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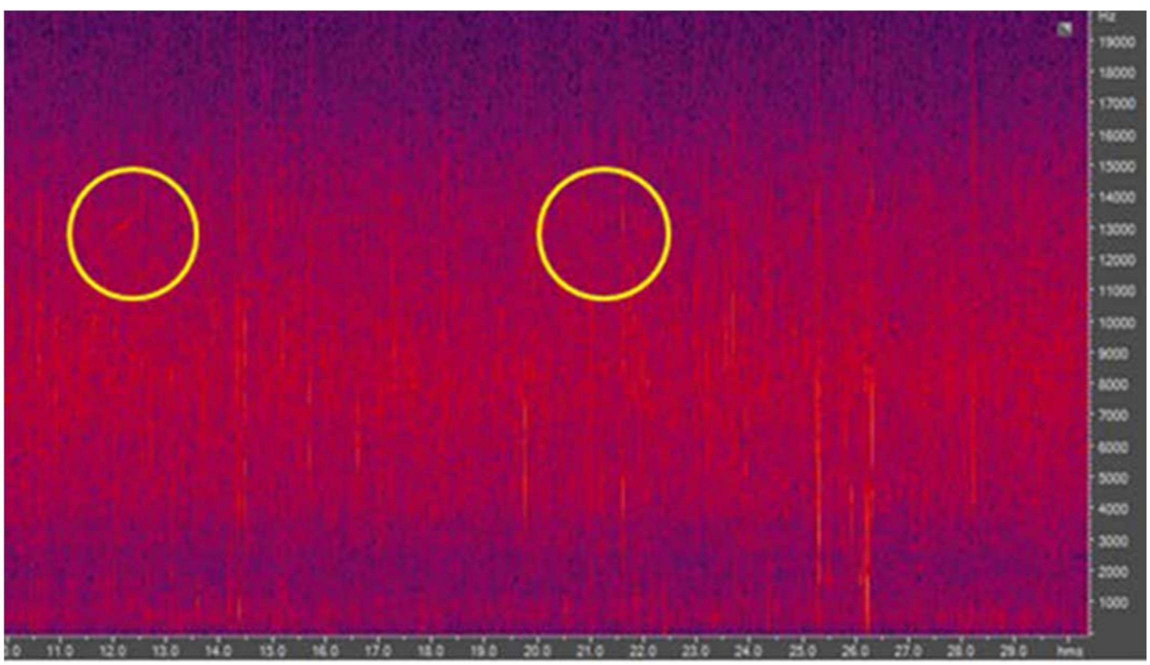
PASSIVE ACOUSTIC MONITORING OF ODONTOCETES IN THE VICINITY OF PU`ULOA UNDERWATER DETONATION TRAINING RANGE, HAWAII RANGE COMPLEX, O`AHU



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14. ABSTRACT Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) was tasked with conducting a thorough investigation and analysis of a passive acoustic data set recorded off O`ahu, Hawai`i from 2010-2013. This effort is the second analysis of the data set, involving many more man hours of labor-intensive manual analysis by researchers after the previous effort reported in SSR-NAVFAC-EXWC-EV-1501 (JUNE 2014) to develop an automatic detection computer algorithm proved unsuccessful due to the high noise in the shallow water environment. This report is a continuation of that effort. This research was funded by Pacific Fleet and included support from NAVFAC EXWC's Marine Resource Assessment Diving Services (MRADS) and the Hawai`i Institute of Marine Biology's Marine Mammal Research Program. The specifics of the study are enclosed in this report as Appendices formatted for publication in the Journal of the Acoustic Society of America (JASA), a spreadsheet of raw data for 800 odontocete whistle detections, and a summary of additional efforts at programming an automated detection algorithm.					
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EXECUTIVE SUMMARY

Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) was tasked with conducting a thorough investigation and analysis of a passive acoustic data set recorded off O`ahu, Hawai`i from 2010-2013. This effort is the second analysis of the data set, involving many more man hours of labor-intensive manual analysis by researchers after the previous effort reported in SSR-NAVFAC-EXWC-EV-1501 (JUNE 2014) to develop an automatic detection computer algorithm proved unsuccessful due to the high noise in the shallow water environment. This report is a continuation of that effort. This research was funded by Pacific Fleet and included support from NAVFAC EXWC's Marine Resource Assessment Diving Services (MRADS) and the Hawai1i Institute of Marine Biology's Marine Mammal Research Program. The specifics of the study are enclosed in this report as Appendices formatted for publication in the Journal of the Acoustic Society of America (JASA), a spreadsheet of raw data for 800 odontocete whistle detections, and a summary of additional efforts at programming an automated detection algorithm. Passive ecological acoustic recorders (EARs) were deployed in waters adjacent to the Pu`uloa underwater detonation range off the coast of O`ahu, Hawai`i from 2010-2013. A bulleted list of major findings detailed in this report follows:

- Of the over 133,000 files analyzed manually, approximately 850 contained odontocete whistles (0.6%);
- The instrument deployed to the west of the detonation range contained three times as many occurrences as the EAR in the eastern location possibly due to differences in substrate composition and/or the behavior of the animals;
- A weak seasonal correlation was found, with more occurrences in late summer/early fall;
- There was no statistically strong relationship between the hour of day and presence of whistles;
- Using passive acoustic monitoring, the recorders do not detect the presence of marine mammals if they are not vocalizing, and resting spinner dolphins do not vocalize often;
- Transiting spinner dolphins do vocalize, and many visual observations of these animals indicate they are transiting the Pu`uloa range when they are detected;
- The very low number of whistle detections at this location is consistent with relationships between the coastal shelf bathymetry and odontocete foraging behavior established in similar studies in various locations in the main Hawaiian Islands; and
- Regulation detonation training in this area has a low chance of detrimental effects to transiting odontocetes.

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ACRONYMS AND ABBREVIATIONS

ARL	Applied Research Laboratory
dB	Decibel
DoD	Department of Defense
EAR	Ecological Acoustic Recorder
EOD	Explosive Ordnance Disposal
EODMU	Explosive Ordnance Disposal Mobile Unit
ESA	Endangered Species Act
EXWC	Engineering and Expeditionary Warfare Center
FSW	Feet of Seawater
GB	Gigabyte
HF	High-frequency
HIMB	Hawai'i Institute of Marine Biology
Hz	Hertz
in	Inch
JASA	Journal of the Acoustical Society of America
kHz	Kilohertz
km	Kilometer
LF	Low-frequency
MDSU	Mobile Diving Salvage Unit
MF	Mid-frequency
min	Minutes
MMPA	Marine Mammal Protection Act
MMRP	Marine Mammal Research Program
MRADS	Marine Resource Assessment Diving Services
ms	Millisecond
NAVFAC	Naval Facilities Engineering Command
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
PACFLT	Commander, Pacific Fleet
PAM	Passive Acoustic Monitoring
PTS	Permanent Threshold Shift
RIMPAC	Rim of the Pacific
RHIB	Rigid-Hulled Inflatable Boat
s	Seconds
SEAL	Sea Air Land
SEL	Sound Exposure Level
SPL	Sound Pressure Level
TEU	Training and Evaluation Unit
TB	Terabyte
TS	Threshold Shift
TTS	Temporary Threshold Shift
μPa	Micropascal
μPa^2-s	Micropascal squared per second
UARC	University Affiliated Research Center

UNDET	Underwater Detonation

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1.0 INTRODUCTION

Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) Marine Resource Assessment Diving Services (MRADS) was tasked with conducting a thorough investigation and analysis of a passive acoustic data set recorded off O`ahu, Hawai`i from 2010-2013. This effort is the second analysis of the data set, involving many more man-hours of labor-intensive manual analysis by researchers after the previous effort to develop an automatic detection computer algorithm proved unsuccessful due to the high noise in the shallow water environment (Reference 1). The present report is a continuation and expansion of the past effort. This research was funded by Pacific Fleet and included support from NAVFAC EXWC's Marine Resource Assessment Diving Services (MRADS) and the Hawai1i Institute of Marine Biology's Marine Mammal Research Program for data analysis. The specifics of the study are enclosed in this report as Appendices. Appendix A is formatted for publication in the Journal of the Acoustic Society of America (JASA). Appendix B is a spreadsheet of raw data for each of the 850 odontocete whistle detections. Appendix C is a summary of additional unsuccessful efforts at programming an automated detection algorithm. This appendix is included for informational purposes, as this effort was given limited funding on this scope of work for further development.

1.1 The Report Within the Report

The purpose of adding Appendix A as a stand-alone scientific publication is to meet the objective of allowing this report to be codified and assigned a report number with NAVFAC EXWC for archiving and future reference by NAVFAC, while not incurring the administrative burden of reformatting the academic publication format which may be used for future submission to the journal. Major findings of this effort are covered in the executive summary above, and detailed in Appendix A.

1.2 Data Archive

All acoustic files recorded as part of this work are archived on a stand-alone hard drive maintained by NAVFAC EXWC MRADS. Copies of these files (approximately 1.2 TB) shall be provided to PACFLT upon request, and are available for future analyses if required. Additionally, video files and still digital pictures of the fieldwork are likewise maintained.

REFERENCES

1) U.S. Navy (**2014**). Naval Facilities Engineering and Expeditionary Warfare Center. Preliminary Analysis of Ecological Acoustic Recorder (EAR) and Sound Data from the Pu`uloa Underwater Detonation Range, O`ahu, Hawai`i.

Note: a full list of academic references is listed in Appendix A.

APPENDIX A

PASSIVE ACOUSTIC DETECTIONS OF ODONTOCETES IN THE VICINITY OF A MILITARY UNDERWATER DETONATION TRAINING RANGE IN HAWAII – JASA FORMAT

Title: Passive acoustic detections of odontocetes in the vicinity of a military underwater detonation training range in Hawai`i

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Running Title: Passive acoustics from an underwater range

Abstract

Passive ecological acoustic recorders (EARs) were deployed in waters adjacent to the Pu`uloa underwater detonation range off the coast of O`ahu, Hawai`i from 2010-2013. The EARs recorded on a duty cycle of 30 seconds every 5 minutes at a sampling rate of 40 kHz. Due to a high biotic and abiotic noise in the shallow water environment, automated whistle detector programs were unsuccessful. Of the over 133,000 files analyzed manually, approximately 800 contained odontocete whistles (0.6%). The instrument deployed to the West of the detonation range contained three times as many occurrences as the EAR in the eastern location. This could be due to differences in substrate composition and/or the behavior of the animals. A weak seasonal correlation was found, with more occurrences in late summer/early fall. There was no strong relationship between the hour of day and presence of whistles. The very low number of whistle detections at this location is consistent with relationships between the coastal shelf bathymetry and odontocete foraging behavior established in similar studies in various locations in the main Hawaiian Islands (Howe, 2016). Regulation detonation training in this area has correspondingly low chance of detrimental effects to transiting odontocetes.

