Comparing the Performance of Bottom-moored and Unmanned Surface Vehicle Towed Passive Acoustic Monitoring Platforms for Marine Mammal Detections

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Comparing the Performance of Bottom-moored and Unmanned Surface Vehicle Towed Passive Acoustic Monitoring Platforms for Marine Mammal Detections

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DEDICATION

Dedicated to my parents and my sister, who always supported me in every endeavor of my life.

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LIST OF ABBREVIATIONS

USV	Unmanned Surface Vehicles
AUV	Autonomous Underwater Vehicles
EARS	Environmental Acoustics Recording System
ESA	Endangered Species Act
GMMs	Gaussian Mixture Models
GOMRI	Gulf of Mexico Research Initiative
LADC-GEMM	Littoral Acoustic Demonstration Center – Gulf Ecological Monitoring and Modeling
PAM	Passive Acoustics Monitoring

CHAPTER 1: INTRODUCTION

Oceans represent the largest ecosystem on earth and thus harbor great biodiversity. Recent data shows that 239,164 identified species live in the ocean [4], and 119 of them are marine mammals [5]. Each species plays a major role in the balance of the ecosystem. Sustaining biodiversity is vital for a healthy environment. Throughout human existence, oceans have been considered a great source of resources and economic opportunities. We depend on the ocean and its marine animals, and their ecological functions, in several ways. We rely on the ocean for food, transportation, offshore energy exploration, mineral extraction, degradable waste disposal, tourism, etc. With the increase in the use of oceans, marine ecosystems are deteriorating rapidly, because of habitat degradation, overexploitation, pollution, increase of anthropogenic noise, acidification, and climate disruption. Recent studies show that anthropogenic and natural stresses are causing increasing rates of extinctions of both populations and species [1, 6]. For example, there are 28 different species of marine mammals known to inhabit the Gulf of Mexico. Sperm whales are listed as endangered under the Endangered Species Act (ESA) [3]. Endangerment of these species calls for monitoring of marine mammals to better understand how the populations and distribution of marine mammals change over time. Cetaceans can be monitored by visual or by acoustics monitoring methods, which can be performed using fixed or mobile platforms. Each monitoring platform has advantages and disadvantages in detecting and identifying different marine mammal species. Thus, choosing an appropriate monitoring platform for a monitoring plan can be challenging. A comparative study of detection performance of the different platforms is important.

Historically, visual observation data were used for estimating the abundance and distribution of marine mammals [1]. However, only a fraction of the animals present can be visually observed since observers can see them only when the animals are at the surface. Visual surveys are also limited to daylight hours and good weather conditions. Perhaps more importantly, results of the visual survey are highly variable since cetaceans stay in large groups and, also, due to the relatively limited spatial and temporal scales of their group size [11]. In recent years, Passive Acoustic Monitoring (PAM) methods have increasingly been utilized for cetacean observation. Seawater is an excellent transmitter of sound and most cetaceans are vocally active throughout most of a given day, as they use echolocation for communication and finding and catching prey. PAM offers many advantages, such as: (i) higher detection rate (one to ten times as many cetacean groups as compared to visual studies [11]), (ii) the ability to record data around the clock, as well as in inclement weather and poor visibility conditions. It is important to note that PAM is based on listening to the acoustic output of cetaceans and thus does not interfere with the animals' behavior [2].

The Littoral Acoustic Demonstration Center – Gulf Ecological Monitoring and Modeling (LADC-GEMM) simultaneously utilizes three PAM platforms (bottom-moored buoys, deep-diving SeaGliders, and Unmanned Surface Vehicles (USVs)) to establish a precedent of long-term PAM of the marine mammal recovery after the Deepwater Horizon oil spill and to test effectiveness of different PAM platforms for near real-time detection, characterization, and monitoring of the impact of environmental changes of different magnitude and duration on deep-diving Gulf of Mexico marine mammals [14]. Each platform works independently, having its own detecting system. No comparative analysis of detection performance among platforms has been published to date. In this thesis, data collected by bottom-moored buoys and an autonomous surface vehicle were compared to investigate the relative detection efficiency of those platforms. The results of this study aid in the development of cost-efficient PAM methodology for environmental impact assessment.

CHAPTER 2: PAM FOR SPERM WHALE DETECTION AND MONITORING

Cetaceans produce a variety of signal types. There are moans, knocks, thumps, buzzes, clicks, pulses, up or down calls, ratchets, trumpets, etc. Mysticete create frequency-modulated or pulsed calls while odontocetes produce tonal calls that are known as whistles and impulsive signals known as echolocation clicks [7]. Like other odontocete species, sperm whales in the Gulf of Mexico produce highly directional clicks for echolocation and also a stereotyped click, called a coda, for communication with other sperm whales [2, 10]. Detection techniques for these different signal categories are quite different. Thus, acoustic species identification depends on extracting relevant information, or features of the signal produced by the species of interest [8]. In this study, Passive Acoustics Monitoring (PAM) methods were applied to detect and monitor sperm whales in the Gulf of Mexico.

2.1 Passive Acoustics Monitoring Platforms

PAM used for marine applications uses hydrophones placed at fixed underwater locations or towed behind vessels to detect marine mammals' vocalization. Different monitoring platforms have specialized applications for cetacean detection and mitigation monitoring purposes. Towed arrays have the great advantage of mobility and large spatial coverage, providing real-time data and, thus, being very useful for monitoring mobile sources over a large spatial area. They can be used as a supplement to visual observations [9]. By contrast, fixed acoustic sensors, either anchored or buoyed, can be deployed to record data over long periods at a fixed location. Furthermore, they can store the data to an internal storage system or transmit it to shore via cable or satellite links. This type of sensor has the potential to provide a relatively cost-effective long-term monitoring platform and also cover large spatial areas, if deployed in a wide baseline array [13]. Choosing the best acoustic system for a particular monitoring project requires a thorough assessment of the project's objectives, a comprehensive evaluation of the regulatory monitoring, and an in-depth understanding of the research site and mitigation requirements as well as the capabilities of available acoustic technologies [15]. Details of the platforms used in experiments performed by LADC-GEMM in 2015 are discussed below.

2.1.1 Environmental Acoustics Record System (EARS) Buoy

Environmental Acoustic Recording System (EARS) [14] is a bottom-moored PAM system used to record marine mammal phonations and other acoustic sources. The EARS is deployed on a fixed mooring approximately 300 to 550 m long in water depths between 1000 and 2000 m. The deployment design is presented in Figure 1. This configuration of EARS is chosen for positioning the recording hydrophone in the water depths of marine mammals' feeding zone to maximize the probability of detection. Data is continuously recorded at 192 kHz sampling rate and stored as 16-bit integers in a proprietary binary format.

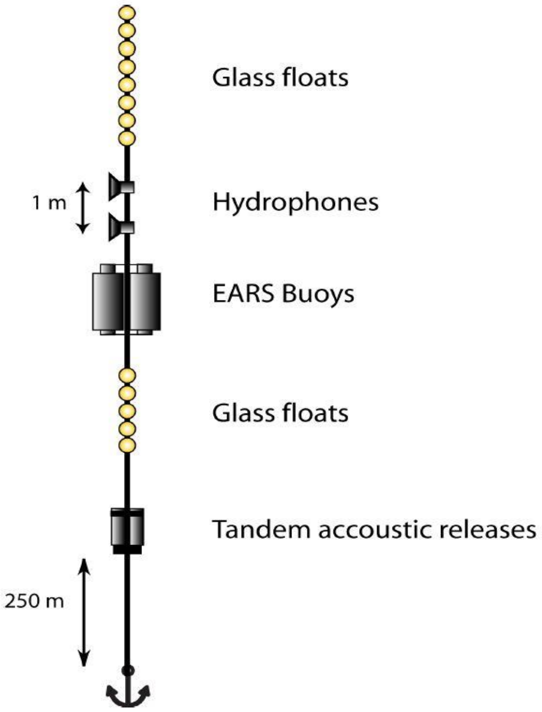

Figure 1: Schematic of the EARS configuration

Acoustic releases are used to detach the EARS from the anchor weight. When a special acoustic message is sent from the surface, the recording package floats to the surface for recovery.

