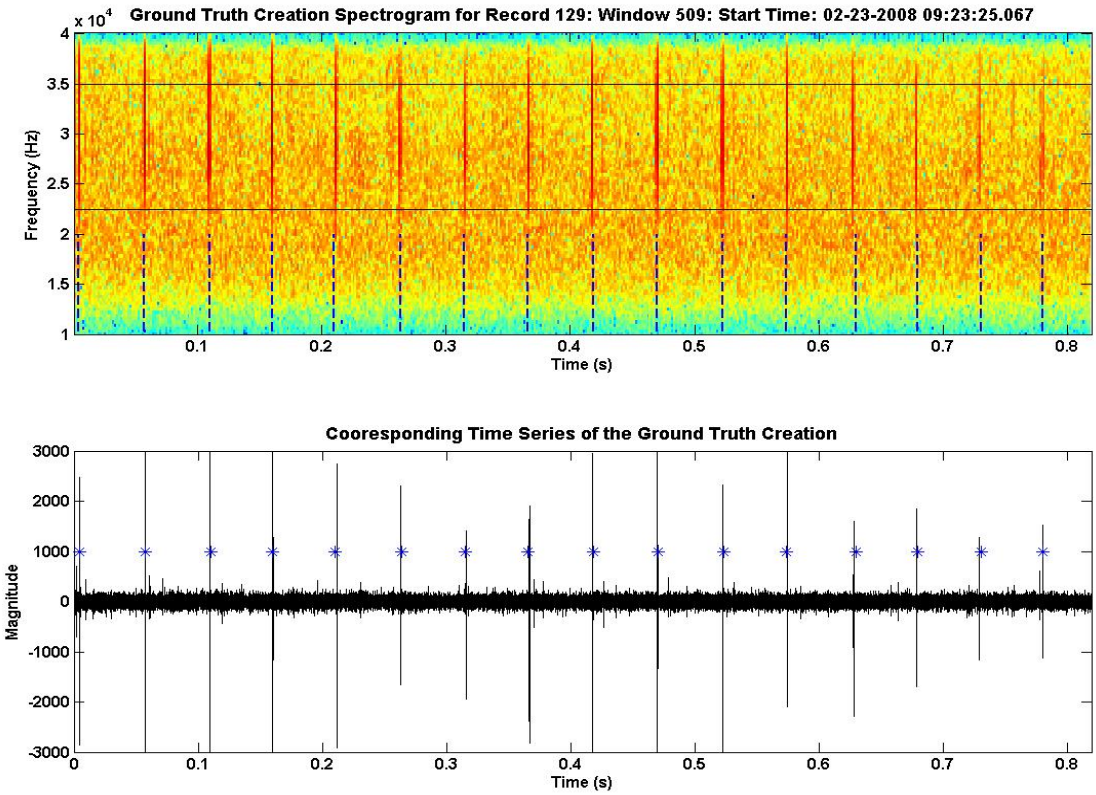

Figure 10. Ground truth example with a distinct 0.05 s ICI: The upper panel is a spectrogram and the lower panel is the corresponding time series of the data that was reviewed to create the ground truth. The solid black lines on the spectrogram at 22.5 and 35 kHz are representative of the ground truth's energy criterion. The dashed blue lines on the spectrogram and blue stars on the time series are representative of click identifications. This figure depicts an ICI of 0.05 s.

III. DETECTOR PERFORMANCE RESULTS

The performance of the automated passive acoustic matched-filter detector was assessed by statistically comparing the detector's output to the ground truth. A detector output hit that corresponded to a ground truth click identification was a correct hit. A detector output hit that did not correspond to a ground truth click identification was a false alarm. A ground truth click identification that did not have an associated detector output hit was a miss. A correct rejection occurred when there were no detector output hits and no ground truth click identifications. Probabilities of detection (P(D)) and probabilities of false alarms (P(FA)) were calculated by the following equations:

$$P(D)=\frac{H}{H+M} \qquad (2)$$

$$P(FA)=\frac{FA}{FA+CR} \qquad (3)$$

where, H is the number of correct hits, FA is the number of false alarms, M is the number of misses, and CR is the number of correct rejections.