I. INTRODUCTION

The objective of this study was to determine odontocete habitat use patterns in the area of Pu`uloa UNDET range from passive acoustic data, where there is increased anthropogenic noise at potentially injurious levels due to routine military operations, including explosions and sonar events.

Marine mammal sensory and signal processing systems are complex, and have evolved specialized adaptations to take advantage of the superior physical properties of acoustics in the water (Au et al. 2016; Roitblat et al. 1995; Nachtigall 1980; Yuen et al. 2005; Lammers et al. 2003; Ketten 1995). Acoustics are the primary method with which cetaceans interact with each other and their environments; anthropogenic sounds of all types can interfere with those sounds and consequently can have negative effects on marine mammals (Mohl et al. 1999; Carrington 2013; Govoni et al. 2008; Parsons et al. 2008; Ketten 1995).

Recently, there has been increased attention from the governments of the world on the question of how sounds generated through commercial and military activities may interfere with the ecosystem, population, and individual health of marine mammals. There are five categories by which acute and impulsive sounds may affect marine mammals. Acute anthropogenic noise could result in mortality, permanent damage to the animal's sensory system (permanent threshold shift), temporary degradation of the animal's sensory systems (temporary threshold shift), negative behavioral response, or have no observable effects (Southall et al. 2007; Nowacek et al. 2007).

Regarding underwater explosions, the parameters that determine which of the above effects an explosive event will have depends on numerous variables. Yelverton et al. (1973) subjected mammals and birds to detonations in a controlled experiment and catalogued the physiological effects of detonations to develop exposure based on magnitude of exposure and distance from the explosion. From these data, additional subsequent curves were created that predicted safe distances for a variety of marine mammal species (Goertner 1982). Ketten (1995) studied possible effects of underwater detonation of high explosives on marine mammals, analyzing the theoretical potential to cause blast damage and barotrauma. Based on the previously outlined differences in ear anatomy and sensitivity from land mammals, she calculated overpressure and correlated it with experimental data from the literature to formulate theoretical zones for acute trauma, permanent hearing loss, and temporary threshold shifts caused by explosions of suspended charges of two different weights. Based on additional research, National Oceanic and Atmospheric Administration (NOAA) published a comprehensive guide in 2013 on the acoustic levels believed to cause permanent and temporary threshold shifts (NOAA 2013).

It is often difficult to confirm the cause of death of marine mammals; only a single mortality event directly associated with explosives has been documented in the literature, though several others are unconfirmed. The deaths of four long-beaked common dolphins (*Delphinus capensis*) during Navy Explosive Ordnance Disposal (EOD) training on the Silver Strand Training Complex in San Diego, California (Danil and St. Leger 2011) prompted implementation of more stringent protective measures to better mitigate potential effects. Threshold shifts (both permanent and temporary) due to explosive events or other anthropogenic noise cannot be studied in natural settings, so researchers have worked to determine the intensity and duration of a sound to cause damage for each species through captive trials (Finneran 2015; Nachtigall et al. 2004; Schlundt et al. 2000; Southall et al. 2007). For example, Finneran et al. (2000) conducted a controlled exposure experiment with two bottlenose dolphins (*Tursiops truncatus*) and one beluga whale (*Delphinapterus leucas*) exposed to simulated distant underwater explosive sounds. The researchers found no temporary threshold shifts occurred when exposed to these distant underwater explosion simulations.

Beyond trauma and hearing effects, behavioral responses in the vicinity of underwater detonation have been observed in a variety of locations and reported by numerous investigators with varying degrees of analysis. Todd et al. (1996) observed humpback whales (*Megaptera novaeangliae*) in Trinity Bay, Newfoundland where increased entanglements in fishing nets were reported during a time when underwater construction blasts were being conducted in the area. Researchers found that directly observed individual whales did not have any noticeable behavioral reaction (i.e. sudden dives, movements) in response to explosions. Dos Santos et al. (2010) observed bottlenose dolphins in Sado estuary, Portugal during explosive obstacle removal. The pod was 5 km from the blast site at time of charge initiation, and sound pressure level (SPL) measurements taken at 2 km from the site saturated the recording system. The sound “clipped” above 170 dB re 1µ Pa, indicating the SPL was much greater than that level. However, researchers detected no apparent changes in dolphin behavior during the observation period.

Another example of a study attempting to observe behavioral impacts on cetaceans due to detonations was conducted in Sarasota Bay, Florida by Buckstaff et al. (2013). Two in-air explosions and one underwater explosion occurred during bridge construction, during which boat based surveys observed bottlenose dolphins responding to the blasts by changing heading, increasing group size, and decreasing nearest neighbor distance.

Studies have been conducted on larval fish mortality rates relating impulse pressure and distance from the detonation to percent killed (Govoni et al. 2008). It is impractical, arguably unethical, and currently illegal to do similar controlled exposure experiments in marine mammals in close proximity to explosive events (U.S. Government 1997). Because such experiments have never and likely will never be performed, the evidence about the actual received level of sound exposure on the animal, and the effects on its sensory and signal processing ability and its behavior, can never be absolutely quantified. Thus, these effects can only be approximated based on anecdotal observations and opportunistic studies.

Sonar is another source of anthropogenic noise in marine ecosystems, and it is easier to quantify its acoustic influence. Studies have shown that marine mammals can change their vocalization frequencies and intensities in response to being in environments with more background noise (Au et al. 1985). Based on a controlled captive study, prolonged, intense sonar pings (214 dB re: 1uPa) can induce physiological and behavioral changes in bottlenose dolphins (*Tursiops truncatus*) (Mooney et al. 2009). In addition, simulated sonar of 142 dB re: 1uPA caused a disruption to foraging behavior and predator avoidance in wild Blainville’s beaked whales (*Mesoplodon densirostris*) (Tyack et al. 2011). Martin et al. 2015 documented effects of military sonar training on minke whales on the Pacific Missile Range in Hawai`i. Southall et al. (2012) have conducted a series of behavioral response studies from 2010-2015 on the Southern California range, recording potential effects of anthropogenic noise on a wide variety of marine mammals.

The area of focus in this study, Pu`uloa underwater detonation (UNDET) range off the coast of O`ahu, Hawai`i, is subject to both frequent explosions and sonar events. Three species of odontocete have been commonly observed in nearshore marine habitats off O'ahu: bottlenose dolphins (*Tursiops truncatus*), false killer whales (*Pseudorca crassidens*), and spinner dolphins (*Stenella longirostris*) (Baird et al. 2013). Additionally, Endangered Hawaiian monk seals (*Neomonachus schauinslandi*) have been detected in the area (Uyeyama et al. 2012).

The most common marine mammal species in the shallow waters of the Hawaiian archipelago is the spinner dolphin (*Stenella longirostris*) (Lammers 2004, Lammers et al. 2006). Due to its life history, it is the species most likely to be affected by UNDET training evolutions at Pu`uloa. Lammers (2004) and Lammers et al. (2006) have studied behavior of spinner dolphins along the leeward coast of O`ahu through acoustic and visual observation techniques from small boats, both systematically and opportunistically. Their studies indicated that spinner dolphin pods were common in the area but showed no specific site preference. Overall, they preferred nearshore environments, transiting along the 20 meter isobath during time periods normally associated with resting. Figures 1 and 2 from Lammers 2004 graphically represent the proportion of encounters based on total number of observations. Pods of animals were intentionally sought out; the low numbers of searching vessels (one or two) precluded exact density mapping. It is important to note that over half of the total surveys took place at the mouth of Pearl Harbor, which may account for the large number of sightings in this area.

The implications of these findings for the Pu`uloa UNDET range are twofold. Firstly, the 20 meter (60 feet) isobath preferentially used by spinner dolphins runs through the demolition range. Secondly, the dolphins showed no specific site preference, but instead were found at random locations along the south shore. Benoit-Bird and Au (2003) found a strong association with the location of spinner dolphins based on the location of their prey species during diel vertical migration of the mesopelagic layer at night, but this remains challenging to predict. This means that predicting exact temporal and spatial patterns of *S. longirostris* or other odontocete species in vicinity of the Pu`uloa UNDET range may be difficult.

II. METHODS

A. Study area overview

The Pu`uloa UNDET Range site is located west of the mouth of Pearl Harbor off the Island of O`ahu, Hawai`i centered approximately 21 degrees 17 minutes 29 seconds North latitude, 157 degrees 59 minutes 14 seconds West longitude (Figure 3). This range is adjacent to Tripod Reef, and gradually progresses in depth from about 35 feet of seawater (FSW) off Ewa Beach, to 90 FSW seaward over an area approximately one square mile.

Benthic cover on the range consists of sandy bottom with sparse seagrass and benthic algae cover on the western edge through the center of the range and seaward. The eastern portion of the range and shoreward consists of a hard lava rock/ fossilized coral substrate with a thin veneer of silt. Many live coral colonies primarily of the genera *Pocillopora*, *Leptastrea*, and *Porites* grow in this area of the range, and it is inhabited by a variety of reef fishes. This coral assemblage can be described as a “pioneer” community consistent with an area exposed to moderate surge currents, and does not consist of high-relief, rugose coral reef habitat (Friedlander and Parrish 1998).

The Pu`uloa UNDET range is primarily used by U.S. Navy special operations and special warfare forces for unit level training and sustainment of underwater demolition skills. The area is also used for combined military mine countermeasures (MCM) live fire explosive neutralization systems training during bi-annual Rim of the Pacific (RIMPAC) exercises. The UNDET range is marked as a prohibited area (334.1370) on DMA chart 19366, adjoining the Pu`uloa small arms range firing area restricted zone. The range is located entirely within the Pearl Harbor Defensive Sea Area established by Executive Order 8143 on May 26th, 1939. Exact locations of the two ecological acoustic recorders (EARs) adjacent to the UNDET range are 21°N 17.449’, 158°W 00.365’ for the east EAR, and 21°N 17.376, 157°W 58.691’ for the west EAR (Figure 3).