In this study, we analyzed the data collected by EARS-buoys deployed during the LADC-GEMM 2015 Gulf of Mexico Experiment cruise. Five bottom-mounted buoys were deployed at three sites (Figure 2) named western, southern, and northern site. The exact mooring positions were: for the western site 28° 24.0389' N-88° 59.6867' W, into 1000 m deep water, for the southern site 28° 25.2810'N-88°37.1121'W, into 1000 m deep water, and a total of three buoys for the northern site within 1000 m of each other, at 28°39.0219'N-88°31.5006'W, 28°39.0663'N-88°31.0523' W, and 28° 38.7227'N-88°31.2224'W. The reason for deploying three moorings at the northern site was to use them as an array for obtaining range and bearing. These parameters are useful for future abundance estimates.

Figure 2: Location of EARS-Buoys near Deepwater Horizon accident site.

2.1.2 Unmanned Surface Vehicles (USV's)

Simultaneously with the bottom-moored system, two Unmanned Surface Vehicles (C-Worker and C-Enduro) [14] with towed PAM arrays were used during the LADC-GEMM 2015 Gulf of Mexico Experiment cruise. Towed arrays consist of two identical, spherical hydrophones. The hydrophones were attached at the end of a tow cable and spaced 2 m apart. The tow cable diameter was 14 mm and 32 mm in the potted sections. Depth and pressure sensors were also included at the rear of the cable. The USV C-Worker (Figure 3) towed cable was 220 m in length and the USV C-Enduro (Figure 3) towed cable was 55 m in length. The tow lengths in water from the stern of each vehicle were 200 m and 50 m, respectively.

The pre-amplifier output of the two hydrophone channels was transmitted via the tow cable to recording electronics housed in a watertight enclosure mounted beneath each USV. A high-pass filter was applied (nominal 20 Hz), and a low-pass anti-aliasing filter (nominal 160 kHz, 0.64×Nyquist frequency). The data was sampled using a National Instruments NI 9222 analogue-digital converter (ADC) with a sampling rate of 500 kHz per channel.

Figure 3: USVs (left: C-Worker, right: C-Enduro) leaving port in Cocodrie (Photo: Douglas Dugas).

Sound recordings were processed using the Pamguard v1.13.04 software running on a mini-PC with Microsoft Windows 7 (64bit). The audio data were continuously recorded as 16-bit Wav-format (.wav) files for the time when USV was activated. The individual recording duration varied from a few seconds to 600 s.

The survey speed was nominally 3 knots. C-Worker and C-Enduro arrays were expected to be towed at the depths of 20-35 m and 7-9 m, respectively, at this speed. USVs operated close to the Research Vessel (R/V) Pelican. The ship track shown in Figure 4 resembles the USV tracks.

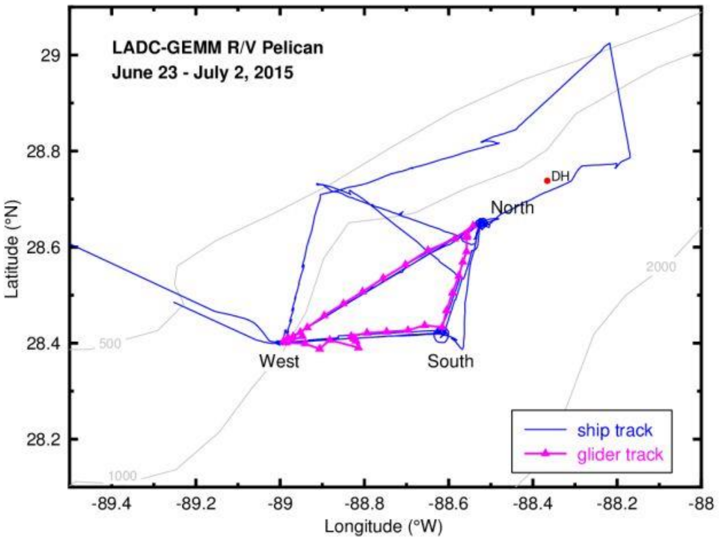

Figure 4: Glider tracks and ship tracks (USVs tracks) during the 2015 LADC-GEMM experiment.

CHAPTER 3: DATA PROCESSING AND DETECTING SPERM WHALE CLICKS

In this chapter, the detector performance to identify clicks of sperm whales in the Gulf of Mexico is discussed. A sperm whale creates three main types of acoustic signal, each for a different purpose. Regular clicks are used for orientation and to find long-range prey, buzzes are used to echolocate short-range prey, and codas are used for communication [17]. The regular echolocation clicks have a unique multipulse nature. Each click may consist of three or more pulses. Each pulse is a few ms in duration and the interpulse interval (IPI) is on the order of 5 ms. Thus, the length of a sperm whale click may reach up to 20 to 30 ms, depending on whale orientation relative to a hydrophone [16]. Sperm whale inter-click intervals range from 1.0 to 1.4 sec, and the energy band is from 3 kHz to 25 kHz [16]. The off-axis click properties are quantitatively different from the on-axis click properties. The on-axis (Figure 6A) monopulse click spectrum is smooth, and peaks at 13.8 kHz [18]; the off-axis (Figure 6B) click spectrum has multiple peaks with a 3–25 kHz frequency band for its multipulse nature [17].

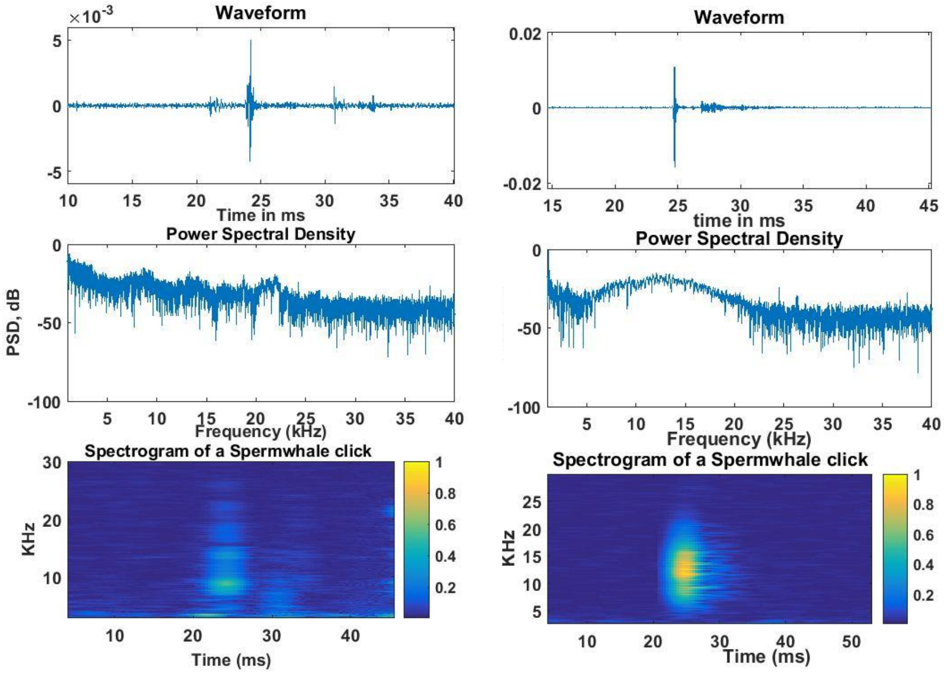

Figure 5: (A) on-axis and (B) off-axis clicks of sperm whale.

Two different detector systems were used to analyze data from two different PAM platforms. The LADC-GEMM band-energy detector was originally developed in Matlab to process EARS buoy data [17]. The PamguardBeta32 (www.Pamguard.com) is an open-source detector used for USV data processing developed in JAVA programing language [19]. Recently, a new detector used in this study was made by modifying the LADC-GEMM band-energy detector to analyze data from both PAM platforms. Using the same detector helps to inspect any differences in results coming from using two original detectors. The qualitative differences between the original two detectors are summarized in Table 1.

Table 1: The qualitative differences between LADC-GEMM energy detector and Pamguard.

Factors	LADC-GEMM band-energy detector	Pamguard
Current availability	Not yet publicly available	Public
Platform	MatLab	Java
Real-time operation	No	Yes
Localization	Not performed yet	Yes
Cost	MatLab	Free
Classifier	Yes	Yes
Spectrogram display	Yes	Yes

3.1 Data processing using LADC-GEMM energy detector

The LADC-GEMM energy detector consists of multiple Matlab scripts that process data to detect acoustic signals from a particular marine mammal species. These acoustic cue counts can be used to estimate regional species abundance [17].