By calculating the P(D) and P(FA) at varying threshold levels, Receiver Operating Characteristic (ROC) curves were created. The ROC curves are shown in Figure 11. Table 1 displays the detector performance results at varying thresholds which were used to create the ROC curves. At an acceptable P(FA) of 0.1%, the automated passive acoustic matched-filter detector had an overall P(D) of 44%. The P(D) increased as the threshold was lowered; however, this detection improvement also increased the P(FA). The tradeoff between P(D) and P(FA) is an important factor to consider when utilizing the detector. The category of data being processed by the detector also affected the P(D) and P(FA) rate. As described in the previous chapter, the data was separated into two distinct categories for further detector assessment. At an acceptable P(FA) of

0.1%: the detector had a P(D) of 61% and 26% in uncluttered and cluttered data, respectively. The detector had a lower P(FA) when processing the uncluttered data in comparison to the cluttered data.

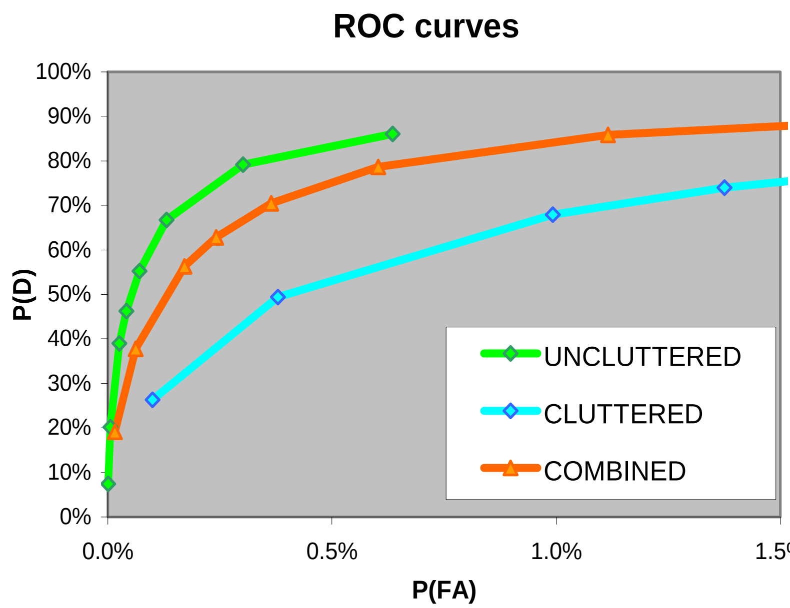

Figure 11. ROC curves to assess the detector's performance: The orange curve is the overall performance of the detector, combining both the uncluttered and cluttered time periods. The detector performed best during the uncluttered time periods, shown by the green line. The detector performance was degraded during the cluttered time periods, shown by the blue line.

DETECTOR PERFORMANCE RESULTS						
	UNCLUTTERED		CLUTTERED		COMBINED	
THRESHOLD	P(D)	P(FA)	P(D)	P(FA)	P(D)	P(FA)
5.00E-04	86.0815%	0.6355%	92.1336%	8.8121%	89.6917%	1.8614%
1.00E-03	79.1634%	0.3016%	90.3412%	5.7345%	85.8094%	1.1161%
1.25E-03	66.7453%	0.1314%	86.7028%	3.2769%	78.6127%	0.6030%
1.50E-03	55.2777%	0.0703%	80.7665%	2.0337%	70.4451%	0.3646%
1.75E-03	46.2646%	0.0416%	74.0090%	1.3750%	62.7993%	0.2415%
2.00E-03	39.0050%	0.0259%	67.9076%	0.9926%	56.2827%	0.1709%
3.00E-03	20.1885%	0.0059%	49.4160%	0.3792%	37.7543%	0.0619%
5.00E-03	7.4456%	0.0010%	26.3202%	0.0996%	19.0952%	0.0158%

Table 1. Automated passive acoustic matched-filter detector performance results for the uncluttered, cluttered, and combined time periods.