B. Ecological acoustic recorders

The instruments used to collect long-term passive acoustic data for this study were ecological acoustic recorders (EARs) developed jointly by Hawai`i Institute of Marine Biology (HIMB) and NOAA’s Coral Reef Ecosystem Division. The EAR is an autonomous underwater recorder controlled by a Persistor CF2 microcontroller that may be programmed to record acoustic information on a duty- cycle schedule (Lammers et al. 2008). The analog sound pressure compression and rarefaction from the hydrophone is converted to digital signal through a custom built conversion board. The EARs at the Pu`uloa range are programmed with an analog-to-digital sampling rate of 40 kHz on a duty cycle of recording 30 second samples every 5 minutes. The only exception to this was deployment 1 WEST, where the duty cycle was one minute every hour. Table I summarizes EAR deployment collection effort.

When active, the EAR records sound information on a 2GB compact flash memory drive. Once this card is full, the on-board hard drive activates and the files are written to the drive. Then, the card is erased and the drive powers down until the next time the memory card fills again. In this manner, power is conserved by not having the hard drive spinning through the entire deployment. This sampling rate and duty cycle enabled an EAR to be operational for approximately 6 months of recording. Hard drives used on this deployment varied in capacity from 180 to 320 GB. EARs have been deployed at the Pu`uloa range for different intervals from June, 2010 until July, 2013. The devices were deployed in the shallow water configuration, inside PVC housings and attached to concrete anchors on the bottom (Lammers et al. 2008).

Characteristics of the Sensor Technology SQ26-01 hydrophone and EAR energy detectors as shown in Figure 4:

- Response Sensitivity of −193.5 dB
- Flat 1.5 dB from 1 Hz to 28 kHz
- “Wideband” event detector from 20 Hz - 20 Hz
- “High Frequency” detector in energy band from 10 - 20 kHz

C. EAR Deployment and Recovery

SCUBA dive teams from Mobile Diving Salvage Unit ONE supported EAR deployments. EAR 1 was located adjacent to a hard bottomed sea floor with some coral substrate. EAR 2 was deployed on a sandy bottom. The bottom depth at both locations was approximately 20 meters, along the 20 meter isobaths delineated on DMA chart 19366 (Figure 3). EARs were placed approximately 1,000 ft. (300 m) outside the nearest border of the range to ensure the devices were an adequate separation distance to avoid damage to delicate instrumentation by underwater shockwaves. This calculation was estimated by using EARs as a proxy for humans, and placing the units at a safe distance according to Navy EOD diver safe swimmer exposure threshold curves determined by the Explosive Ordnance Disposal Tactical Decision Aid (EOD TDA) Program. Weighted buoy lines were deployed on GPS marks. Divers used salvage lift bags to lower the concrete anchors to the bottom. Then, the EAR units were secured to the anchor with cable ties. Upon completion of deployment, a recovery dive was scheduled with MDSU ONE. EAR GPS points are re-visited, and divers are deployed. The divers then reacquire and recover the EAR units for data recovery, refurbishment, and redeployment.

D. Data Analysis

A total of 397,919 passive acoustic files, each file containing 30 seconds or 60 seconds of acoustic data have been collected to date at the Pu`uloa UNDET range from June 2010-July 2013. The duty cycle was modified from one minute every hour to 30 seconds every 5 minutes after the initial deployment. Due to an analog to digital converter (ADC) circuit board failure during the first deployment, EAR data from the first deployment, EAR 1 EAST, were lost and no files were recovered.

All the data were analyzed with an automatic odontocete whistle detector written in MATLAB by Dr. Helen Ou of the Marine Mammal Research Program (MMRP) at HIMB. This whistle detection program, findWhistles.m, searched individual files in the data set looking for patterns in time, frequency, and amplitude that matched pre-programmed parameters. In the event such conditions are met, a “whistle” is detected, and the file is marked for further analysis or cataloging. In this particular environment, detection of whistles above the intense background noise masking them was the main challenge for the algorithm.

Manual examination of the files of interest was conducted visually and aurally by human researchers. Detonations at the Pu`uloa range are only conducted during working hours (8:00-16:00); files were subsetted using a MATLAB script. Because the aim of this study was to understand odontocete habitat range usage during times that would coincide with detonations, only files recorded during operating hours at the range were reviewed manually; a total of 133,715 files were reviewed by human technicians.

A team University of Hawai'i at Manoa undergraduates was trained by graduate student researchers in MMRP experienced with acoustic data analysis. A training dataset was provided by the experienced researcher that included example sounds in order to standardize training across researchers before any actual data from the site were analyzed. During analysis of the Pu`uloa data, each file was opened in .wav format in Adobe Audition. Files were visualized in spectrogram mode (time on the X-axis, frequency on the Y-axis, and intensity indicated by color). Simultaneously, the researcher listened (using high quality Bose AE2 headphones) for any sounds in addition to standard background noise (primarily snapping shrimp) such as odontocete whistles, explosions, sonar, vessels, and any unidentified sounds.

Observations were cataloged into a spreadsheet, and the experienced MMRP researcher was consulted on any sounds that could not be identified easily. Files that were positively identified as containing odontocete whistles were confirmed by the experienced researcher. In addition, 3 files (approximately 15 minutes) before and after each whistle positive file were re-checked for whistles.

A generalized linear model was run in R using month, hour, and location (east or west) and their interactions, with presence or absence of whistles the binomial dependent variable.

III. RESULTS

A. Automated odontocete whistle detection

In order to avoid false alarms from the background noise, the threshold of the whistle detector algorithm was set so high that odontocete whistles were masked, and not discernible. This algorithm did not detect any dolphin whistles because the high level of snapping shrimp sound and the very low level of the dolphin vocalizations resulted in a low signal to noise ratio. Shown in Figure 5 is an example of a spectrogram that contains dolphin whistles. The figure indicates the difficulty of detecting dolphin whistles at this location with an automated computer program. The whistle is received at similar level to snaps from shrimp, therefore not distinguishable from shrimp to the detector above the background noise.

A second attempt was made at developing an automatic detector capable of discriminating in a high noise environment. In this case, the test target was a humpback whale song. The approach was different, in that a code was written to discriminate the recordings in which no whales are present, and screen the files in this manner with as few false negatives as possible. To determine the efficiency of the test algorithm, an analysis was conducted on a data set of 3,430 files that had previously been manually analyzed and verified for whale sounds. The best performance of the algorithm was a "miss" percentage of 15% (Volphiliere, 2016). Given these initial findings, effort was abandoned at attempting to write an algorithm for the much more difficult to detect odontocete calls.

B. Manual odontocete whistle detection on Pu`uloa Range

Of the 133,715 files manually examined, 804 files (0.6%) were found to contain odontocete whistles. Figures 5 and 6 show examples of spectrograms that include whistle signals (Figure 6 in the presence of sonar) visually confirmed by researchers.

Location was a significant factor in the generalized linear model ($p<0.001$). The instrument deployed to the West of the detonation range contained three times as many occurrences as the EAR in the eastern location (Figure 7). Month was also significant in the model, though less strongly than location ($p=0.01170$), with more occurrences in late summer/early fall (Figures 8 & 9). Time of day (hour) was not significant ($p=0.66709$) in the model, though when percent of files with positive whistle detection is visualized, there appears to be a trend toward more positive detections during the morning hours, on both the east and west ranges (Figures 10 & 11). Two of the four interaction coefficients tests were significant: month x hour ($p= 0.02462$) and location x hour ($p<0. 00459$).

IV. CONCLUSIONS

A. Automated odontocete whistle detection

Automated searches of passive acoustic data for odontocete whistles at Pu`uloa have proven problematic, although software development efforts continue. HIMB is attempting to develop a whistle detection algorithm for use specifically on the Pu`uloa data, and would be applicable to other sites. Additional algorithms that are designed to eliminate sound files that only contain standard background noise are being tested, in order to isolate files that may have marine mammal or anthropogenic noise (vessels, sonar, and explosions) for manual review. A report on this method as tested with humpback whale song data collected during this effort is included as Appendix A. Currently, the best success rate at automatic detections with humpback songs is approximately 70%. Since these vocalizations are high energy below 2 KHz, and dolphin whistles are much harder to generalize, this method may ultimately prove ineffective at automatic detection as well - the background may simply be too noisy.

B. Manual odontocete whistle detection on Pu`uloa Range

Spinner dolphins have demonstrated a preference for transiting the coastal areas of leeward O`ahu along the 20 meter isobath (Lammers 2004; Lammers et al. 2006). Since the 20 meter isobath runs directly above the EAR locations and through the UNDET range, a whistle detection rate of only 0.6% of files indicates this area is not likely commonly frequented by odontocetes. Additionally, the coastal shelf bathymetry on this particular section of coastline on O'ahu is not consistent in general with preferential foraging grounds for odontocetes, based on rates of animal detection at the 1km coastal shelf isobath recorded in similar presence/absence studies elsewhere in the main Hawaiian Islands (Howe, personal communication). This may be due to the comparatively long horizontal transit time from the potential shallow water resting area at Pu`uloa out to sea to the shelf where nightly feeding begins (Benoit-Bird, Au 2003) as compared to other sites investigated (Howe, personal communication). Figure 12 shows the Pu`uloa UNDET Range in context with the surrounding bathymetry.

Of the whistle positive files detected, the strong location (east vs west of the range) effect in the generalized linear model may be explained by two different factors both influenced by differences between substrate compositions. The western EAR was located in an area with a sandy, flat bottom, whereas the eastern EAR was in an area of hard substrate with individual corals (U.S. Navy 2014). This could affect the results in two ways. First, the higher number of whistles detected on the west side could reflect a true difference in behavior of the odontocetes in the area. They may prefer this area because it is quieter (Navy 2016) on average which may be preferential while they are resting during the day, or because the transit time from the resting habitat out the deep water shelf is shorter (25km) in the west than it is in the east (40km). Second, the rate of background noise (primarily snapping shrimp) was higher on the east side with coral substrate. This may have had a masking effect on the sound of odontocete whistles to the researchers - in short, the odontocetes may have been on the east side just as often, they just could not be heard as easily.

Month was a significant variable in the model, with a higher percent of whistles detected in the late summer/early fall than during other times of the year.