The detection and counting of clicks using the LADC-GEMM band-energy detector is done in several steps. First, a spectrogram with no overlap is calculated for a given sensor's time series of acoustic data sampled at 192 kHz using 512-point short-time Fourier transforms (Figure 6). Each column of the spectrogram represents the frequency content in a 2.7 ms window of the signal. The clicks discrimination by species can be done by summing over frequencies of a desired frequency band of interest. For example, a sum over frequency bins in the frequency band 3–20 kHz is used in the detection of sperm whale clicks [17]. The technique of comparing energy distribution in three bands was used to classify clicks from different marine mammal species: 3–20 kHz for the sperm whale, 25–55 kHz for the beaked whale, and 60–90 kHz for the dolphin. In this thesis, the low-frequency band (3–20 kHz) is used in the detection of sperm whale clicks. After the calculation of a spectrogram and click separation, data is automatically saved into a file called “spectral sum” in .mat format and a figure is plotted (Figure 7). The spectral sum files are then used for further analysis.

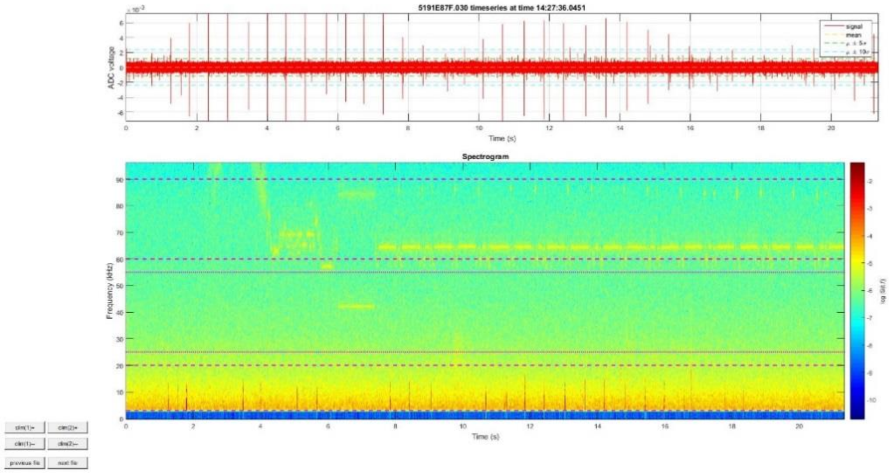

Figure 6: Waveform and Spectrogram of an EARS-buoy file.

Spectral sums of EARS-Buoy and USV data of overlapping recording times were made. To analyze USV data using the LADC-GEMM band-energy detector, USV data were down-sampled from 500 kHz to 192 kHz, and one channel of the recordings was used.

False positives were estimated manually by randomly checking 30 detected clicks in each hour. For each of the 30 clicks, the temporal waveform, power spectral density, and spectrogram (Figure 5) were plotted to investigate whether a click was TRUE or FALSE. The ratio of a total number of false clicks to the total number of clicks checked in a day was reported as the false positive rate of the day. To get the estimated total clicks in an hour of a day, a total number of detected clicks of an hour is then multiplied by 1-false positive.

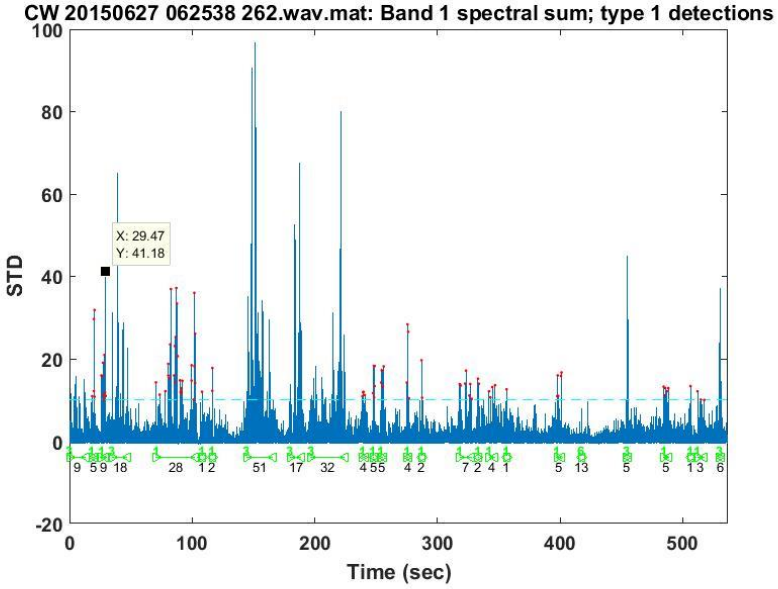

Figure 7: Output of a spectral sum file. Red dots represent detected sperm whale clicks.

3.2 Data processing using Pamguard

The Pamguard is an open source platform-independent software infrastructure for acoustic detection, localization, and classification of marine mammals, as well as for research into their abundance, distribution, and behavior [12]. In this thesis, the PamguardBeta32 version was used to analyze USV data. Pamguard consists of 29 plug-in modules to perform different of data handling tasks. Individual modules may be used for acquiring sound data, managing the Pamguard database, or searching for a particular sound type, e.g. clicks, whistle etc. [19]. The click detector module of Pamguard was used in this study to detect sperm whale clicks. When building a click detector, a user can define a set of parameters, including the signal threshold, the minimum number of samples between clicks, and the maximum length of clicks. Additionally, the automated classifier can be used to detect the signal from an animal-type of interest. A click classifier allows for setting the signal's primary energy band, the peak and mean frequencies.

The detection and counting of clicks using the Pamguard click detector is done in several steps. First, the Pamguard click detector was configured to pre-filter the data using a 1.5 kHz high-pass, eighth-order, Butterworth filter. The pre-filter output went to a 2-20 kHz bandpass, eighth-order, Butterworth filter, called a trigger filter. The trigger level was set to select signals with an energy of 10 dB above background noise in the 2–20 kHz band. After that, three click classifiers in Pamguard were used. The first one was used to identify the R/V Pelican's 12 kHz echosounder, which is a source of false positives for sperm whale clicks (Figure 8 and Figure 9). The second classifier was used to identify sperm whale clicks with the energy above the threshold in 6-18 kHz band. Sperm whale click trains with energy below 5 kHz remained unclassified and could not be separated in spectral or temporal domains from noise. The third classifier was used to classify and remove the remaining low-frequency noises with the energy above the threshold in 0-9 kHz band.

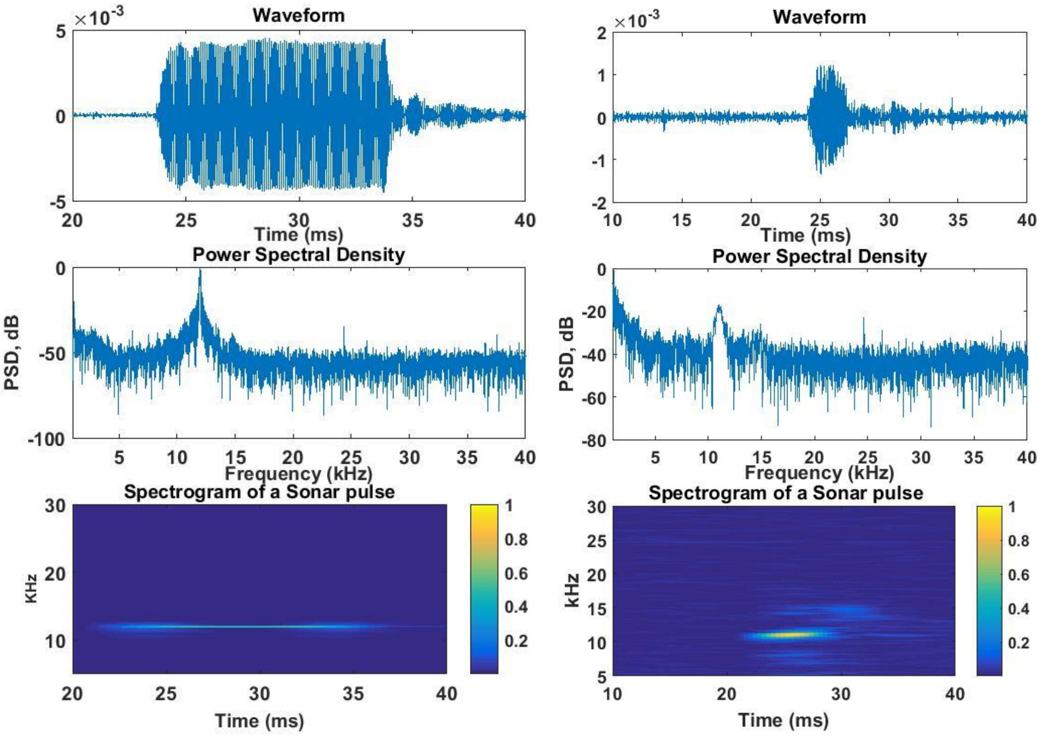

Figure 8: Frequently detected two types of sonar signals (false positive contribution). Both have a 12 kHz center frequency.