Figure 12 is an example of a cluttered time period. The detector output statistics are depicted for two different threshold levels, which are accentuated with a horizontal orange line in the middle and bottom panels. The dashed blue lines on the spectrograms indicate the location of the ground truth selections. When the threshold level is set at 0.005, as in the middle panel of Figure 12, the number of false alarms, even in a cluttered time period is acceptably low. The detector does hit on several of the ground truths; however, at this threshold the detector misses even more *Ziphius* clicks than it correctly detects. When the threshold is lowered by an order of magnitude, as in the bottom panel, the detector is able to accurately hit each of the ground truths with zero misses. The tradeoff is the significant increase in false alarms because the threshold level is now located within the clutter. These low values of detector output may contain *Ziphius* clicks; however, the statistics declare these as false alarms when compared to the ground truth. The ground truth is a conservative estimate because of the inability to visually detect a *Ziphius* click when it is embedded in the noise. The actual statistical output for the cluttered data would contain fewer false alarms if it were being compared to a perfect ground truth. The cluttered ROC curve would be shifted significantly to the left in the case of a perfect ground truth.

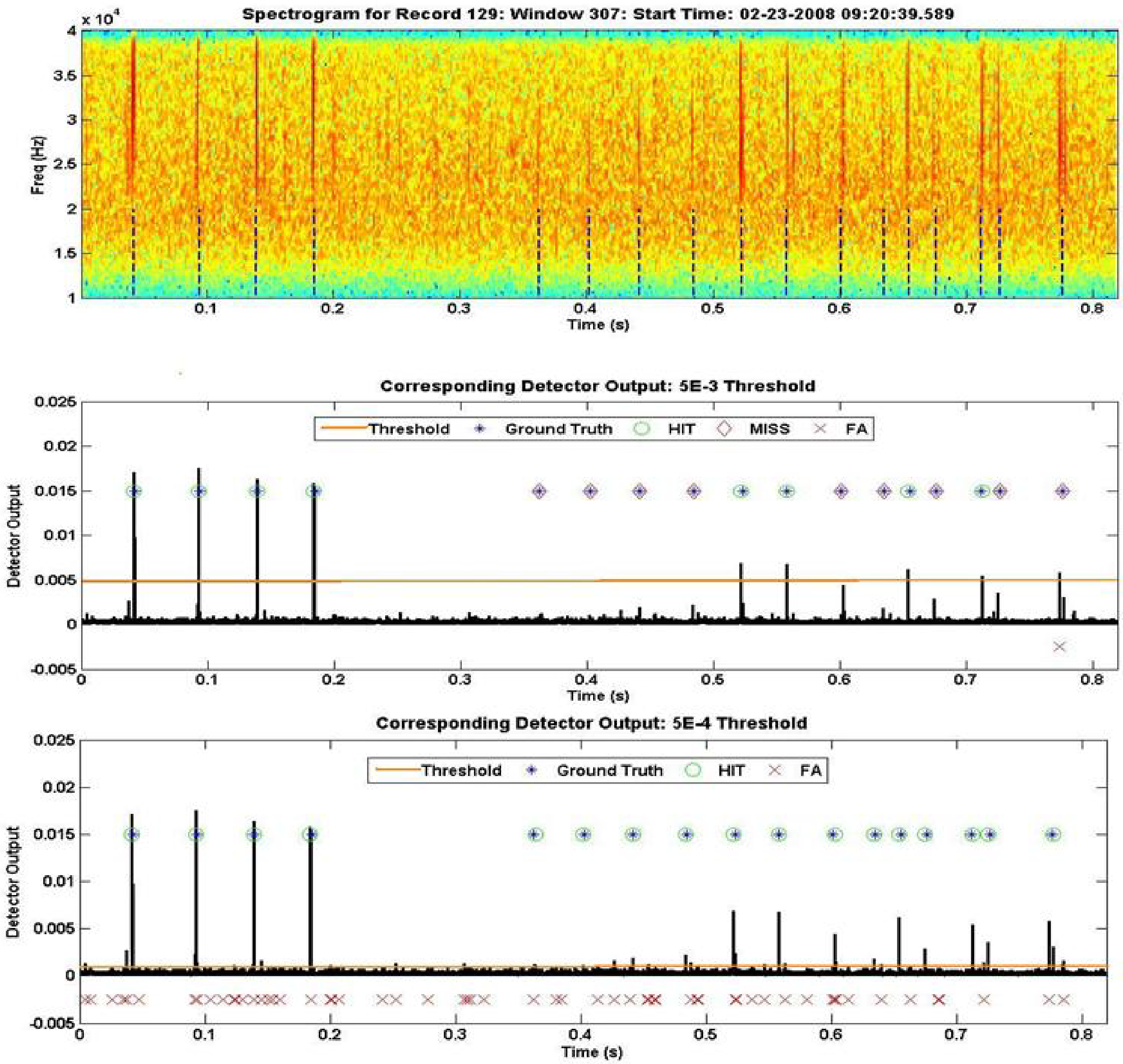

Figure 12. Detector output statistics for a cluttered time period: The upper panel is the spectrogram with ground truth click identifications marked by the dashed blue line. The middle panel is the corresponding detector output for a given threshold and the bottom panel is the corresponding detector output for a lowered threshold. The threshold level is denoted by the solid orange line on the middle and bottom panels. In the middle panel, the detector