There was no strong statistical relationship between time of the day and presence of whistles, at least during the working hours analyzed (0800-1600). This may indicate there is no set daily transit pattern used by coastal odontocetes, which is consistent with the findings of Lammers (2004) and Lammers et al. (2006). As the daytime hours analyzed are associated with times when the animal is resting, it may be informative in the future to investigate if any pattern is found at crepuscular hours, when the animals would be coming in from or going out to deeper waters to forage. Manual examination of files outside the time periods when underwater detonations may occur was outside the scope of this study, but the full data set is archived and could possibly be analyzed in the future either manually or with improved automated detection programs.

While acoustic monitoring is a powerful ecological tool than can inform policy and procedure, it is important to note its limitations. One of the challenges of this study is that files only record 30 seconds every 5 minutes and therefore miss some animals that are vocalizing. This is an inherent concern of using duty cycling as a method of sample collection, as it gives a smaller sample size than consistent recording. Another limitation is that files were classified with presence/absence of whistles; it could not be determined if a file included multiple whistles if they were from a single animal or multiple animals.

Another critical point of passive acoustic monitoring is that the recorders do not detect the presence of marine mammals if they are not vocalizing. Odontocetes are often resting during the daylight hours, which in a natural marine soundscape, is the quietest time of the day (Heenehan 2016; Navy 2016) and therefore they may not be vocalizing frequently. Based on behavioral observation of spinner dolphins in other parts of the main Hawaiian islands (Brownlee, S.M. & Norris, K.S.,1994), resting spinner dolphins do not vocalize often at all. However, transiting spinner dolphins do, and many visual observations of these animals indicate they are transiting the Pu`uloa range when they are detected.

While it is important to note that the absence of vocalizations doesn't indicate the absence of animals, the work of this study must be viewed in the context of all available ecological and behavioral information. The low occurrence of whistle-positive files manually detected in this study, the low numbers of visual sightings of coastal odontocetes from past studies off southern O`ahu, and the relationship between the bathymetry off Pu`uloa range and areas of low rates of animal detection by similar instruments in ongoing research all indicate detonation training in this area likely has lower potential to detrimentally affect odontocetes than other areas in the Hawaiian islands due to a low likelihood of their presence.

C. Future Directions

For this study, researchers did not attempt to identify the species of odontocete vocalizing on the whistle positive files. The three most common odontocete species in Hawaiian coastal waters, spinner dolphins, bottlenose dolphins, and false killer whales have similar enough calls they cannot easily be differentiated visually or aurally, especially in environments with background noise. In general, the vocalization frequency is correlated with animal size, such that spinner dolphins typically have much higher frequency vocalizations than bottlenose, and false killer whales the lowest of the three (Lammers, 2016). Cursory examination of the files indicated low frequency, mid frequency, and high frequency signals may be present at Pu`uloa from time to time. In the future, these 800 whistle files could be isolated from background noise manually, then processed by an automated program such as Real-time Odontocete Call Classification Algorithm (ROCCA) or similar program for species identification (Lin and Chou 2015; Barkley et al. 2011; Oswald et al. 2007).

Passive acoustic monitoring has limitations, but much potential as technology of both the recorders themselves and of the available analyses tools improves. In the future, it may be possible to localize marine mammals with respect to the recording instrument and determine which direction and speed they are moving as they cross within the detection threshold of the recorder with minimal effort. Directionality of whistle has been found in spinner dolphins, and seems to related to direction of movement (Lammers and Au 2003). It can be difficult to get localization information from acoustic recorders when there are many marine mammals moving together, but the technology is improving (Nosal 2013). Other studies have used multiple hydrophones to determine vertical and horizontal swim speeds of sperm whales (Nosal and Frazer 2007; Nosal and Frazer 2006), though a lower budget technique using a single hydrophone is a viable option as well (Aubauer et al. 2000). Pu`uloa UNDET range, due to its varying substrate composition, military value, proximity to land and distance to the coastal shelf would be an interesting site to use multiple hydrophone arrays to study odontocete vocalization distance and direction.

Valuable information can be obtained by the use of Passive Acoustic Monitoring (PAM) devices adjacent to underwater explosives ranges such as the Pu`uloa range. Efforts are ongoing at the Silver Strand Training Complex (Baumann-Pickering et al. 2013) and the Virginia Capes Mine Exercise Range (Hotchkin et al. 2013) to characterize potential effects of detonations on marine mammal species, and obtain range usage data by coastal marine mammal populations.

In addition, comparisons between odontocete habitat usage at Pu`uloa UNDET range could be made at sites with similar bathymetry and temperatures that are not used for military underwater detonations. Currently, data are being collected at other locations around O'ahu, Kauai, and Maui that could provide interesting comparisons and help determine which factors influence odontocete habitat choice (Howe, unpublished data).

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FIGURES

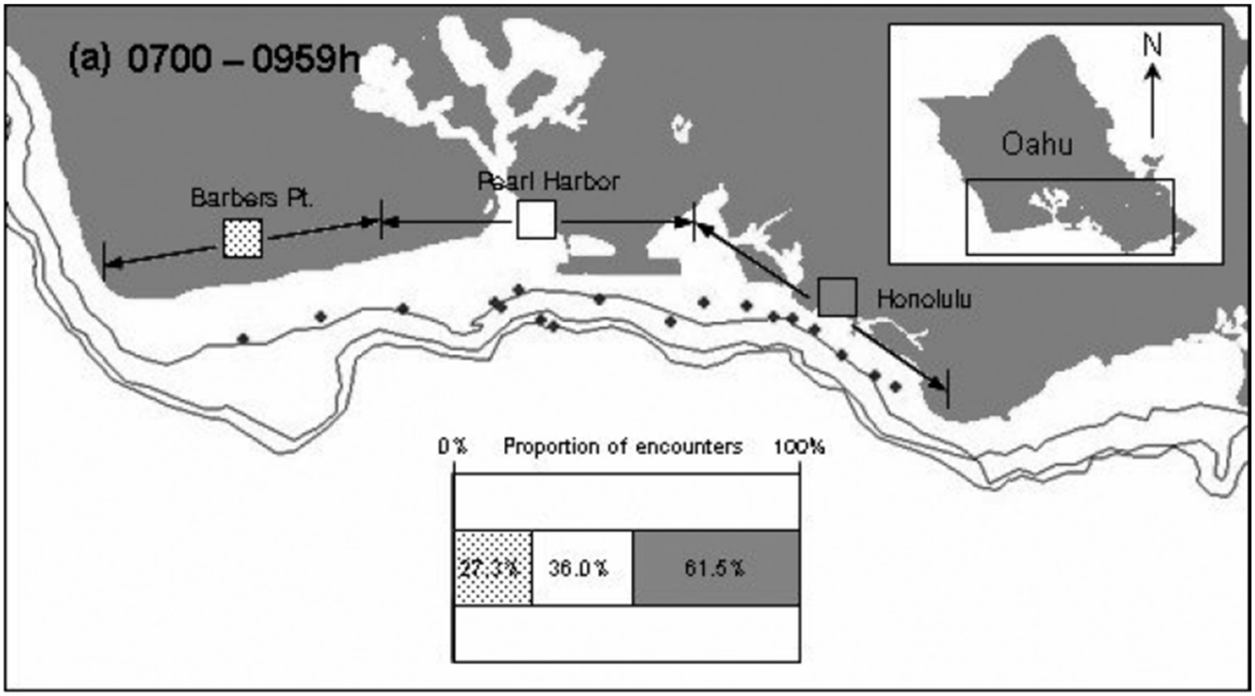

Figure 1. Occurrence of spinner dolphins off the leeward coast of O`ahu from 0700 to 0959 as observed by Lammers 2004.

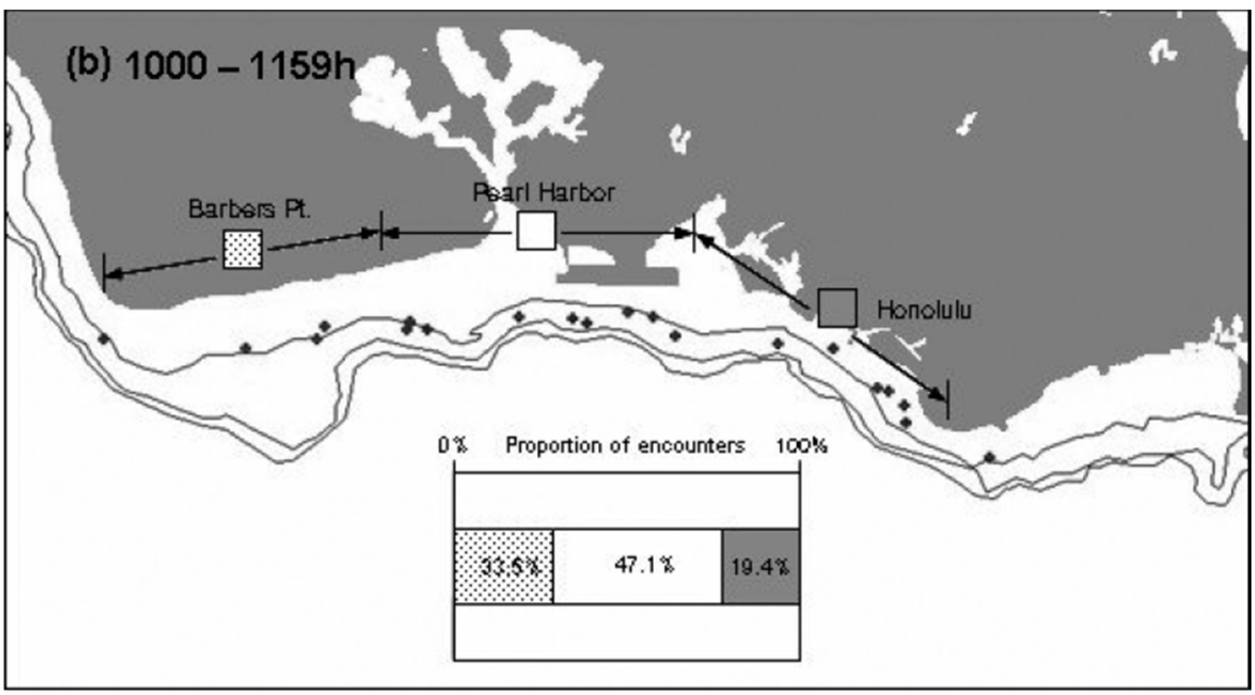

Figure 2. Occurrence of spinner dolphins off the leeward coast of O`ahu from 1000 to 1159 as observed by Lammers 2004.

