WARFARE ECOLOGY ON AN UNDERWATER DEMOLITION RANGE: ACOUSTIC OBSERVATIONS OF MARINE LIFE AND SHALLOW WATER DETONATIONS IN HAWAI’I

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI’I AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ZOOLOGY
(MARINE BIOLOGY)

MAY 2017

By
Lee H. Shannon

Dissertation Committee:

Whitlow Au, Chairperson
Marc Lammers
Paul Nachtigall
Robert Richmond
Eva-Marie Nosal
ACKNOWLEDGEMENTS

This research was supported by Naval Facilities Engineering Command Pacific, Commander U.S. Pacific Fleet, Office of Naval Research, Naval Facilities Engineering and Expeditionary Warfare Center, and the Montgomery G.I. Bill (Chapter 33). The primary study site, Pu'uloa Underwater Detonation Training Range, is managed under the auspices of U.S. Pacific Fleet. I gratefully acknowledge Pacific Fleet as well as the supporting military units for allowing access to record underwater detonations while training evolutions were occurring, and for support in placing and recovering passive acoustic recorders in the waters adjacent to the range. I'd like to thank Dr. Sean Hanser of Naval Facilities Engineering Command Pacific and his entire team of dedicated marine resources managers. I'd also like to thank Ms. Julie Rivers and the operational staffs of U.S. Pacific Fleet and U.S. 3rd Fleet for their support in gaining access to the training areas. I am deeply grateful for successful collaboration with Dr. Peter Dahl and the Applied Physics Laboratory at the University of Washington. Most especially I'd like to thank the hardworking, dedicated soldiers and sailors of Mobile Diving Salvage Unit ONE, Explosive Ordnance Disposal Mobile Unit THREE, Navy Explosive Ordnance Disposal Detachment Mid-Pacific, U.S. Army 7th Engineer Company (DIVE), and Australian Clearance Diving Team ONE.

It is with deepest appreciation I recognize my dissertation advisor, Dr. Whitlow Au. There are too many things to list specifically. He took a chance bringing me onboard his lab, and for that I am eternally grateful. He is always incredibly gracious about his own esteem and reputation, and he never hesitates to use his influence, star power, and network to help others.
I have thoroughly enjoyed my time at University of Hawai`i at Manoa learning from Dr. Au and my committee members. Dr. Paul Nachtigall epitomizes the ethos of the research scientist, one who is always curious, and seeks knowledge for knowledge’s sake. His ability to mentor students and his political acumen in setting up a research lab husbanding live marine mammals is a testament to his vision and his skill as a negotiator and deal maker, as well as a scientist. Ever the empirical acoustician, Eva-Marie Nosal constantly challenged me, and helped me to learn more about a difficult field that was outside my realm of specialization or previous education. I appreciate her willingness to put up with me, as well as the use resources from her lab to help me with my research. Dr. Bob Richmond and his knowledge of coral reefs made a significant impression on me, and my understanding of ecosystems is stronger because of him. I enjoyed spending time in the field with Dr. Marc Lammers on board the R/V Miriam (affectionately known to us as the “Delirium”) off Kauai and O`ahu. I would simply not have learned the things I needed to learn without Dr. Lammers’ willingness to share his knowledge, as well as and his graduate researchers time and talent with me. I have much appreciation for the support, comradery, and friendship of Marine Mammal Research Program members past and present, including Dr. Alison Stimpert, Dr. Aaron Mooney, Dr. Laura Kloepper, Michael Richlen, Dr. Alexis Rudd, Dr. Giacomo Giorli, Dr. Adrienne Copeland, Adam Smith, Dr. Aude Pacini, Megan McElligott, and “honorary members” Dr. Andy Dewald and Brendan Rideout. A special thank you to Dr. Jessica Chen for being the quiet, stern voice that always kept me on track, being able to keep a spreadsheet like a ninja warrior, and leading our undergraduate researchers. I appreciate the extensive efforts of my research assistants Brijonnay Madrigal, Carly Maliliglig, Kara Rockstad, and Allison Kirby for patiently straining their ears through the noise to listen for the faintest dolphin whistles over 130,000 times, and Jake Buehler, who systemically counted and identified fish frame by frame for what may be the most interesting study in this
dissertation. I’d also like to recognize my friends within the graduate school at the University of Hawai`i at Manoa. They have rounded out my life here in Hawai`i, without them I would have never escaped from Waikiki, rubbed a tiger shark’s belly, or been able to dress as Ming the Merciless on Halloween. I look forward to future scientific collaborations and many costume changes in the future. Mahalo nui loa to my family. All that I am, all that I have, and all that I have fought for in my life I owe to their support, their love, and the example that they have set. It is my sincerest hope that this work honors them. I am fortunate that my family, my heroes, and my role models are the same people. Dr. Kira Krend has my deepest respect as a scientist, educator, and as a person. She is my partner, my friend, and at times my bodyguard. She is the kindest person that I have ever known, and her smile could stop a war. She’s been behind me for years, being patient, being supportive, being kind and never being the center of attention. It is a simple, scientific and mathematical fact that this dissertation would not have been completed without her, and I will never be able to thank her enough. I love you, Danger Floof.