misses several of the ground truth click identifications; however, the false alarm rate is very low. The detector is able to hit all of the ground truth click identifications with no misses when the threshold is at the lowest level; however, there is a significant increase in false alarms.

In comparison to the cluttered time periods, the detector output statistics indicated much lower false alarm rates when the detector was processing uncluttered data. Figure 13 is an uncluttered example wherein the false alarm rate remains low even at a threshold level of 0.0005. The ground truth for the uncluttered time periods is also conservative in comparison to what a perfect ground truth would indicate. As in the cluttered data, this inherent flaw causes a resultant increase in the false alarm rate. The availability of a perfect ground truth would serve to lower the P(FA) and shift the uncluttered ROC curve to the left. However, it is not as significant of a shift as would occur with the cluttered data ROC curve.

The unavoidable ground truth bias does not alone account for the detector's performance failures. Even in uncluttered data, the detector has displayed limitations when in the presence of a vocalizing Cuvier's beaked whale. Figure 13 exemplifies the detector's failure to hit a ground truth even at the lowest analyzed threshold level. In this instance, the detector correctly hits 10 of 11 ground truths within a distinct click pattern. Unexpectedly, the detector fails to correctly hit one of the seemingly stronger clicks within the click train. This statistical miss could potentially be a consequence of multipaths or environmental effects. The cross-correlation of the kernel to the SCORE click ensemble, shown in previously in Figure 5, verifies this resultant decrease in the correlation value when multipath effects are present. However, it can most likely be attributed to the low signal to noise ratio (SNR).