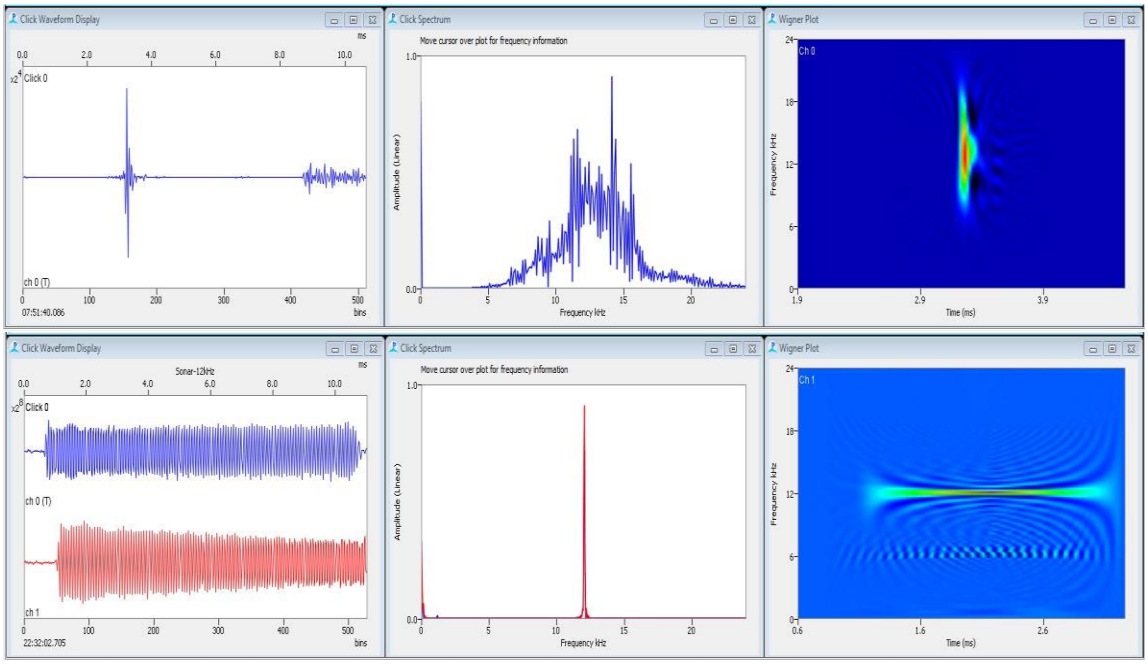

Figure 9: A detected sperm whale click (top) and a sonar pulse (bottom) by Pamguard.

Different sets of parameters were tested for the low-frequency noise classifier. The one which can cause minimum loss of actual sperm whale clicks by human observation was chosen. The configuration of these three classifiers is given in Table 2 below.

After running all three classifiers, an amplitude selector was used with the minimum amplitude 90 dB re 1 μ-Pa to disregard low amplitude clicks, including noise from the USV and recording system, which is difficult to classify correctly. In addition, an Echo detector was used to exclude echoes that came less than 0.1 s after a detection. Angle vetoes were set to exclude clicks with a bearing angle of less than 20 degrees relative to north direction, a sector dominated by echosounder pulses. After running all automatic click classifications, additions and exclusions of clicks were made manually, checking classified clicks of every hour using a click display. Selecting a click from the click display automatically plots the click waveform, power spectral density, and a Wigner plot. A demonstration of every stage in click classification is given in Appendix A.

Table 2: Parameters of Pamguard click classifiers.

Parameters	Sonar 12 kHz	Sperm whale	Low-frequency noise
Pre-filtering	Band pass 9 -14 kHz	6-20 kHz	Low pass 9 kHz
Zero crossing	10 -300	NA	NA
		Energy bands	
Test Band	9-14 kHz	6-20 kHz	0-6 kHz
Control band 1	0-9 kHz Th 4 dB	0-6 kHz Th 6 dB	0-0.1 kHz Th 1 dB
Control band 2	20-24 kHz Th 4dB	20-24 kHz Th 6 dB	9-20 kHz Th 1 dB

*Threshold (Th) re 1 µ-Pa.

In Table 2, “Test band” is the frequency band of the energy band comparison method, in which we expect the peak energy for our target vocalizations, e.g. sperm whale clicks. The “Control bands” are bands in which target vocalizations are expected to have relatively very little energy compared to the test band. “Zero crossing” represents the number of oscillations in the signal waveform.

CHAPTER 4: RESULTS AND DISCUSSION

False positives of the USV data, analyzed using the LADC-GEMM energy detector, were calculated as described in the data processing section in Chapter 3. False positives for each day are shown in Figure 10. The result shows that USV data contains a very high false-positive rate. The USV operates near the ocean surface. Since the near-surface area of the ocean is extremely noisy due to ambient and anthropogenic noises, e.g. ships and construction work, it is expected that USV data contains much more noise than bottom-moored EARS-buoy data. Another source of detected false clicks is the 12 kHz echosounder from the sonar used for acoustics releases during the LADC-GEMM 2015 experiment, and another sonar from R/V Pelican. Echosounder pulses get classified as sperm whale clicks because the frequency band for sperm whale detections is from 3 kHz to 20 kHz. Because changes in false positives vary greatly from day to day, taking the overall average can significantly increase or decrease the total number of real clicks on any particular day. Therefore, the false positive rate of each day was used to calculate the approximate number of real clicks. Data of every hourly false positive are given in Table 3 in Appendix B.

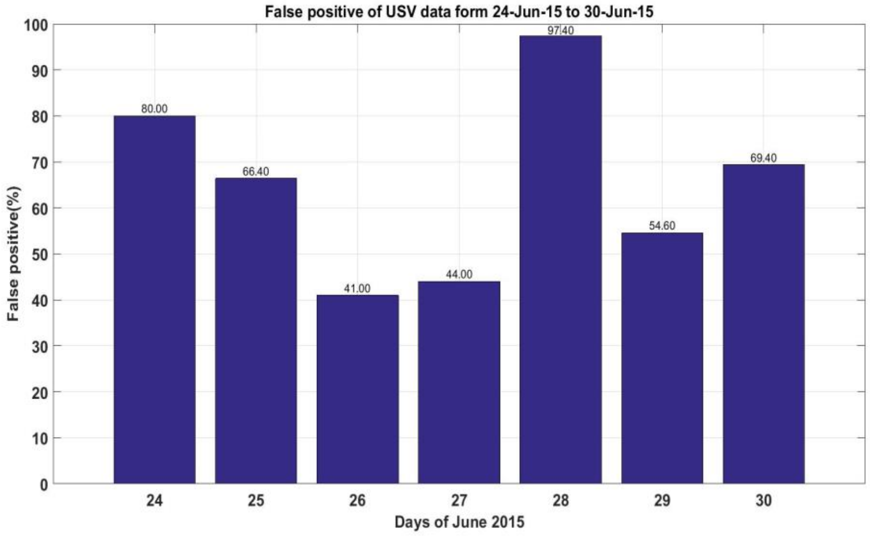

Figure 10: Daily false positives of the C-worker detections analyzed with the LADC-GEMM energy detector.

Traditionally, two different types of platforms are used with their two independent detector systems. We decided to make a comparison of the detectors by analyzing the same dataset by both Pamguard and LADC-GEMM energy detector, in order to investigate the detection efficiency of the detectors to detect sperm whale clicks. A comparison of detection rates between Pamguard and LADC-GEMM band-energy detector is presented in Figure 11. These datasets were collected by the USV C-worker from June 28, 2015, to June 30, 2015. The LADC-GEMM energy detector shows higher detection rates than Pamguard, but the detection trends appeared to be similar from both detectors. There are several factors that could lead to higher detection rates for LADC-GEMM energy detector.