This work is respectfully dedicated to the memory of Dr. Eugenie Clark, who through her writings taught me about sharks when I was growing up in West Virginia, and who I was fortunate enough to once meet in person and express my gratitude. It is also dedicated to Lieutenant Shawn Jacobs, Lieutenant Christopher Mosko, Senior Chief Petty Officer Timmy Johns, Chief Petty Officer Patrick Wade, Petty Officer Louis Souffront, Petty Officer Matthew Draughon, and Seaman Gordon Racine. These men I had the fortune of serving with before they lost their lives in service to our country; allowing not just me, but thousands of other scientists to pursue their work to benefit the United States, mankind, and the planet in peace. Finally, this dissertation is dedicated in memoriam of the life of my father, Dr. Harry Lee Shannon III. In the words of his favorite poet, Rudyard Kipling, he filled the unforgiving minute with sixty seconds worth of distance run. Now his run is finished, and his rest is well deserved.
ABSTRACT

Most studies investigating the effects of military-associated anthropogenic noise concentrate on deep sea or open ocean propagation of sonar and its effect on marine mammals. In littoral waters, U.S. military special operations units regularly conduct shallow water explosives training, yet relatively little attention has been given to the potential impact on nearshore marine ecosystems from these underwater detonations. This dissertation research focused on the Pu'uloa Underwater Detonation Range off the coast of O'ahu, and examined multiple aspects of the surrounding marine ecosystem and the effects of detonations using acoustic monitoring techniques. The soundscape of a nearshore reef ecosystem adjacent to the UNDET range was characterized through analysis of passive acoustic recordings collected over the span of 6 years. Snapping shrimp were the predominant source of noise, and a diel pattern was present, with increased sound energy during the night hours. Results revealed a difference of up to 7dB between two Ecological Acoustic Recorder locations 2.5km apart along the 60ft isobath. Passive acoustic recording files were searched visually and aurally for odontocete whistles. Whistles were detected in only 0.6% of files analyzed, indicating this area is not frequently transited by coastal odontocete emitting social sounds. The study also opportunistically captured a humpback whale singing during a detonation event, during which the animal showed no obvious alteration of its singing behavior. Four separate underwater detonation events were recorded using a surface deployed F-42C transducer, and the resulting analysis showed no measurable drop in the biologically produced acoustic energy in reaction to the explosive events. Coral reef fishes were recorded visually and acoustically during detonation events at a known distance and bearing from a known explosive sound source. Individual fish behavioral responses to the explosion varied, and a sharp uptick in fish vocalizations was recorded immediately following the blast, with rapid (within 30s) return to baseline visual and acoustic behavior. The results and conclusions of these studies are placed within the broader context of warfare ecology as an emerging scientific discipline.
# TABLE OF CONTENTS