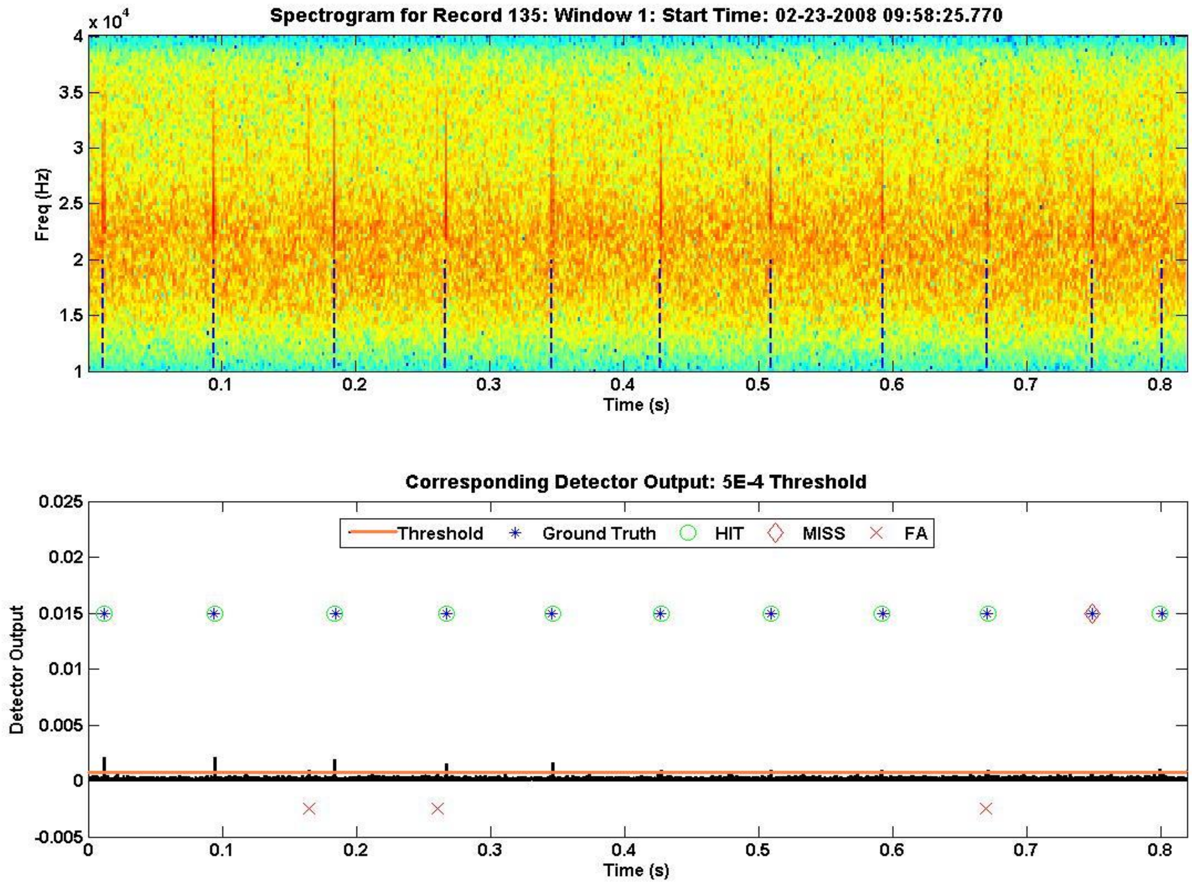

Figure 13. Uncluttered data example portraying the detector's limitations with a low SNR: The upper panel is the spectrogram of an uncluttered time period, with the ground truth click identifications emphasized with the dashed blue line. The lower panel is the corresponding detector output for a threshold of 5E-4, which is depicted with the solid orange line

Another shortcoming of the detector is its performance when other marine mammals are vocalizing within the same time period as Cuvier's beaked whales. Figure 14 is a designated cluttered time period wherein there appears to be delphind activity as well as *Ziphius* clicks. The detector performed well to hit each of the ground truths at a threshold of 0.001, shown in the bottom panel; however, it also hits on the apparent delphind clicks. The correlation values for the non-*Ziphius* vocalizations vary throughout the time period which makes it difficult to select a threshold that will still detect the Cuvier's clicks while correctly rejecting the undesired vocalizations. Increasing the threshold, shown in the middle panel of Figure 14, improves the detector's performance by dramatically lowering the number of false alarms. However, at this particular threshold level, there are several missed detections.