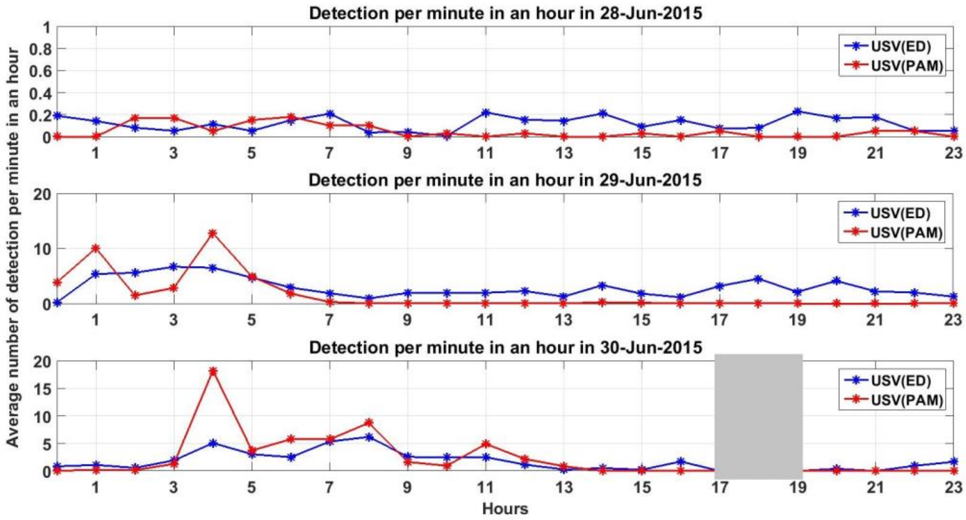

Figure 11: Comparison of detection rates of LADC-GEMM energy detector and Pamguard. Processing results of the USV collected datasets for three days are presented. The gray shaded part represents the time interval when its recording system was not working.

The LADC-GEMM band-energy detector identified the 12 kHz echosounder pulses as sperm whale clicks, which added a large number of false clicks to total detections. At the same time, setting the 12 kHz echosounder click classifier in Pamguard allowed for classifying and excluding the echosounder pulses from total detections. Also, the false positive rate varies considerably from hour to an hour, so taking an average false positive rate for a day can increase or decrease the detection rates significantly for hours with high or low false positives. For example, for June 29, 18:00 to 23:00 hours UTC the false positives rate is 100%, but the average false positive rate of 54.6% for this day results in higher detection rates by the LADC band-energy detector over the evening hours. The Pamguard detections for those hours are nearly zero. And, for 04:00 to 07:00 hours UTC of June 30, taking the average false positive rate 69.4% for this day results in lower detection rates by the LADC energy detector as compared to Pamguard.

The comparison of platforms was done by comparing the results from a dataset collected and analyzed by both platforms with their independent detectors, looking at overlapping recording periods. To compare the detection efficiency of the two platforms, the detection rates vs. horizontal range are plotted in Figures 12 and 13 for the two platforms. Due to the finite detection range of clicks from sperm whales present in this area, data were chosen from when the C-worker was within 10 km from EARS-Buoy [20, 21]. Data of June 26, 18:00 to 22:00 hours UTC and June 28, 2015, 16:00 to 19:00 hours UTC versus average horizontal distances between the platforms were plotted in Figure 12. And, data of June 28, 07:00 to 10:00 hours UTC and June 30, 2015, 06:00 to 13:00 hours UTC versus average horizontal distances between the platforms were plotted in Figure 13. The distances between the EARS-buoys and USV were calculated using their GPS position by a published Matlab script called pos2dist.

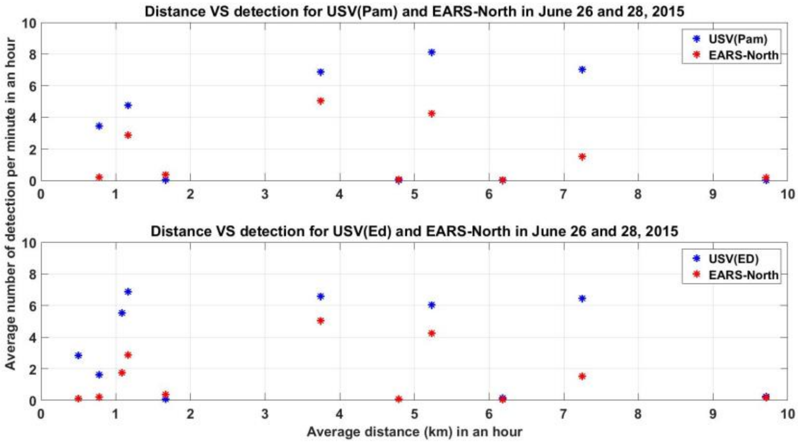

Figure 12: Comparison of the detection rates of bottom-moored EARS and USV towed array vs. the horizontal distance between the northern site EARS-buoy and USV (C-worker). Here USV data were analyzed by Pamguard (top) and LADC-GEMM energy detector (bottom).

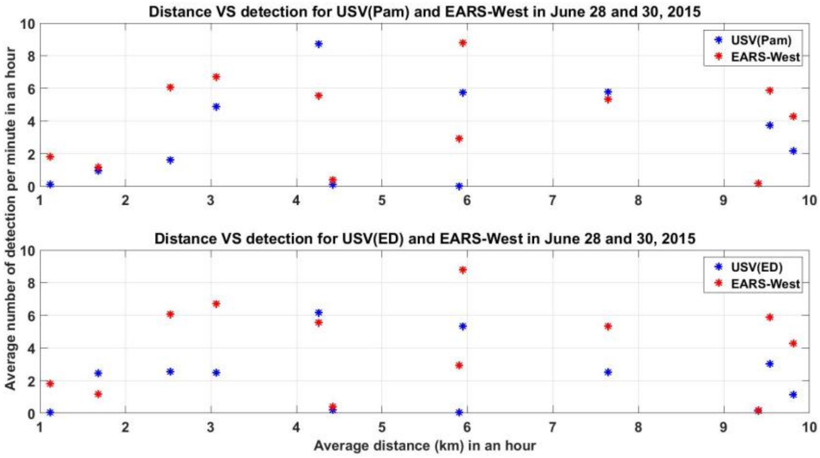

Figure 13: Comparison of the detection rates of bottom-moored EARS and USV towed array vs. the horizontal distance between the western site EARS-buoy and USV (C-worker). Here USV data were analyzed by Pamguard (top) and LADC-GEMM energy detector (bottom).

Figure 12 and Figure 13 show that on June 26 and June 28, 2015, the USV detected a higher number of sperm whale clicks than the EARS-Buoy at the northern site but detected a lesser number of sperm whale clicks on June 28 and 30, 2015 at the western site. The western site is a shallower site and more active in sperm whale vocalizations, in accordance with previously analyzed EARS data. We can speculate that it would be a preferred feeding site in comparison with the Northern site. One possible explanation for this variation is that deep-water placed hydrophones are more efficient in detecting sperm whales when they vocalize at feeding depth. At the northern site, detections are associated with surface-produced signals which are more reliably picked up by the surface array. However, this notion requires additional investigations.

Both graphs in Figure 12 and Figure 13 show a similar detection trend. Results for June 26 and June 30 with respect to their corresponding UTC hours of the day are plotted in Figure 14 and Figure 15, which makes the similar detection trend much more obvious.

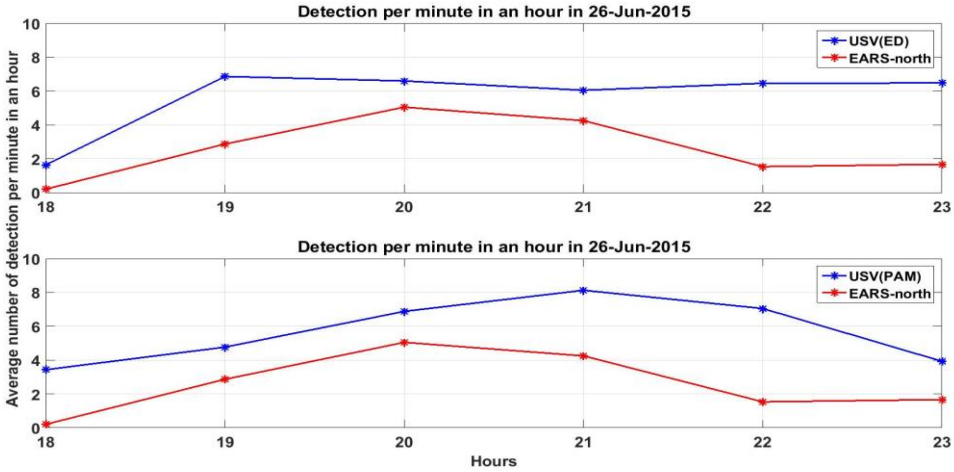

Figure 14: Comparison of hourly detection rates. Here USV data were analyzed by Pamguard and LADC-GEMM energy detector and compared with the EARS-Buoy northern site respectively.