Acknowledgements ........................................................................................................ iii 
Abstract ....................................................................................................................... vi 
List of tables ............................................................................................................. viii 
List of figures ............................................................................................................ ix 
Chapter 1. Introduction .............................................................................................. 1 
  Warfare ecology ........................................................................................................ 1 
  Nearshore environments, especially coral reefs ....................................................... 4 
  Sound and marine organisms .................................................................................. 5 
  Acoustics and an ecological tool ............................................................................. 6 
  Dissertation outline ................................................................................................. 8 
  Research significance .............................................................................................. 8 
Chapter 2. Acoustic soundscape analysis .................................................................... 9 
  Introduction ............................................................................................................ 9 
  Methods ................................................................................................................ 10 
  Results .................................................................................................................. 13 
  Discussion ............................................................................................................. 14 
Chapter 3. Marine mammal habitat use near an underwater detonation range .......... 39 
  Introduction ............................................................................................................ 39 
  Methods ................................................................................................................ 42 
  Results .................................................................................................................. 44 
  Discussion ............................................................................................................. 46 
Chapter 4. Detonation observations in nearshore habitats associated with Navy use .. 61 
  Introduction ............................................................................................................ 61 
  Methods ................................................................................................................ 64 
  Results .................................................................................................................. 66 
  Discussion ............................................................................................................. 68 
Chapter 5. Acute behavioral response of reef fishes to underwater detonation ............ 92 
  Introduction ............................................................................................................ 92 
  Methods ................................................................................................................ 94 
  Results .................................................................................................................. 95 
  Discussion ............................................................................................................. 97 
Chapter 6. Conclusions ............................................................................................ 107 
  Application of research and future directions ...................................................... 108 
  Broader scope ....................................................................................................... 113 
  Complexity of the relationship between military conflict and the environment ..... 118 
Literature Cited .......................................................................................................... 123
LIST OF TABLES

Table 2.1. Summary of EAR collection effort from Jul 2010-Jun 2013 .................. 18
Table 4.1. Results from automated explosion event detector.............................. 71
Table 4.2. Explosions detected automatically in EAR files ................................. 72
Table 4.3. UNDET data from surface deployed F-42C Transducer........................ 73
Table 5.1 Paired t-test of fish in frame before and after detonation..................... 101
LIST OF FIGURES