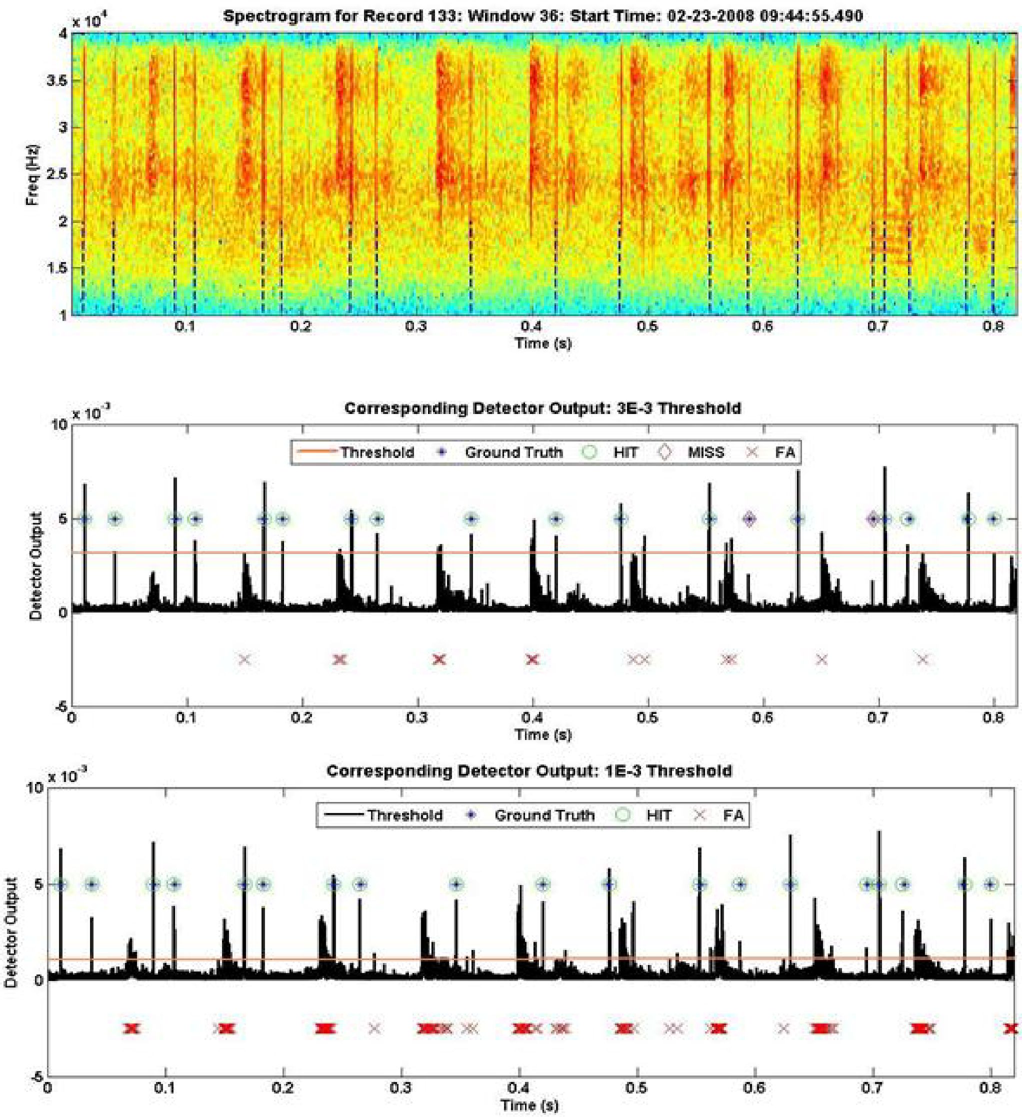

Figure 14. Detector performance in the presence of delphinid activity: The top panel is a spectrogram with the ground truth identifications marked with dashed blue lines. The middle and lower panels display the corresponding detector output at a given threshold, marked with the orange line. The P(D) is better at the lower threshold; however, the P(FA) increases as well.

The detector performance was degraded when other marine mammals vocalized within the same time period as a Cuvier's. In spite of this, the detector performed well in the presence of multiple *Ziphius*. Figure 15 portrays an ICI that is approximately one half the routinely observed 0.05s ICI. The shortened ICI and alternating magnitude strengths on the spectrogram suggest that there are two Cuvier's beaked whales vocalizing intermittently. This example also depicts the conservative bias inherent to the ground truth. The false alarms in the initial portion of this window most likely contain *Ziphius* clicks that were visually indiscernible.