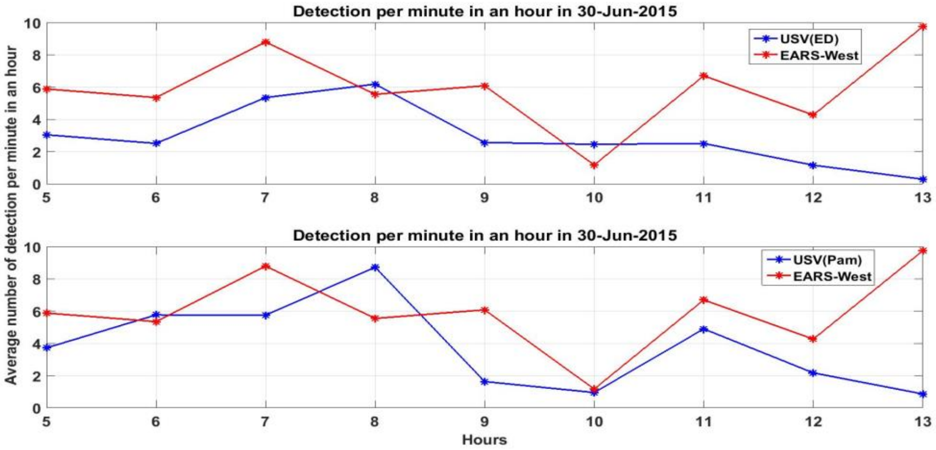

Figure 15: Comparison of hourly detection rates. Here USV data were analyzed by Pamguard and LADC-GEMM energy detector and compared with the EARS-Buoy western site, respectively.

Collected data from all detectors and platforms are given in Appendix B.

CHAPTER 5: CONCLUSION

The primary objective of this study was to investigate the efficiency of bottom-moored and USV-towed PAM systems to detect sperm whales in the area and, possibly, to use the data from both platforms to estimate regional abundances. Both platforms had their independent detector, allowing for a comparison of detection rates from both the LADC-GEMM band-energy detector and the Pamguard detector-software on the same datasets. This allowed us to investigate the detection-efficiency of both detector systems for sperm whale clicks. Results show that the version of the LADC-GEMM band-energy detector used gives higher counts than the Pamguard detector software used, with both showing similar detection trends. The detection rates for EARS-buoy and USV performing as indepepndent platforms were also analyzed in this study. Both detectors are effectively able to detect sperm whale clicks. Further studies are needed to investigate the actual reason for obtaining higher counts in the LADC-GEMM band-energy detector than Pamguard. For the platform comparison, EARS-Buoy shows higher detection rates than USV at the shallower western site than at the northern site, but trends of detection rates were found to be similar in both cases. The study suggests that the combined datasets can be used for an abundance estimate that may improve the accuracy of the estimates. Further abundance studies using the datasets collected by EARS-buoy and USV will provide more information about the efficiency of the platforms in detecting sperm whale through assessing the probability of detection of each platform [22]. The effectiveness of marine mammal monitoring could be increased by using combination EARS-buoy and USV. The entire study has also shown that USV-towed arrays could be chosen as a cost-effective near real-time solution for sperm whale monitoring instead of more broadly used deployment of bottom-moored buoys.

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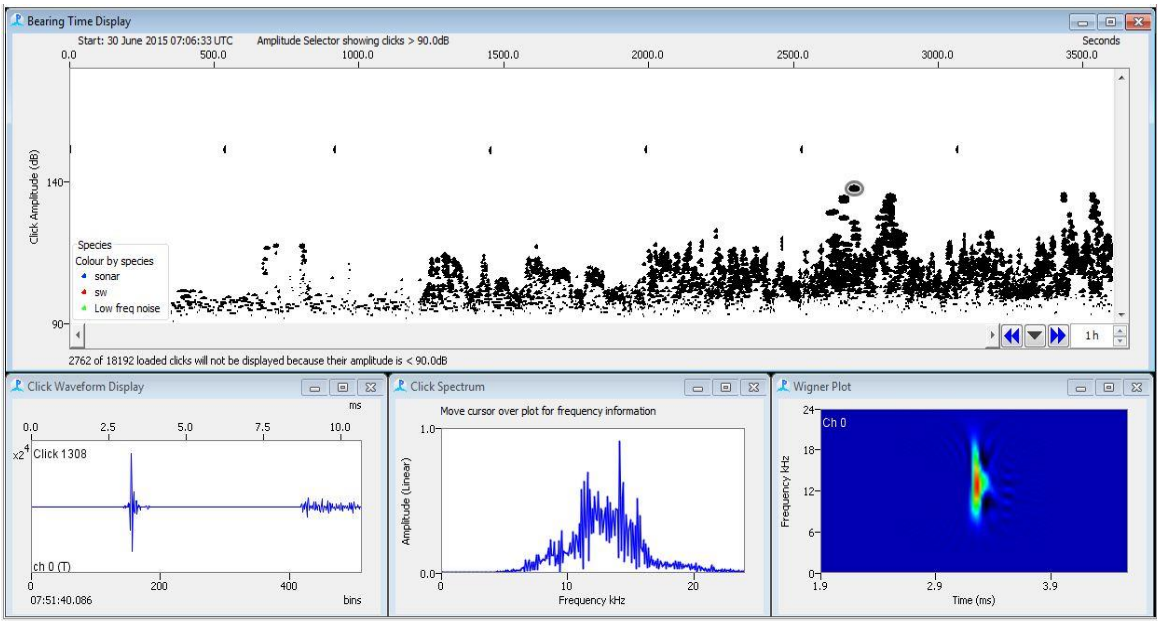
APPENDIX A

Reclassification of detected clicks by Pamguard are illustrated step by step.

1. The first step is to process all raw clicks using click detector.



2762 of 18192 loaded clicks will not be displayed because their amplitude is < 90.0dB

Figure 16: Raw click detector output normalized re 1 µ-Pa. Click amplitude on the vertical axis, time on the horizontal axis.

2. Next, three click classifiers were run. Blue, red, and green dots are primarily classified 12 kHz echosounder pulse, sperm whale clicks, and low-frequency noise sources, respectively.

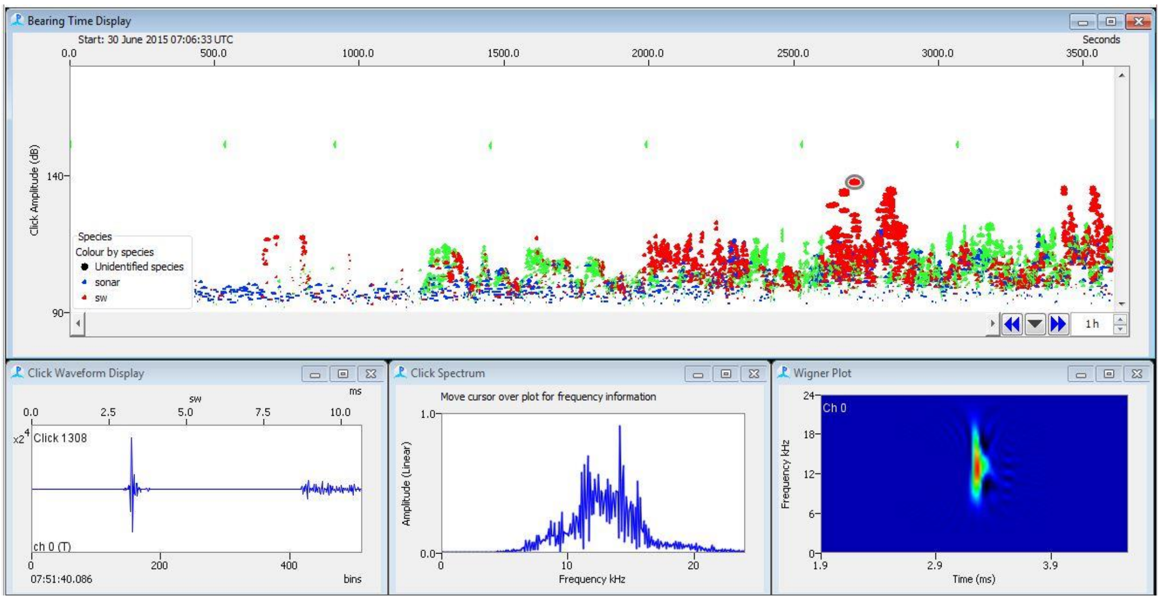


Figure 17: Classified 12 kHz echosounder pulses (blue), sperm whale clicks (red), and low-frequency noise (green).