Figure 2.1. Map of Pu‘u‘ola UNDET Range ................................................................. 19
Figure 2.2. Image of a training range detonation surface ............................................. 20
Figure 2.3. Image of an EAR deployment in shallow water .......................................... 20
Figure 2.4. Schematic design of an EAR .................................................................... 21
Figure 2.5. Daily sound levels of East and West EARs ................................................ 22
Figure 2.6. Monthly sound level means of East and West EARs ................................. 23
Figure 2.7. Diurnal sound level means West EAR Deployment 1 ................................. 24
Figure 2.8. Diurnal sound level means East and West EARs Deployment 2 .......... 25
Figure 2.9. Diurnal sound level means East and West EARs Deployment 3 ......... 26
Figure 2.10. Diurnal sound level means East and West EARs Deployment 4 ......... 27
Figure 2.11. Diurnal sound level means East and West EARs Deployment 5 ......... 28
Figure 2.12. Mean SPLs by energy bands by date and hour ...................................... 29-37
Figure 2.13. Diel Patterns and RMS SPL for Kane‘ohe Bay (top) and Waikiki ......... 38
Figure 3.1. Spinner dolphin occurrence near O‘ahu 0700-1000 (Lammers 2004) ....... 52
Figure 3.2. Spinner dolphin occurrence near O‘ahu 1000-1200 (Lammers 2004) ....... 52
Figure 3.3. Spectrogram illustrating dolphin whistles .................................................. 53
Figure 3.4. Spectrogram with dolphin whistles and sonar ........................................... 53
Figure 3.5. Total number of whistle positive files from East and West EARs ............ 54
Figure 3.6. Percent of whistles positive files by month from Eastern EAR ................. 54
Figure 3.7. Percent of whistles positive files by month from Western EAR ................. 55
Figure 3.8. Percent of whistles positive files by hour from Eastern EAR ................. 55
Figure 3.9. Percent of whistles positive files by hour from Western EAR ................. 56
Figure 3.10. Spectrogram of humpback whale singing in presence of detonation ... 57
Figure 3.11. Spectrogram of humpback whale singing .............................................. 57
Figure 3.12. Waveform and spectrogram of whale calls and detonation .......... 58
Figure 3.13. Variability in calculated SNR levels ........................................ 59
Figure 3.14. Map of O`ahu and surrounding bathymetry ........................... 60
Figure 4.1. UNDET Shot plan and schematic ........................................... 74
Figure 4.2. Diagram of a mid-water explosive charge ................................. 75
Figure 4.3. UNDET simulation of an idealized detonation ............................ 76
Figure 4.4. UNDET simulation with low pressure behind shock front .......... 77
Figure 4.5. Pressure wave over time data graph ....................................... 78
Figure 4.6. Safe swimmer distance curves ............................................... 79
Figure 4.7. Satellite image of Pu`ula UNDET Range .................................. 80
Figure 4.8. Basic specifications for the F-42 transducer series ..................... 81
Figure 4.9. Free field voltage sensitivity for the F-42 transducer series ........ 82
Figure 4.10. Spectrogram and waveform of detonation .............................. 83
Figure 4.11. Spectrogram and waveform of mid-frequency sonar signal ...... 84
Figure 4.12. Four UNDET waveforms from Pu`ula ................................... 85-86
Figure 4.13. Waveform of detonation indicating snapping shrimp signal ...... 87
Figure 4.14. Histograms of RMS, SEL, and peak values for four explosions ... 88-89
Figure 4.15. Peak energy levels from Pu`ula and other site detonations ....... 90
Figure 4.16. SELs from Pu`ula and other site detonations .......................... 91
Figure 5.1. Spectrogram of the soundscape including detonation ............... 102
Figure 5.2. 5kHz spectrogram of detonation .......................................... 102
Figure 5.3. SPL of detonation and frequency spectrum .............................. 103
Figure 5.4. Mean number of total reef vocalizations ................................. 104
Figure 5.5. Mean number of total reef fishes in video frame ...................... 105
Figure 5.6. Mean number of reef fishes by family in video frame .............. 106
CHAPTER 1: INTRODUCTION

In this chapter, I will introduce the concept of warfare ecology, an emerging scientific discipline studying a subset of anthropogenic disturbances with dramatic impact on the environment. I will then discuss more detailed examples of warfare ecology as it relates to maritime military operations and training in nearshore environments, as well as introduce the critical role of sound in marine organisms, and the use of acoustics to study these topics. This chapter ends with an outline of the dissertation and the significance of this research.

Warfare Ecology

In the present time, the conservation of species and whole ecosystems is challenging due to the ubiquitous presence of humans and ecological disturbances they cause across the Earth. Anthropogenic influences have been increasing dramatically, causing disruptions in nearly every environment humans have been able to populate; some researchers have deemed this new era the Anthropocene (Lewis and Maslin, 2015; Steffen et al., 2007). Conservation efforts are difficult in areas that have been heavily used by humans, or that have unhindered access to humans and their activities.

There is no single human spectrum of activity that has more potential to immediately, adversely, and irrevocably affect ecological landscapes than the conduct of warfare. During times of conflict, the emphasis in operations and the direction of most human energy is to resolving the conflict through violence. Warfare may include activities that are aimed at destroying the opposing belligerent’s infrastructure, food supplies, water resources, and human population.