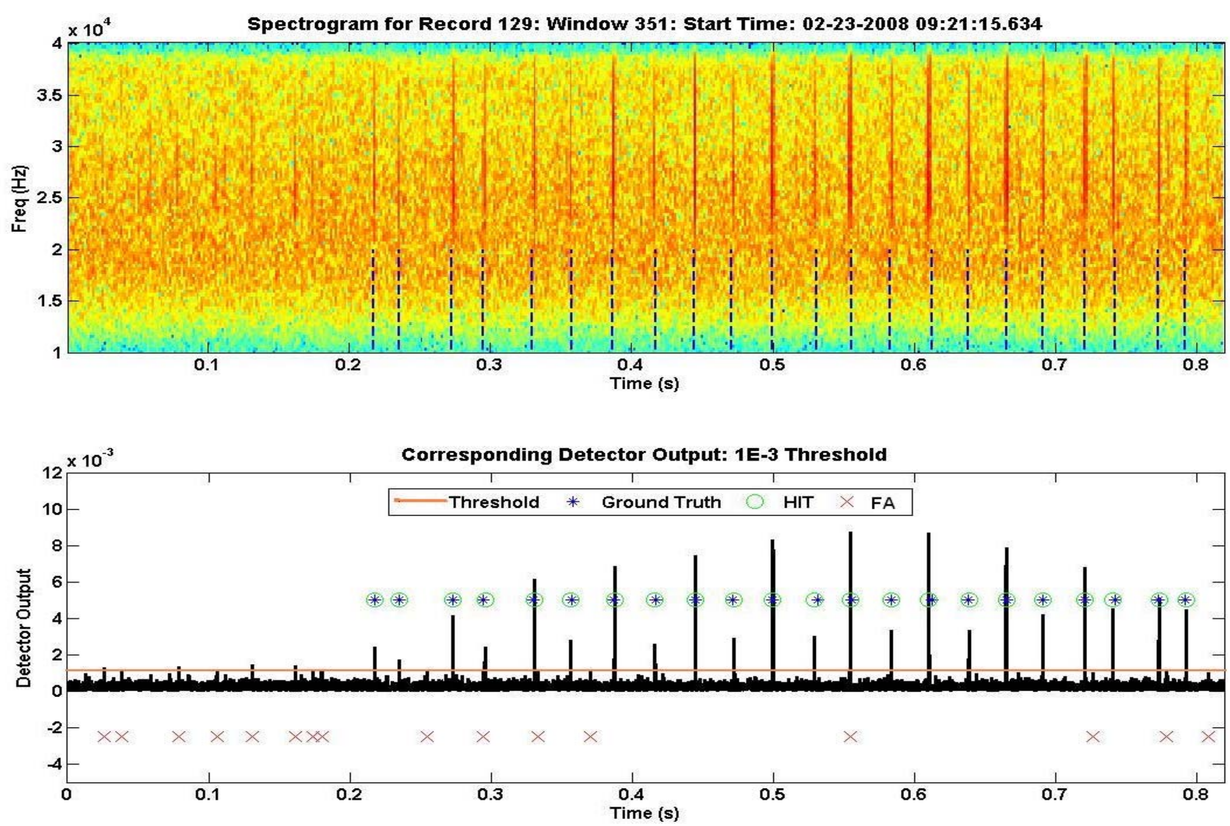

Figure 15. Detector performance in the presence of two Cuvier's beaked whales: The upper panel is the spectrogram and the ground truth click identifications are emphasized with the dashed blue lines. The lower panel is the corresponding detector output. The detector performs well in the presence of multiple *Ziphius*.

The detector performance was also analyzed during time periods where no *Ziphius* activity was observed. The detector performed perfectly in these instances where the ground truth contained zero clicks. The respective detector output statistics indicated zero hits, zero misses, and zero false alarms at all analyzed thresholds during these known quiet periods.

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IV. CONCLUSIONS

The unique spectral and temporal structures of Cuvier's beaked whales' vocalizations are favorable for automated detection via a matched-filter. A kernel was generated for two different types of acoustic recording devices: a HARP and a SCORE hydrophone. The kernel, that was generated from data band-pass filtered between 15 – 40 kHz, had a 390 μs duration. This is slightly greater than the click durations cited in recent research: 175 μs (Johnson et al., 2004), 200 μs (Zimmer et al., 2005), 250 μs (Johnson et al., 2004 and Tyack et al., 2006), and 300 μs (Pavan et al., 2006). This difference can likely be attributed to the available bandwidth of the acoustic recording instrument or the nature of the comparison. An acoustic recording instrument with a narrower bandwidth would capture a shorter duration of the click than an instrument with a wider bandwidth. Also, this is not a direct click to click comparison. The kernel is a compilation of 150 different clicks that were statistically analyzed to extract one dominant component, which accounted for 73% of the variance.