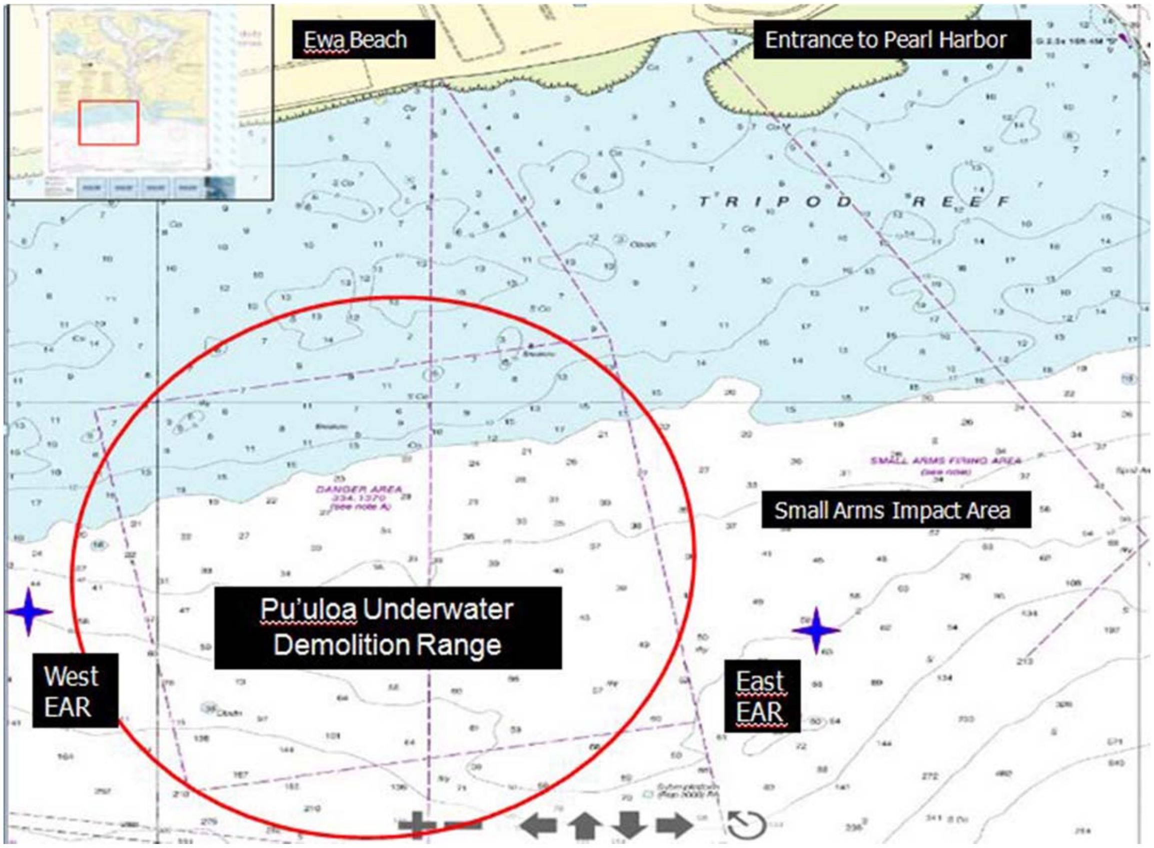

Figure 3. Pu`uloa UNDET Range (Purple dashed square danger area) west of the mouth of Pearl Harbor, with approximate location of EARs annotated. Source is DMA Chart 19366.

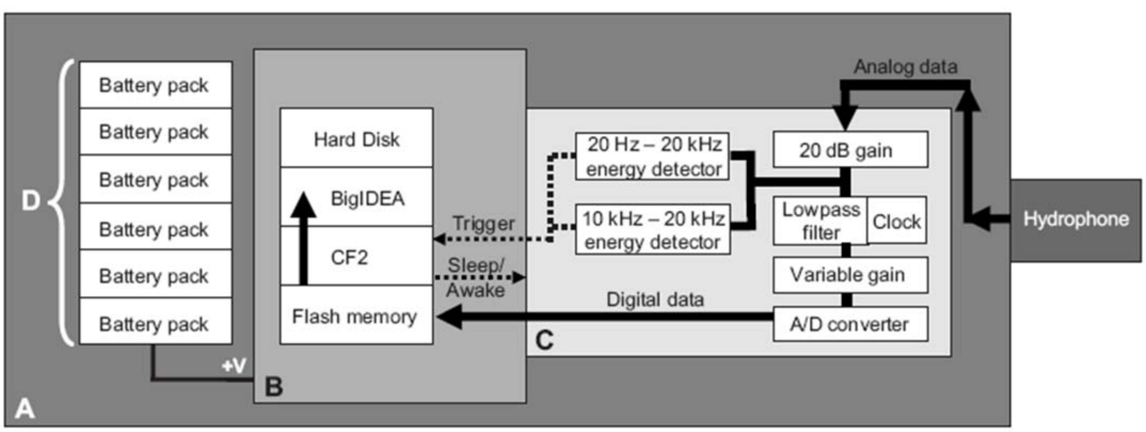

Figure 4. Schematic diagram of EAR (Lammers et al. 2008)

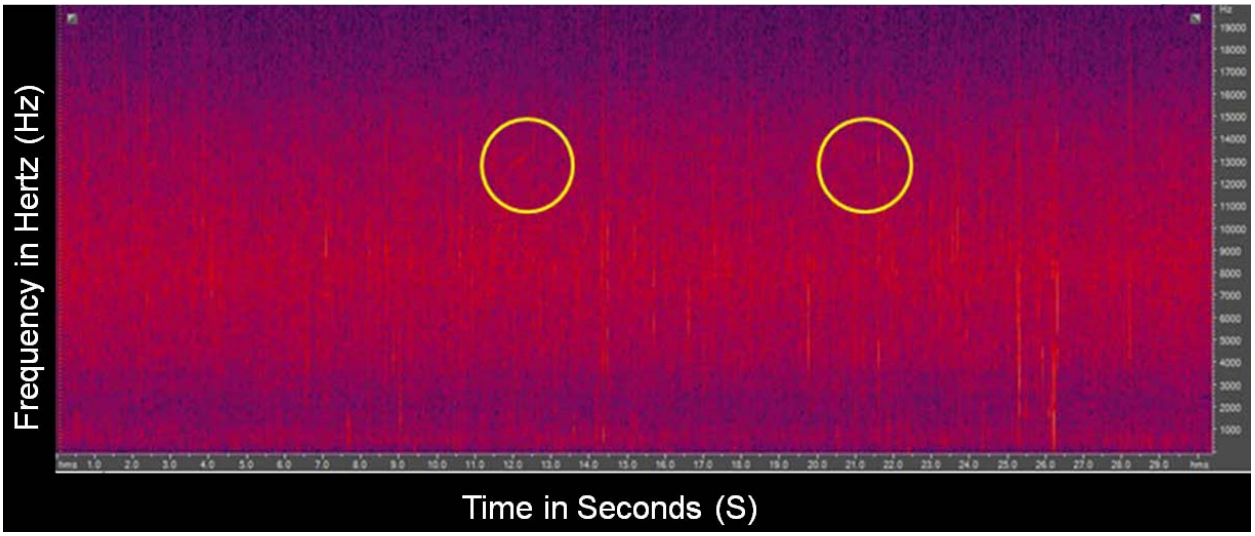

Figure 5. Example of spectrogram containing dolphin whistles nearly concealed in background noise (masking).

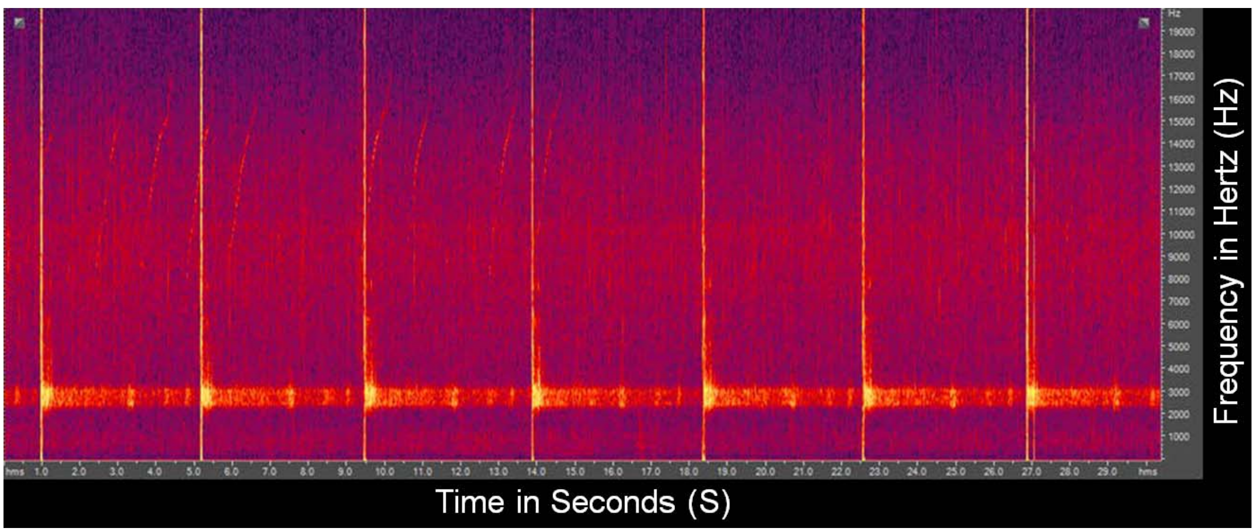

Figure 6. Dolphin whistles in presence of sonar.