In 2008, Machlis and Hanson coined the term “warfare ecology” and outlined the need for ecological studies at different stages of warfare, as well as how warfare ecology can inform policy. The authors divide human generated impact on the environment temporally into three major parts: preparations for war, violent conflict, and post war restoration (Machlis and Hanson, 2008).

The first stage, preparations for war, is the time during which standing militaries around the world conduct training and prepare for an actual armed conflict. A wide range of activities are conducted, including training with small arms (firing lead and copper bullets on ranges in a concentrated area), munitions practice (which includes expelling rocket and missile propellant, as well as the chemical residue from the detonation of high explosives) and training with sensor
systems (such as active sonars and transmissions of high energy in the electromagnetic spectrum). In order to limit dangers to civilian populations during training and to control the impact of the operations, military training ranges and bases restrict access to the general public.

These training events occur regularly all over the world, even during “peacetime”, and can be considered a “chronic” form of ecological disturbance. Less common events also occur, causing locally unique acute impacts. For example, ships from the world’s navies constantly travel the marine environment and sometimes run aground in shallow ecosystems; in the past decade U.S. Navy ships have run aground in the Pacific five times. Recent grounding events involved the USS San Francisco, the USNS Niagara Falls, the USS Port Royal, the USS Guardian, and the USNS SGT Matej Kocak. The latter two incidents will be discussed further in the Conclusion chapter (Department of the Navy (DoN), 2013a; 2015).

During periods of peace, the level of required military preparedness is balanced between social concerns, the degree of training realism necessary, and the impact on the environment. When purely training operations are being conducted, militaries are bound to civilian authority and law to a greater degree than during times of active armed conflict. This is to preserve the utility of the training range and minimize the negative impact on the military installation and its surrounding ecosystem.

The second area of concern outlined by Machlis and Hanson (2008) is the conduct of actual combat operations between armed belligerents, the most destructive phase of human conflict. During this phase, environmental and social concerns are secondary to successfully ending the military campaign and achieving the military objectives. There are few if any environmental regulations that are given primary consideration over a military tactic, technique, or procedure during conflict operations. There is limited environmental protection or benefit provided by the rules of war. In general the Law of Armed Conflict prohibits wanton destruction and conduct of war crimes (Johnson and Lee, 2014). However, these concerns are rooted in the desire to limit human suffering from a humanitarian perspective, not with regard to ecological systems, and primarily focus on humanitarian issues separately from environmental concerns.

For example, the environmental damage caused by the defoliant Agent ORANGE during the Vietnam War was deemed a secondary concern to the immediate military need of removing cover by which enemy troops could conceal their positions and prosecute their attacks (Stellman et al., 2003). Another example of direct environmental damage caused during wartime was the detonation of coral reefs to create shipping channels and enable access to
south pacific islands during World War II (Endean et al., 1976). During the 1991 Gulf War, discharged oil in Kuwait formed lakes covering almost 50km², contaminating the soil in the surrounding ecosystems (Al-Adahanii et al., 2015; Al-Awadhi et al., 1996). The oil fires released significant amounts of sulfates into the atmosphere. Sulfate coating of dust and soot change the particles from hydrophobic to hydrophilic, resulting in condensation of clouds, fog, and smog that spread worldwide (Bodhaine et al., 1992; Parungo et al., 1992).

Post conflict restoration, the third and final phase of warfare ecology identified by Machlis and Hanson (2008), is often a low priority or even neglected by the conflict participants. The degree to which environmental restoration occurs is largely dependent on the resolution of the conflict where economic, social, and political structure are given priority consideration, with environmental concerns usually secondary.

These efforts have met with mixed and sometimes unpredictable results. For example, After the military operation to retake the island Guam during World War II, the United Stated re-foliated the island with plant cover to prevent soil erosion. Plant species used were non-native, fast growing, and ultimately invasive on Guam. This “restoration” permanently altered the forest ecosystems, as well provided habitat for additional invasive species on the island (Ewel et al., 1999).