The consistently observed ICI in this study was approximately 0.05 s. This observation is in disagreement with other recently published research: 0.38 s (Pavan et al., 2006), 0.40 s (Johnson et al., 2004 and 2006, and Tyack et al., 2006), 0.43 s (Zimmer et al., 2005). The ICI was not the focus of this project. It was, however, a consistently observed phenomenon during the ensemble and ground truth creation. The difference of an entire order of magnitude is a significant result. One possible explanation is that there were multiple animals vocalizing intermittently. However, the extremely concise and repetitive intervals are suggestive of a single animal. It is also possible that these vocalizations are made by a species other than a *Ziphius cavirostris* or that this species simply vocalizes at varying ICIs. Further exploration of this unexpected disparity was beyond the scope of this research.

A total of 174.8 minutes of data from NPS's DAS recordings at a SCORE hydrophone were reviewed. Specific criteria were adhered to in an attempt to limit subjectivity. The objective selection criteria included: spectrogram energy between 22.5

and 35 kHz and/or a distinctive click train pattern, and a single selection of a cluster. Following this criteria, 28,434 clicks were selected for inclusion in the ground truth. Time segments when the data recordings were interrupted or when the signal could not be confidently discerned due to indistinguishable clutter were removed. 28.89 minutes were purposefully excluded from the statistical analysis. The remaining ground truth was then separated into categories of cluttered and non-cluttered data to further distinguish the ROC curves.

Despite all attempts to produce a precise ground truth, it was an inherently conservative estimate. At times, signals could not be visually discerned that the detector was able to detect. The cluttered data times were affected by this prejudice more so than the uncluttered data times. During the cluttered time periods, actual signals became hidden with the noise; thus, causing misses in the ground truth. These ground truth misses became detector false alarms in the detector evaluation. If this bias could be removed, the detector performance would be improved. The detector's performance in cluttered time periods would improve significantly as compared to a slight improvement during the uncluttered time periods.

At an acceptable false alarm rate of 0.1%: the overall detector's P(D) is 44%. The detector performed best in uncluttered time periods with a 61% P(D) for a 0.1% false alarm rate The detector's performance degrades in cluttered data: the detector has a P(D) of 26% at a 0.1% false alarm rate. The detector performance is perfect in the absence of clicks. The detector does not distinguish well between non-ziphid type vocalizations and Cuvier's beaked whales' vocalizations.

The greatest problem for the detector is the significant number of false alarms from other than desired marine mammals. The detector definitely detects clicks. However, it cannot be absolutely certain as to what species' clicks are being detected due to the inability to visually discern the differences at the time scale used. The kernel that was developed from the second sub-set of the ensemble, which was band-pass filtered from 15-60 kHz, was not utilized or assessed in this research. Assessing this second kernel with HARP data recordings can provide further insight as to the competency of the detector.

Potential follow-on research that could build upon the premises established in this thesis includes:

* An in-depth investigation of the ICI disparities between this thesis and other research
* Increasing the ensemble sample size, performing a PCA, and then comparing the resultant kernel to the kernel used in this research
* With the availability of an enhanced kernel, repeating the detector performance analysis
* Applying the detector to other SCORE hydrophones within the NPS DAS
* Duplicating this research with the unevaluated kernel and assessing the detector's performance when processing NPS and/or SIO HARP data
* Comparing temporally coincident detector results from a SCORE hydrophone with results from the nearby SIO site H HARP
* Assessing the classification performance of the kernel to correctly identify a *Ziphius* click from other marine mammals' vocalizations
* A study utilizing the optimum detector to assess the geographic call density distribution
* A study utilizing the optimum detector to assess the seasonal and/or diurnal variability call patterns

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