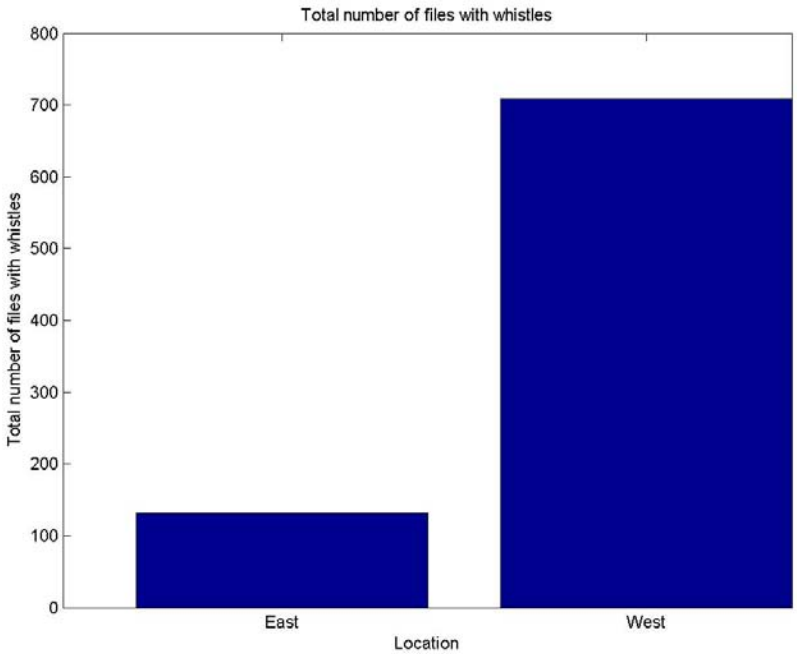

Figure 7. The total number of whistle positive files detected for the east and west EARs on Pu`uloa UNDET range.

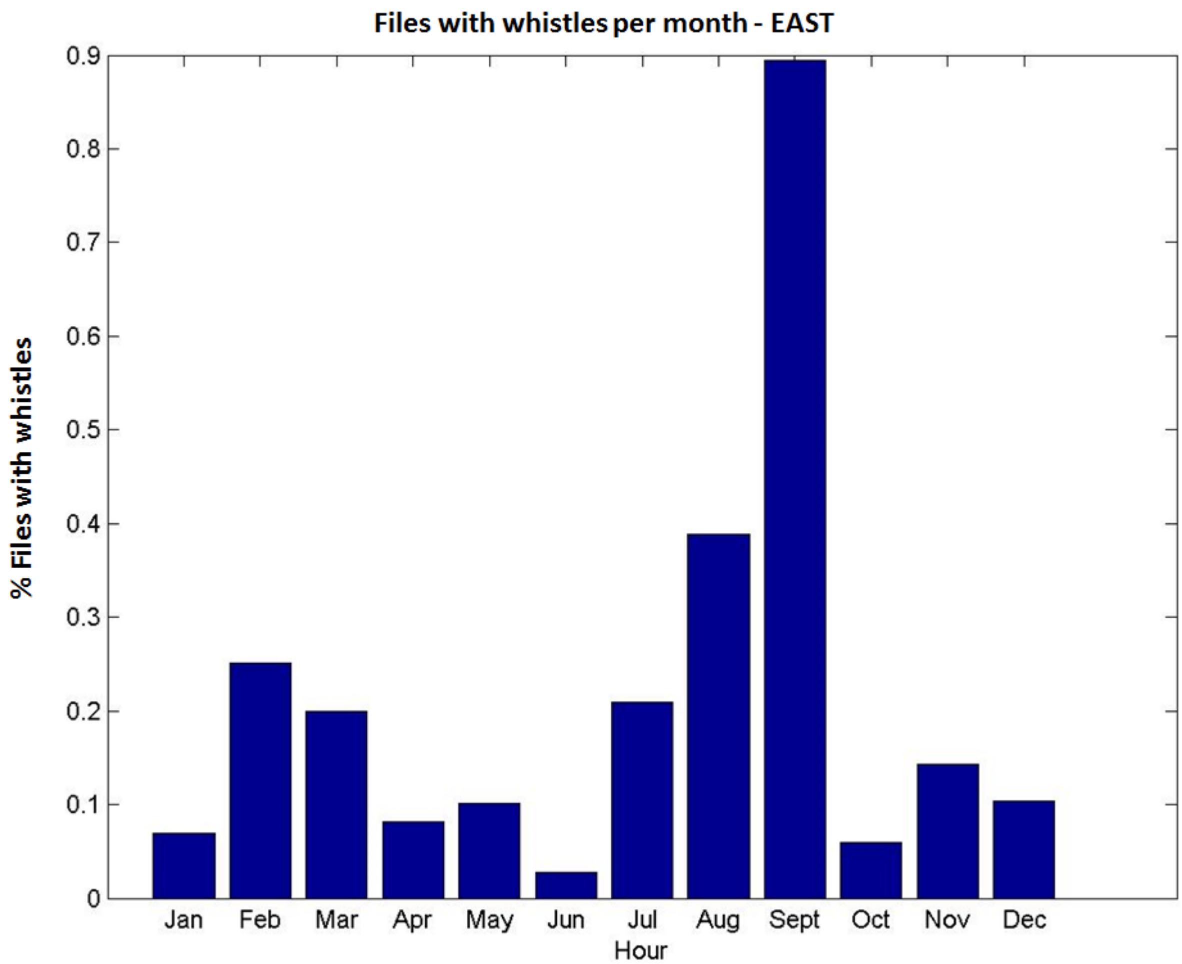

Figure 8. The percent of files with positive whistle detections by month from the EAR location on the eastern edge of the UNDET range.

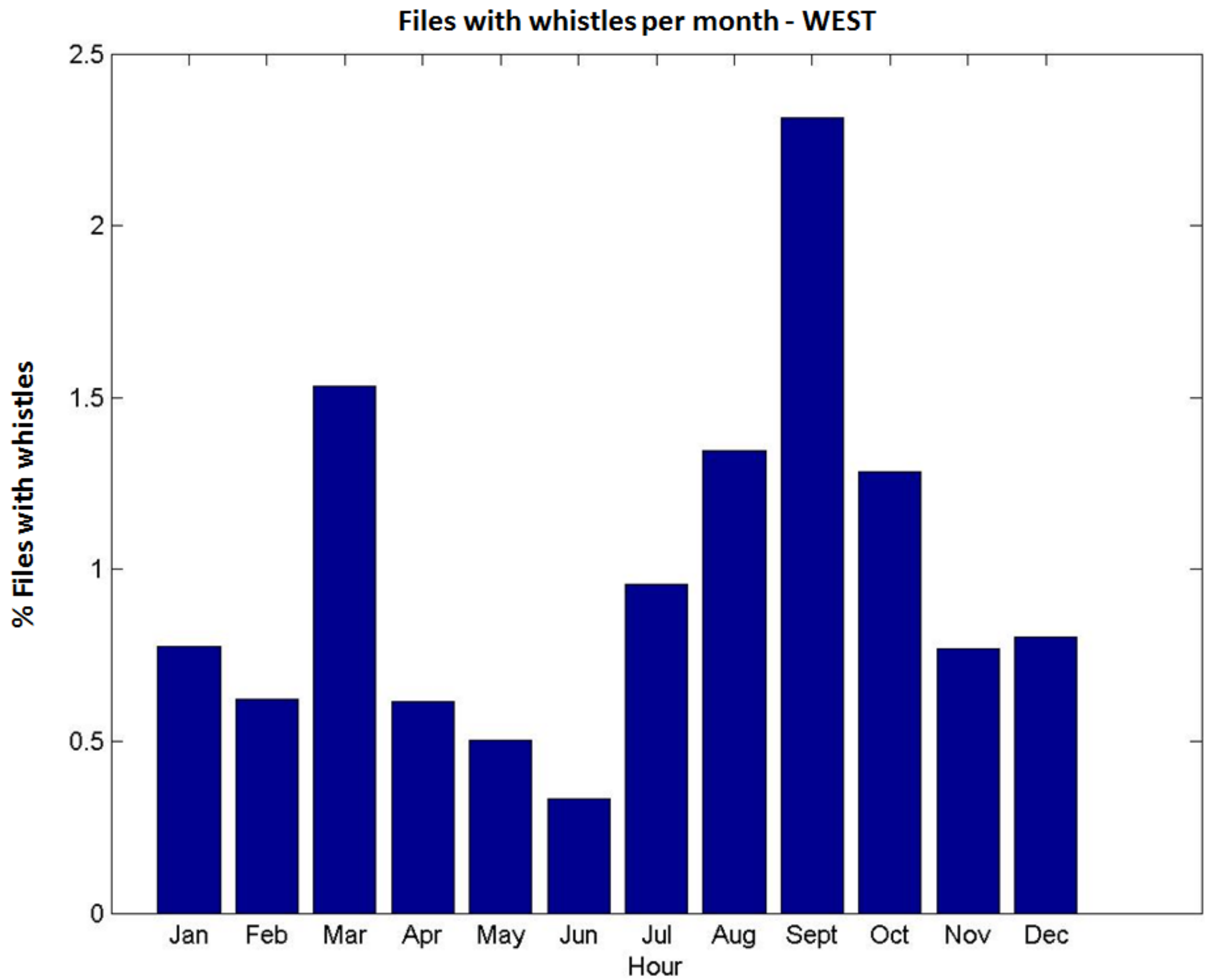

Figure 9. The percent of files with positive whistle detections by month from the EAR location on the western edge of the UNDET range.