Prior to Gulf War I, marshes in southern Iraq were drained by Saddam Hussein’s army to destabilize the region; reflooding of the area has led to plants and animals repopulating the habitat (Richardson et al., 2005). Once the oil fires in Kuwait were extinguished, bioremediation using a number of different methods was required to remove the freestanding oil, decontaminate the soil, and restore the ecosystem (Omar et al., 2009).

In the case of ship groundings, once the ship is physically removed from the site, the amount of restoration required varies with the specific biotic and abiotic concerns of the grounding site (Precht et al., 2001; Schroeder et al., 2008). In some cases the area will recover on its own relatively quickly, while other locations may never return to preexisting conditions without restoration efforts such as algae removal or coral transplantation (Forrester et al., 2013; Jaap, 2000; Rinkevich, 2005).

The focus of this dissertation research is the first stage of warfare ecology specific to training and preparation of the United States Navy in the Pacific. Routine naval training and readiness exercises are continually affecting nearshore environments at U.S. Naval bases around the world.
Nearshore environments, particularly coral reefs

Human populations, including military forces, interact directly and indirectly with the marine environment predominantly in nearshore ecosystems, though no region is completely unaffected by human influence (Halpern et al., 2008). Ninety percent of worldwide commercial trade is via oceanic trade routes (International Maritime Organization, 2016) and navies of the world are responsible for providing security patrols for greater than 70% of the world’s surface (National Ocean Service, 2016). Multiple anthropogenic stressors have been increasingly affecting marine ecosystems inshore and in the open ocean as its resources are exploited for an increasing human population.

Naval bases significantly impact their surroundings; piers, harbors, shore infrastructure and a plethora of required engineering projects drastically alter the natural ecosystems of the area, including intertidal zones, coral reefs, wetlands, salt marshes, and estuaries. Building Navy bases can directly impact the marine ecosystems by physical destruction of substrate and biological resources, or indirectly impacted through sedimentation and pollution (Fabricius, 2005; Rogers, 1990). Of particular interest is the effect of naval activities on coral reefs. In a military historical context, coral reefs have been viewed primarily as obstacles to be removed in order to build shore infrastructure, or viewed as a source of construction material (Maragos, 1993).

However, coral reefs are a nearshore habitat of increasingly vital importance and attention worldwide; they are an ecosystem with very real economic, social, and strategic value. For example, coral reefs of the main Hawaiian Islands are considered an asset valued at $10 billion dollars (Cesar and Van Beukering, 2004). Valuation is based on fisheries, tourism, recreation, storm event barriers and erosion protection, carbon sequestration, and the scientific and educational value of its biodiversity (Birkeland, 1997; de Groot et al., 2012).

Coral reefs are increasingly in critical danger worldwide due to myriad factors including habitat destruction, overexploitation of fisheries, unsustainable tourism, runoff/pollution, nitrification, and invasive species introductions (Bryant et al., 1999). In addition, destructive fishing practices such as poison or blast fishing directly destroy reefs and their inhabitants (Fox et al., 2005). The most complex conservation challenge of our planet, climate change, strongly impacts coral reefs: warming seas cause coral bleaching and mortality events, and acidification inhibits corals’ ability to build skeletons and create reef structure (Hoegh-Guldberg et al., 2007; Hughes et al., 2003).
Beginning with the environmental movement in the 1970s, the U.S. Navy has given increased attention to mitigating damage to nearshore environments including coral reefs. Millions of dollars are spent annually to ensure the military remains in compliance with marine conservation applicable laws such as National Environmental Policy Act, Marine Mammal Protection Act, Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Endangered Species Act (Department of Defense (DoD), 2011). Since listing of 3 species of coral (Cantharellus noumeae, Siderastrea glynni, and Tubastraea floreana) as Endangered and 22 species of coral as Threatened in 2014, even more detailed ecological assessments must be taken of the invertebrate communities of coral reefs used by the U.S. military (DoN, 2012a; 2013b; 2013c).