3. 12 kHz echosounder pulse and low-frequency noises are muted in this step. Remaining sounds are expected to be sperm whale clicks.

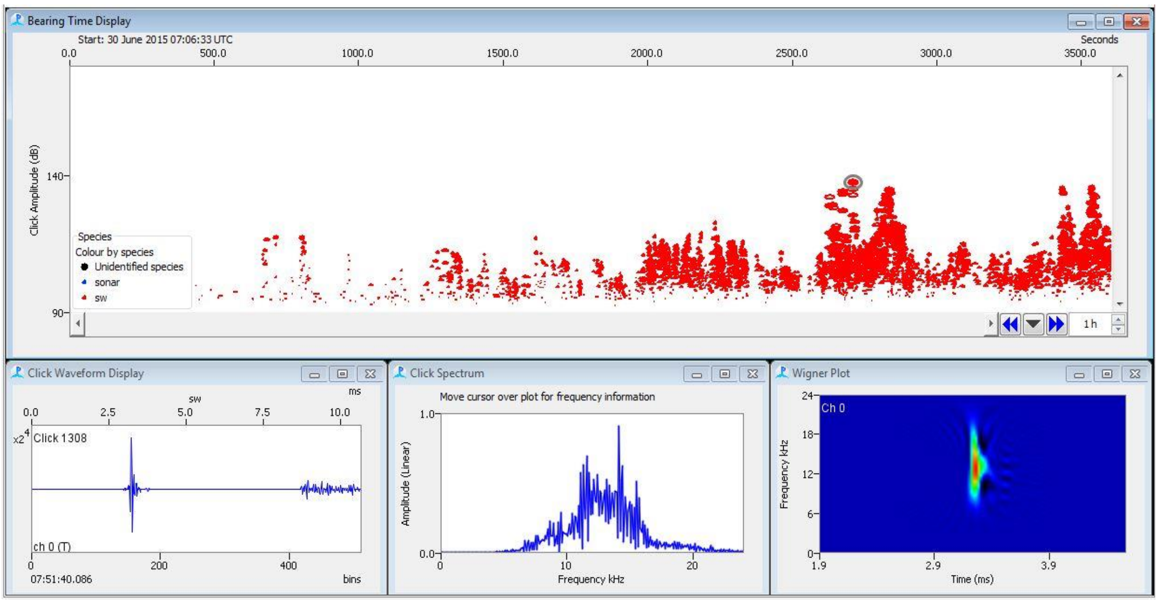


Figure 18: Remaining clicks after 12 kHz echosounder pulse and low frequency noises are removed.

4. At this stage, angle vetoes and echo detector were removed.

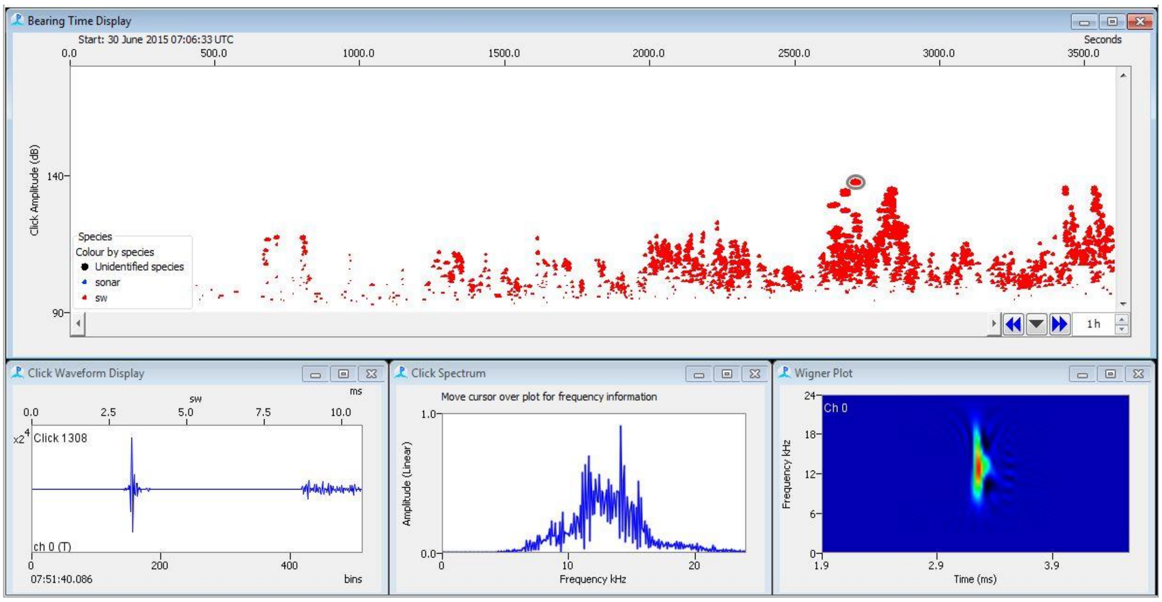


Figure 19: Expected total number of sperm whale clicks after all automatic removals of noises.

Finally, the manual effort has been made to reduce the loss of actual clicks and also the removal of falsely detected clicks.

APPENDIX B

Table 3: Hourly false positive percentage of the C-Worker data analyzed with LADC-GEMM energy detector.

Hours	24-Jun	25-Jun	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun
0	NA	46.7	63.3	26.7	100.0	60.0	83.33
1	NA	100.0	53.3	16.7	96.7	0.0	96.7
2	NA	96.7	63.3	46.7	100.0	60.0	80.0
3	NA	83.3	93.3	13.3	100.0	0.0	53.3
4	NA	66.7	76.7	10.0	100.0	0.0	0.0
5	NA	80.0	76.7	0.0	90.0	0.0	13.3
6	NA	76.7	86.7	6.7	100.0	80.0	36.7
7	NA	33.3	100.0	23.3	96.7	80.0	30.0
8	NA	52.0	93.3	43.3	96.7	100.0	56.7
9	NA	48.0	16.7	26.7	100.0	90.0	50.0
10	NA	30.0	3.3	0.0	90.0	0.0	56.7
11	NA	40.0	6.7	6.7	100.0	0.0	50.0
12	NA	40.0	50.0	16.7	93.3	0.0	73.3
13	NA	44.0	0.0	6.7	100.0	60.0	83.3
14	NA	50.0	26.7	26.7	100.0	40.0	100.0
15	NA	70.0	26.7	50.0	100.0	20.0	100.0
16	NA	96.7	46.7	80.0	93.3	40.0	80.0
17	NA	86.7	30.0	90.0	90.0	80.0	NA
18	76.67	80.0	43.3	100.0	100.0	100.0	NA
19	43.33	40.0	6.7	96.7	100.0	100.0	NA
20	100.00	100.0	0.0	76.7	100.0	100.0	100.0
21	90.00	80.0	0.0	93.3	96.7	100.0	100.0
22	96.67	80.0	10.0	100.0	93.3	100.0	96.7
23	73.33	73.3	10.0	100.0	100.0	100.0	100.0
Average	**80.00**	**66.4**	**41.0**	**44.0**	**97.4**	**54.6**	**68.57**

Table 4: Hourly averages of detections per minute for C-Worker data using Pamguard.