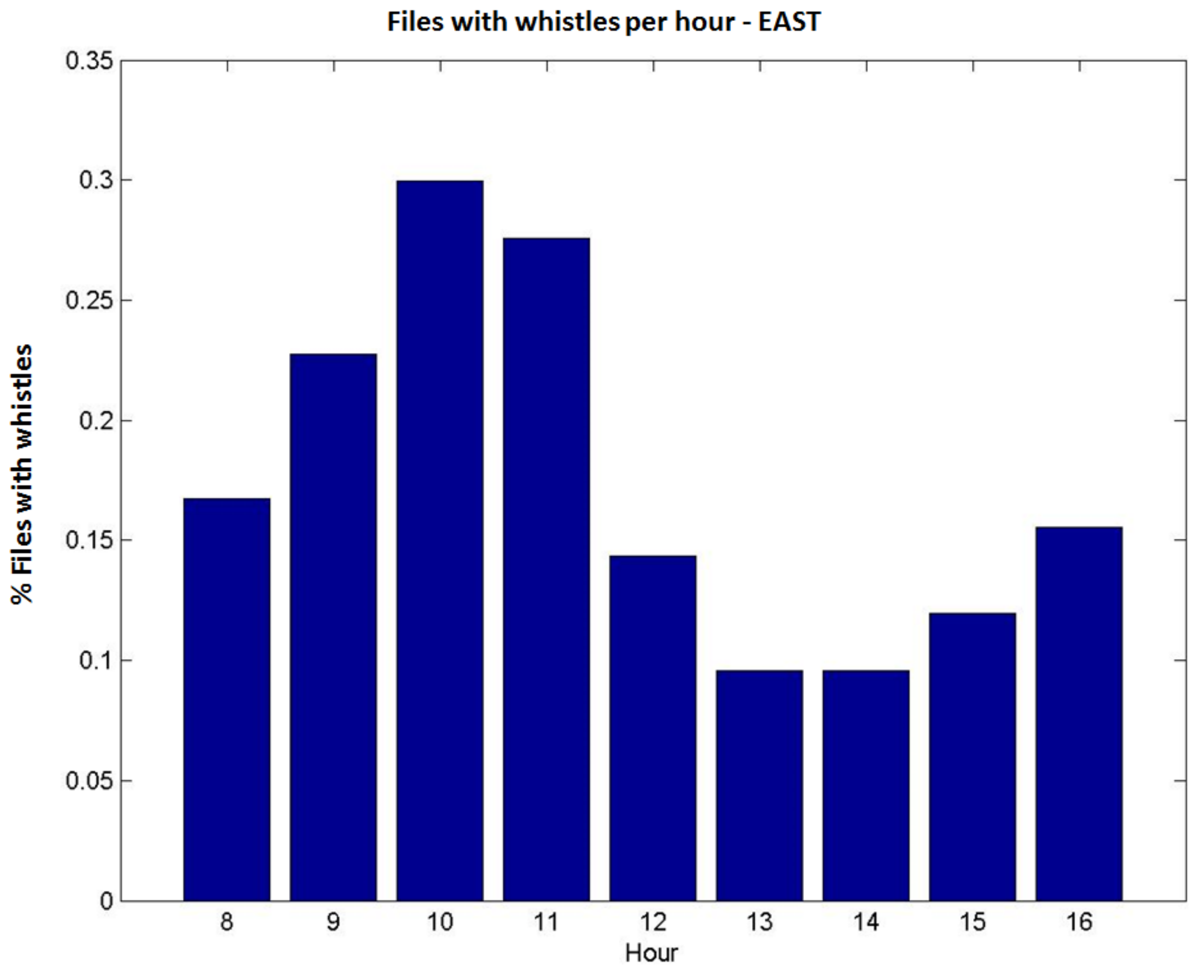

Figure 10. The percent of files with positive whistle detections by hour (0800-1600) from the EAR location on the eastern edge of the UNDET range.

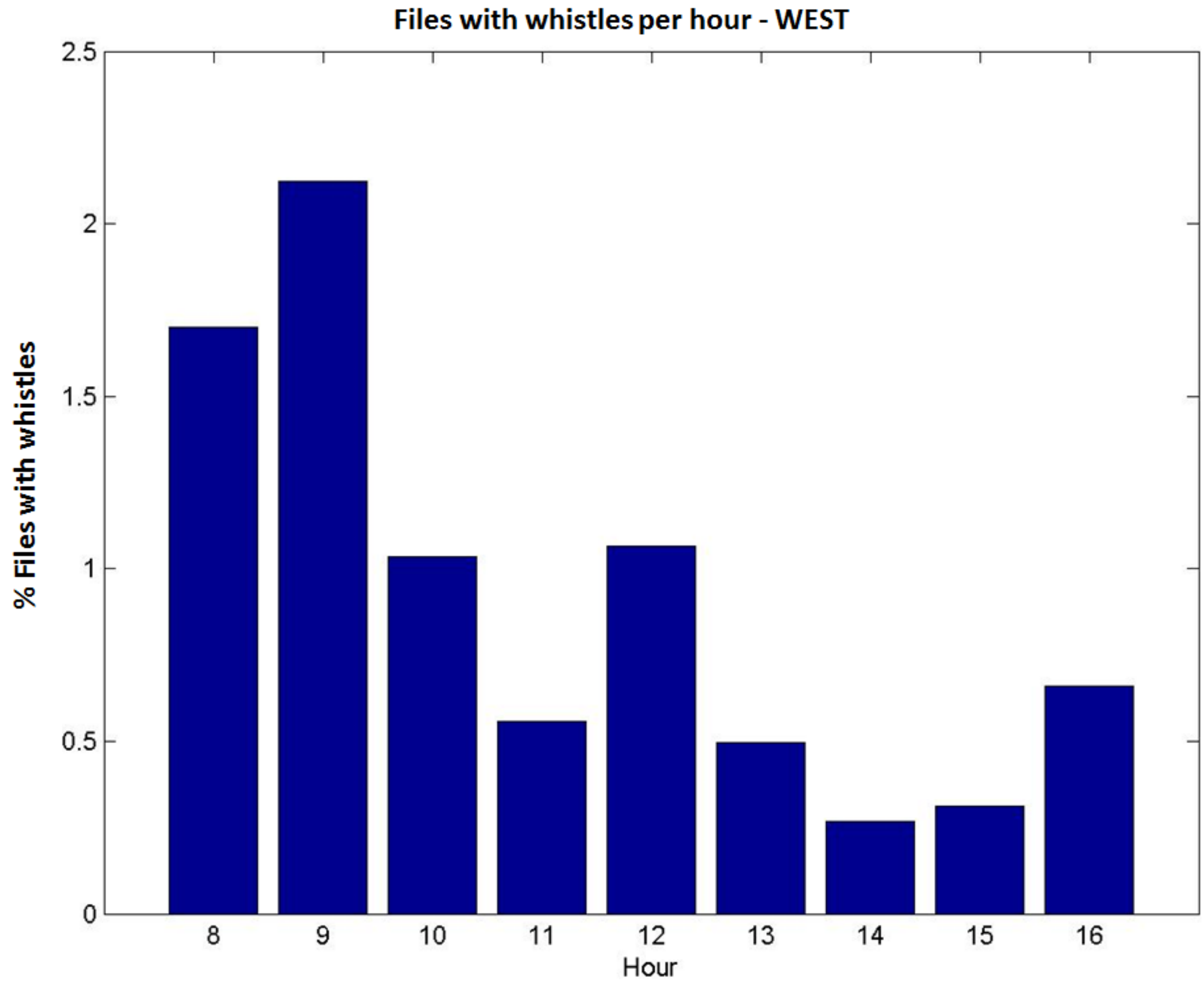

Figure 11. The percent of files with positive whistle detections by month from the EAR location on the western edge of the UNDET range.

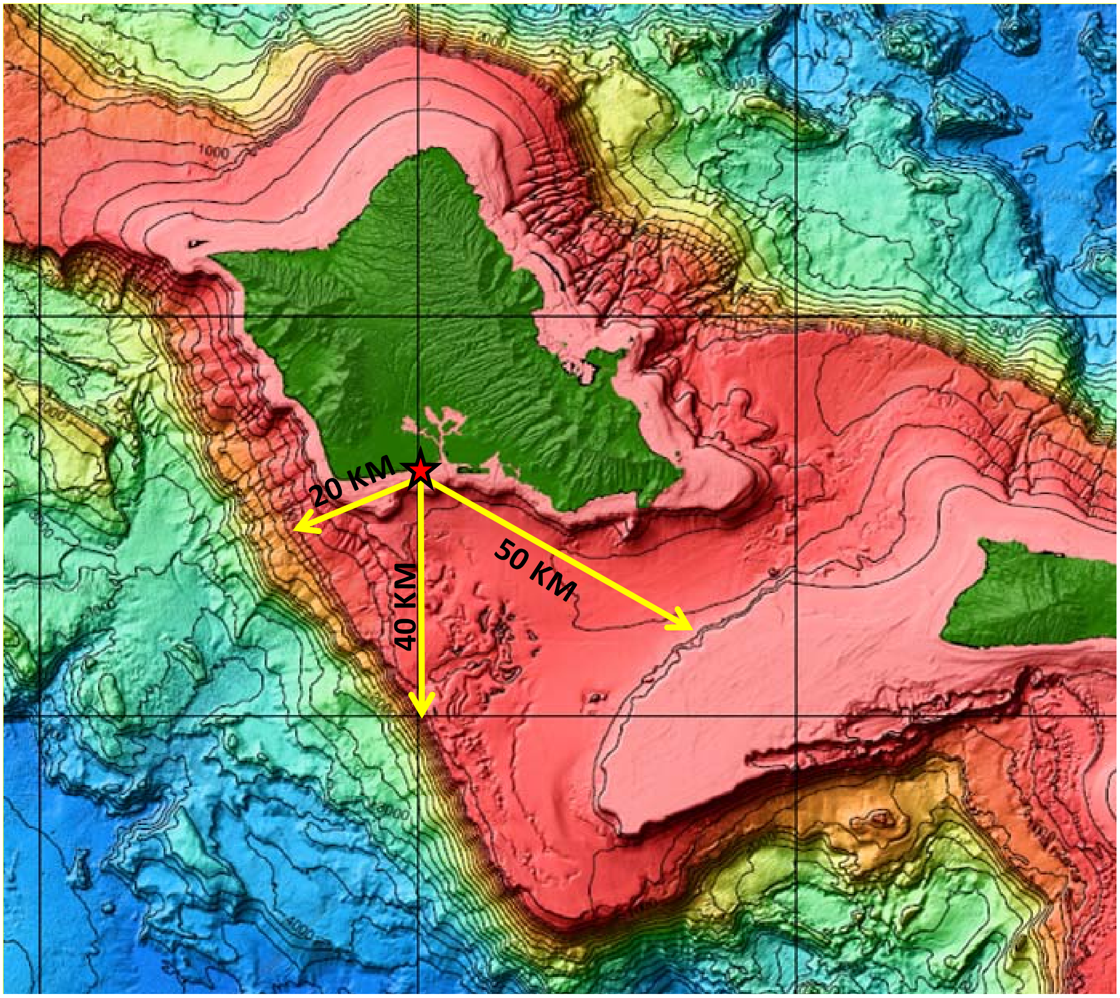

Figure 11. The Pu`uloa UNDET Range in context with surrounding bathymetry, showing distance to 1km shelf isobath. Source is Hawaiian Islands Multibeam Bathymetry Data Synthesis, University of Hawaii School of Ocean and Earth Sciences, NOAA.

Table I. Summary of EAR Collection Effort From July 2010 to June 2013.