**Sound and marine organisms**

Jacques Cousteau (Cousteau and Dumas, 1953) referred to the marine environment as "the silent world," but in the decades since, researchers have discovered it is actually rich with biological sounds (Au and Lammers, 2016; Farina, 2014). Many marine animals send and receive acoustic signals. Sound is a much more efficient way for an animal to sense and interact with its environment than light underwater (Au and Hastings, 2008; Lythgoe, 1988). Light dissipates very quickly, whereas sound travels faster with less attenuation underwater (Michelsen, 1978). Sound is important to marine organisms for mating displays, finding conspecifics, detecting and capturing prey, avoiding predators, underwater navigation, and acoustically detecting suitable habitats (Hopp et al., 2012). Significant work has been undertaken to elucidate how marine animals produce, process, and respond to sounds (Gedamke et al., 2011; Lammers and Castellote, 2009; Madsen et al., 2010; Myrberg, 1980; Simpson et al., 2004).

There are many sources of anthropogenic noise in the ocean. These sounds can be low level and chronic, or high intensity and acute (Hildebrand, 2004). Chronic noise is usually from vessel machinery and propeller cavitation (Richardson et al., 2013; Rolland et al., 2012), though it is worth noting that military vessels (as compared to commercial or recreational vessels) are generally "quieted" using specific technologies to avoid detection (Scott, 2004). Acute acoustic disturbances include seismic air guns for mineral explorations (Dunlop et al., 2016; Madsen et al., 2006; McCauley et al., 2000), piledriving for shore construction, military mid-frequency active sonar (D’Amico and Pittenger, 2009), and underwater detonations from military ordnance and special operations training (Finneran and Jenkins, 2012; Keevin and Hempen, 1997).
The United States Navy works closely with civilian scientists to monitor and mitigate the effects of anthropogenic noise on marine organisms (Debich et al., 2015a; Debich et al., 2015b; Moretti, 2015). There are high profile concerns about acute acoustic disturbances, particularly sonar and underwater detonations (Carrington, 2013; Govoni et al., 2008; Ketten, 1995; Parsons et al., 2008). Significant research has been conducted to try to understand exactly how underwater explosions effect marine life and how to mitigate their impacts, although this is an extremely challenging field of study (Keevin and Hempen, 1997). Acute anthropogenic noise could result in mortality, permanent damage to the animal’s sensory system, temporary degradation of the animal’s sensory systems, negative behavioral response, or have no observable effects (Nowacek et al., 2007; Southall et al., 2007).

The exact physiological damage that results in mortality caused by acute acoustic disturbance may vary depending on the species and the circumstances of the acoustic event. Human generated noise sources in the water have been implicated in causing mortality events of marine mammals through pathologic bubble formation in tissues due to immediate ascent and extended surface intervals (Nowacek et al., 2007), hemorrhagic diathesis, or lethal tissue damage caused by acoustic resonance (Cox et al., 2006). In addition, a behavior response that causes stranding may lead to death (England et al., 2001; Faerber and Baird, 2010). Rarely, the mechanism of death is acute blast overpressure from direct exposure to an underwater explosion (Danil and St. Leger, 2011).

The true extent to which increasing anthropogenic noise, both chronic and acute disturbances, affect marine life is not fully understood (Cox et al., 2006; Life, 2016). Even when mortality or tissue damage is not the result, there is evidence that an increase in ocean noise could cause “acoustic masking” where marine organisms cannot communicate as effectively with each other (Erbe et al., 2016b). In response, some species are altering vocalizations and acoustic behavior (Baumann-Pickering et al., 2013; Miksis-Olds and Nieukirk, 2016; Risch et al., 2012; Tyack, 2009). A louder ocean may also be causing chronic stress for marine animals (Wright et al., 2011). To conduct research on these questions, technology and tools have been developed to more clearly observe the underwater acoustic world.