Hour	24-Jun	25-Jun	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun
0	NA	1.18	3.00	1.483	0.00	3.85	0.05
1	NA	0.52	1.47	3.667	0.00	10.02	0.19
2	NA	0.50	2.47	3.067	0.17	1.47	0.16
3	NA	1.03	3.50	5.883	0.17	2.82	1.28
4	NA	0.60	3.08	3.083	0.05	12.77	18.20
5	NA	0.87	1.20	3.383	0.15	4.90	3.72
6	NA	0.67	0.23	2.833	0.18	1.80	5.77
7	NA	2.23	0.07	1.383	0.10	0.27	5.75
8	NA	4.08	0.05	0.300	0.10	0.02	8.73
9	NA	3.55	3.33	4.200	0.00	0.02	1.63
10	NA	4.55	5.53	7.483	0.03	0.02	0.95
11	NA	3.68	3.97	3.383	0.00	0.05	4.90
12	NA	2.98	7.27	1.850	0.03	0.02	2.17
13	NA	0.25	4.62	9.483	0.00	0.00	0.86
14	NA	0.23	3.63	16.083	0.00	0.23	0.00
15	NA	0.88	5.25	3.483	0.03	0.13	0.02
16	NA	0.38	5.62	0.433	0.00	0.05	0.03
17	NA	0.52	4.08	0.067	0.05	0.00	NA
18	0.90	0.52	3.43	0.150	0.00	0.02	NA
19	1.90	3.52	4.77	0.150	0.00	0.00	NA
20	1.78	0.58	6.88	0.050	0.00	0.00	0.00
21	1.18	0.53	8.13	0.150	0.05	0.00	0.00
22	1.83	1.40	7.05	0.333	0.05	0.00	0.00
23	0.77	1.17	3.93	0.250	0.00	0.02	0.02

Table 5: Detection per minute of C-Worker using LADC-GEMM energy detector.

Hour	24-Jun	25-Jun	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun
0	NA	2.81	10.76	6.60	0.19	0.14	1.48
1	NA	3.10	12.51	5.43	0.14	3.58	1.92
2	NA	1.62	5.95	3.30	0.08	3.75	1.02
3	NA	4.68	5.06	6.99	0.05	4.47	3.38
4	NA	3.31	4.23	5.09	0.11	4.35	8.97
5	NA	3.86	5.88	5.07	0.05	3.16	5.38
6	NA	1.32	3.26	7.07	0.15	1.93	4.44
7	NA	3.15	1.26	8.20	0.21	1.25	9.48
8	NA	3.79	1.10	3.72	0.04	0.62	10.95
9	NA	2.34	5.14	6.25	0.04	1.28	4.54
10	NA	1.75	3.51	9.95	0.01	1.27	4.34
11	NA	0.77	3.27	4.52	0.22	1.30	4.43
12	NA	2.66	4.05	5.11	0.16	1.51	2.04
13	NA	1.20	3.79	4.57	0.15	0.83	0.50
14	NA	0.16	5.27	10.14	0.21	2.22	0.91
15	NA	1.59	5.40	2.59	0.09	1.19	0.41
16	NA	4.01	5.65	1.64	0.15	0.76	3.04
17	NA	4.99	2.88	4.87	0.07	2.12	NA
18	0.89	3.94	1.67	2.99	0.08	3.02	NA
19	1.91	1.44	7.01	2.14	0.23	1.41	NA
20	1.96	3.63	6.74	1.17	0.17	2.75	NA
21	1.19	3.46	6.18	1.07	0.18	1.48	0.00
22	2.52	4.33	6.60	0.84	0.05	1.33	1.69
23	1.33	3.60	6.62	1.21	0.05	0.84	2.94

Table 6: Detection per minute for EARS-Buoys of three sites.

EARS-Buoy South						EARS-Buoy North					EARS-Buoy West				
Hours	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun	26-Jun	27-Jun	28-Jun	29-Jun	30-Jun
0	0.02	12.48	1.62	0.00	0.03	NA	2.25	1.55	0.20	0.90	9.65	0.25	0.02	0.17	0.10
1	0.00	13.08	2.32	0.02	0.00	NA	0.43	0.10	0.03	0.13	6.18	0.38	0.13	0.07	0.22
2	0.00	15.73	0.88	0.00	0.00	NA	2.87	0.18	0.18	0.33	4.78	0.87	0.00	1.67	0.45
3	0.02	9.37	0.62	0.02	0.00	NA	10.28	0.38	0.05	0.35	1.20	12.25	0.15	1.18	3.30
4	0.35	2.78	0.08	0.00	0.15	NA	12.53	1.00	0.12	0.22	4.15	8.72	1.20	0.77	6.33
5	0.07	0.72	0.07	0.00	0.00	NA	4.33	0.35	0.10	0.07	4.35	6.00	3.72	0.00	5.88
6	0.08	0.38	0.10	0.00	0.00	NA	4.10	0.08	0.08	0.08	3.87	4.92	0.17	1.07	5.35
7	0.13	0.25	0.22	0.57	0.00	NA	4.90	0.03	0.13	0.17	6.25	2.67	0.42	5.02	8.80
8	0.25	0.12	0.93	0.00	0.02	NA	0.60	0.05	0.13	2.77	2.17	8.40	1.82	2.88	5.55
9	0.08	1.45	0.40	0.00	0.00	NA	17.07	0.00	0.00	0.02	8.70	5.35	2.92	6.20	6.08
10	0.15	13.27	0.28	0.05	0.00	NA	22.08	0.68	0.10	0.07	8.60	9.00	2.13	1.32	1.17
11	1.85	7.85	7.58	0.02	0.02	NA	10.08	0.07	0.10	0.00	3.38	3.77	0.10	7.38	6.70
12	0.55	2.57	13.48	0.00	0.00	NA	11.25	0.02	0.00	0.02	1.97	4.13	0.00	13.92	4.27
13	0.67	1.20	6.30	0.00	0.10	0.03	6.88	0.00	0.02	0.00	11.62	0.87	0.02	0.18	9.75
14	0.18	3.63	0.45	0.03	0.00	0.05	0.87	0.02	0.08	0.05	18.63	2.00	0.03	3.50	6.05
15	0.55	0.27	5.35	0.00	0.00	0.00	5.03	0.02	0.08	0.00	3.90	14.13	0.02	8.50	3.18
16	2.18	0.50	12.37	0.00	2.10	1.73	12.52	0.03	0.08	0.02	3.20	3.22	0.02	7.03	9.52
17	2.45	1.08	2.68	0.00	9.00	0.10	9.70	0.38	0.03	0.02	3.98	4.57	0.02	6.33	8.50
18	3.80	2.42	0.03	0.03	0.02	0.20	7.20	0.08	0.18	0.02	3.68	7.85	0.03	13.95	5.22
19	7.13	3.53	0.03	0.02	0.02	2.87	16.77	0.18	0.05	0.00	1.53	3.80	0.23	17.30	2.97
20	17.35	2.83	0.02	0.00	0.00	5.05	16.00	0.52	0.23	0.00	2.58	2.97	0.02	6.25	0.47
21	21.32	6.23	0.03	0.00	0.02	4.25	13.77	0.37	0.17	0.02	2.27	8.18	0.25	6.12	0.45
22	4.63	0.32	0.08	0.00	0.03	1.53	12.13	0.23	0.02	0.00	2.10	3.28	0.33	0.25	2.30
23	0.75	2.28	0.00	0.00	0.02	1.67	3.23	0.20	0.30	0.05	0.32	10.48	0.25	0.28	2.10

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Thesis Chair: Dr. Natalia Sidorovskaia
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ABSTRACT

Passive acoustic monitoring (PAM) is a more effective method of monitoring cetaceans' distribution and abundance than conventional visual surveys. Cetaceans are highly vocally active and produce identifiable acoustic signals during echolocation and communication. Three different PAM platforms recorded data in overlapping time periods in the vicinity of the 2010 Deepwater Horizon oil spill site: bottom-moored buoys (EARS), Unmanned Surface Vehicle towed arrays (USV), and subsurface glider-mounted hydrophones. Detection rates of the EARS and USV were compared to investigate their efficiency in detecting marine mammals. Detection events were obtained using independent detectors for each platform and then compared by feeding data through a common detector. Results from both detectors and platforms were compared, and a comparable trend of detection rates was found. The purpose of this study is to aid in the development of cost-efficient PAM methodology for mitigation and environmental impact assessment purposes.

BIOGRAPHICAL SKETCH

Sakib Mahmud was born on July 12, 1987 to his loving mother, Late Delwara Begum, in Sherpur, Bangladesh. He graduated with Bachelor of Science and Master of Science degrees in physics from Shahjalal University of Science and Technology, Bangladesh, in 2010 and 2011, respectively, and earned a Master of Science in physics from the University of Louisiana at Lafayette in 2017. Sakib plans to continue his education in the field of acoustics and its application.