Data Set	Location	Start Date	End Date	Duty Cycle	Sample Rate	Total Files
1 EAST	21N 17.449, 158W 00.365	08 JUL 10	14 SEP 10	60 s / 3600 s	40 kHz	0*
1 WEST	21N 17.376, 157W 58.691	08 JUL 10	22 SEP 10	60 s / 3600 s	40 kHz	1,826
2 EAST	21N 17.449, 158W 00.365	15 NOV 10	20 APR 11	30 s / 300 s	40 kHz	44,855
2 WEST	21N 17.376, 157W 58.691	15 NOV 10	28 MAY 11	30 s / 300 s	40 kHz	55,968
3 EAST	21N 17.449, 158W 00.365	01 DEC 11	08 MAY 12	30 s / 300 s	40 kHz	45,805
3 WEST	21N 17.376, 157W 58.691	01 DEC 11	14 MAY 12	30 s / 300 s	40 kHz	47,552
4 EAST	21N 17.449, 158W 00.365	14 MAY 12	03 DEC 12	30 s / 300 s	40 kHz	58,443
4 WEST	21N 17.376, 157W 58.691	07 JUN 12	03 DEC 12	30 s / 300 s	40 kHz	51,612
5 EAST	21N 17.449, 158W 00.365	06 DEC 12	07 JUL 13	30 s / 300 s	40 kHz	58,938
5 WEST	21N 17.376, 157W 58.691	06 DEC 12	09 JUL 13	30 s / 300 s	40 kHz	60,357

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APPENDIX B

ODONTOCETE WHISTLE DETECTION LOG, RAW DATA

Whistle log.xlsx

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APPENDIX C

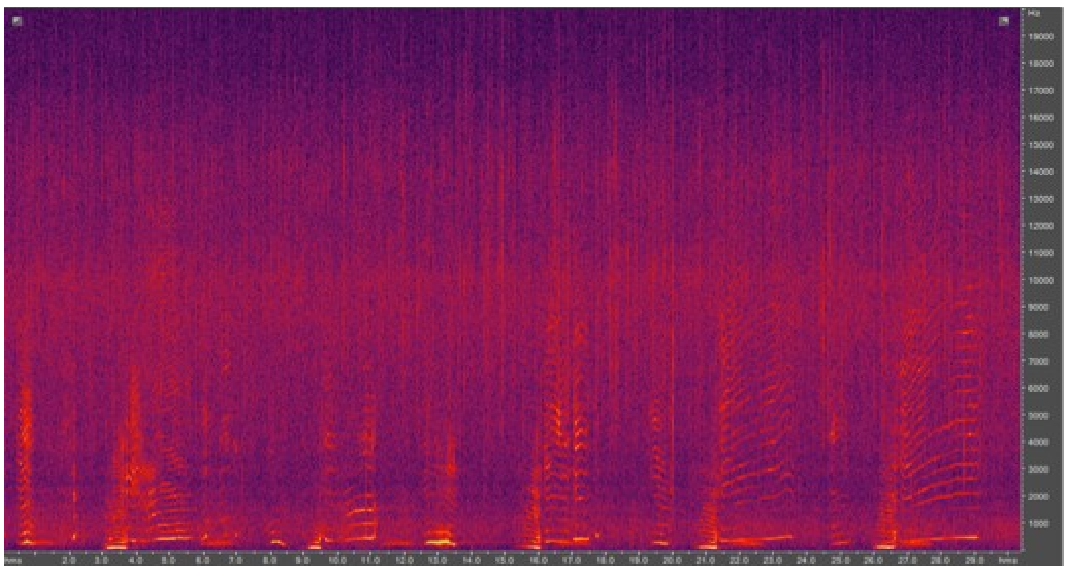
REPORT ON DETECTION ALGORITHM RESULTS

2 Detection of whale sounds in ocean recordings

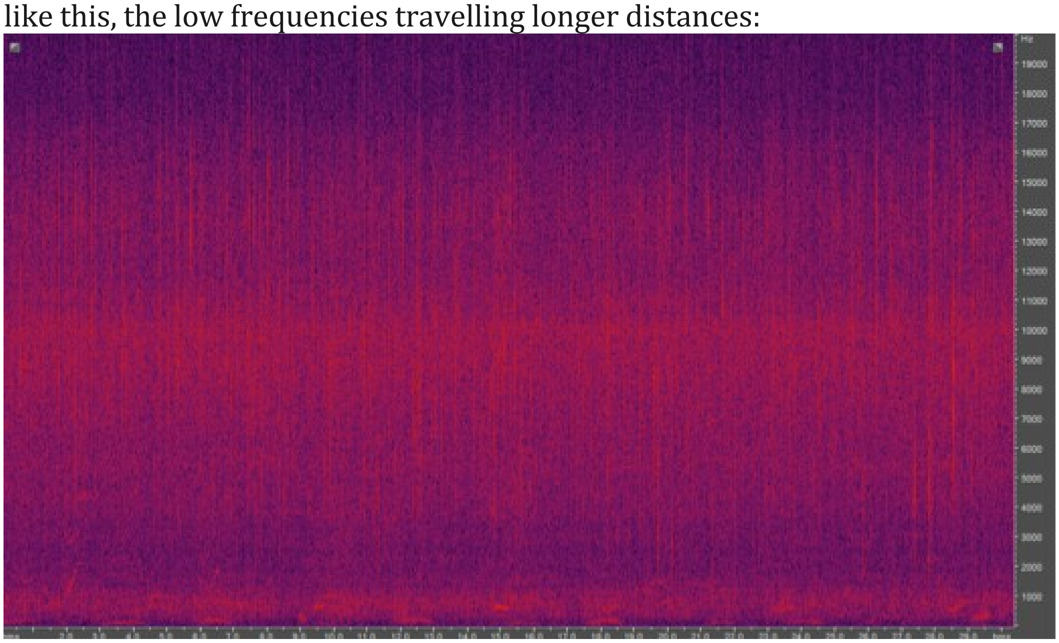
2.1 The Problem

Ocean sound recordings have been conducted in a place near Hawaii where navy trainings are taking place to determine when whales are present.
We have been asked to write a code to discriminate the recordings in which no whales are present. The point was then to write a code which would target a humpback whale sound with relatively large conditions but which would have the lowest possible rate of missed shot.

The frequency spectrum of a typical sample with the presence of a humpback whale close to the hydrophone looks like this:



However, most of the samples recording the presence of more distant humpback whales are like this, the low frequencies travelling longer distances:



The point was to target the samples with a pattern of humpback whale sound. After analyzing a group of different samples within which whale sounds were present, we pinpointed the main characteristics which were common to all the samples where a humpback whale was present, in terms of frequency:

- The main frequencies of the sound are under 2 kHz
- The sound lasts at least 0.1 second
- The intensity of the signal is either very high on a restricted range of frequency or less high but more spread in terms of frequency or temporally

Since the sampling of the recordings was 40kHz, the maximum resolvable frequency is 20kHz and since the whale sounds last at least 0.1 second, we worked with fft representing the spectrum of samples of 0.1 second.
The frequency resolution of the fft was : f=20/(40*0,1)=5 Hz.

<u>The Pseudo code is:</u>

```
do fft for each 0.1 sec sample
for each fft
   for k=length(fft) steps
         if there is a pick under 2kHz above Intensity1 during 0.1 sec in a row
                  return there is a whale
         else if there is an energy under 2kHz above Intensity2 during 1 sec
                  return there is a whale
         else if there are 3 picks under 2kHz above Intensity3 on a range of  1 s
                  return there is a whale
         else
                  return there is no whale
         end if
   end for
end for
```

2.2 Optimization

To determine the efficiency of the algorithm, we conducted an analysis on a data set that had previously been manually analyzed. It contains 3430 recordings so the analysis of this data set can be a good indicator of the efficiency.

Since the point of the algorithm is to target the recordings where there are no whales, the main error indicator of the algorithm is the percentage of samples with a whale which were categorized without whales. We call this percentage **miss**.

The percentage of samples where a pattern of whale sound has been recognized but where there were actually no whales must also be considered: we call this percentage **target**.

The priority is to have the lowest **miss** percentage since the goal is to ease the task of targeting in which samples there are whales by putting aside some samples.
Our goal was to reach a percentage of **miss** below 10%.

Thereafter is the table of the two percentages **[miss, target]** in function of the different parameters Intensity1, Intensity2 and Intensity3 of the pseudo-code.

Intensity3=0,8					
Intensity2/Intensity1	**0,7**	**0,8**	**0,9**	**1**	**1,1**
5	[17;89]	[18;86]	[21;85]	[20;77]	[21;77]
5,5	[15;85]	[17;80]	[20;78]	[20;77]	[21;77]
6	[16;83]	[18;76]	[20;72]	[21;70]	[22;70]
6,5	[15;82]	[18;73]	[20;68]	[21;65]	[22;64]

Intensity3=0,7					
Intensity2/Intensity1	**0,7**	**0,8**	**0,9**	**1**	**1,1**
5	[17;90]	[18;86]	[20;85]	[20;85]	[20;85]
5,5	[17;86]	[18;80]	[20;79]	[20;78]	[20;78]
6	[15;84]	[17;76]	[20;74]	[20;73]	[21;72]
6,5	[16;83]	[18;73]	[20;70]	[20;69]	[21;68]

Intensity3=0,6					
Intensity2/Intensity1	**0,7**	**0,8**	**0,9**	**1**	**1,1**
5	[17;90]	[20;88]	[19;88]	[19;88]	[19;88]
5,5	[15;86]	[18;84]	[19;84]	[19;83]	[19;83]
6	[16;84]	[17;82]	[18;81]	[18;81]	[19;81]
6,5	[15;83]	[17;81]	[18;80]	[18;80]	[19;80]

It appears that the lowest miss percentage is 15%.

After looking at the missed samples, it turned out that the missed whale signals were too low to be detected by the algorithm. However, lowering the values of the Intensities in the conditions of the algorithm would mean raising the **target** percentage, and, for example, for Intensity1=0,5, it reaches 100%...

2.3 Conclusion

To conclude, our goal was to write a program that would discriminate the samples without whales. Our goal was to reach a miss percentage under 10%, but we only managed to reach 15%.
To lower the **miss** percentage without raising too much the **target** percentage, we would need to add more conditions to our algorithm. A possible condition would be to discriminate the spectrums with an energy spread on a specific range of frequencies, but to do so we would need a more accurate fft, which would mean a less accurate sampling of the recordings… Another possibly efficient way would be to implement machine learning algorithms in the program.

Overall, this internship was a great experience to get an insight in research and to learn about bioacoustics. Even if I don't plan to work in this field, these four months convinced me that I want to work in a field related to biology with a strong mathematical content.

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