**Acoustics as an ecological tool**

Acoustics is considered an increasingly important technique to remotely evaluate, assess, and monitor both marine and terrestrial ecosystems (Eldredge et al., 2016; Farina and James, 2016; Sueur and Farina, 2015). Acoustic recorders can be used to measure the
distribution and activity of sound producing organisms (Ricci et al., 2016) and have been successfully applied particularly for avian and anuran communities (Heyer et al., 2014; Pieretti et al., 2011). These tools can also be used to assess the biodiversity of an area. Sueur et al. (2008) developed algorithms and successfully applied them, conducting a rapid acoustic analysis of Tanzanian dry lowland forest communities.

Many technological developments have allowed us to understand to a greater degree just how valuable sound is to the marine environment. New diving techniques and equipment, as well as advances in underwater recording and hydrophones have combined to catapult the study of sound in the ocean. Investigations into marine mammal acoustics, particularly dolphin biosonar, began in the 1940s (Au, 2015; Au, 2012) but did not fully form as a field of biological study until the 1970s (Au et al., 1974). Still, marine bioacoustics is considered somewhat of a nascent field; it is exponentially more difficult to assess marine ecosystems because of inherent access limitations to deep waters and the harshness of the environment. The development of autonomous systems at lower cost and the ability to handle complex signal processing have advanced the field markedly in recent years (Au and Hastings, 2008; Zimmer, 2011).

Research using bioacoustics is varied in methodology and study objectives. Active acoustics emits sound, and the resulting “reflection” returned can be interpreted by researchers (Benoit-Bird et al., 2009). Diel migrations patterns of mesopelagic prey layers can be detected (Benoit-Bird et al., 2001; Copeland et al., 2016) and odontocete foraging habits at depth can be determined with active acoustics (Benoit-Bird and Au, 2003). Fisheries commonly use active acoustics for fish abundance surveys (MacLennan, 1990). These are just a few examples; see Au and Lammers (2016) for a more comprehensive overview.

Passive acoustics involves listening only, without broadcasting any sounds (Mellinger et al., 2007). For example, hydrophones were used to identify populations of fin whales (Balaenoptera physalus) (Castellote et al., 2012a) as well as foraging patterns of odontocetes in the Mediterranean (Giorli et al., 2016). Passive acoustics has also been used to characterize acoustic patterns of remote reefs and detect humpback whales (Megaptera novaeangliae) in the Northwest Hawaiian Islands (Lammers and Munger, 2016; Lammers et al., 2011). Differences in southern right whale (Eubalaena australis) vocalizations under varying background noise conditions was quantified by Parks et al., (2016). Researchers have determined that sea urchin (Evechinus chloroticus) skeletons resonate to create a crepuscular chorus while they are feeding off the coasts of New Zealand (Radford et al., 2008a), and larval fish use acoustic cues to orient themselves toward appropriate ecosystems (Rossi et al., 2016b).
Acoustic techniques allow researchers to answer questions that would be difficult if not impossible to answer using visual observations or video recordings alone, which are limited to daylight and calm sea conditions. Not only can these obstacles be overcome, information from greater depths and across larger time scales can be gathered in a relatively cost-effective manner. Massive amounts of empirical data can be archived and continually re-analyzed as new data processing technologies become available. This dissertation research focuses only on a small aspect of the broadening field of bioacoustics, providing new information at a novel study site.

Dissertation Outline

Passive acoustic recorders were used to investigate acoustic characteristics on Puʻuʻulaʻa Underwater Detonation Range off the coast of Oʻahu. Chapter Two of this dissertation analyzes the soundscape of the range and identifies seasonal and daily patterns in volume, frequency, and intensity of biological sounds at the range. Chapter Three addresses the habitat usage of the underwater detonation range by odontocetes through confirming their presence via whistle recordings, and quantifies the locations, times of day, and months that odontocetes are most likely to be present on the range. Chapter Four examines acute acoustic changes in local soundscapes before, during, and after underwater explosion events. Chapter Five discusses visual and acoustic behavioral changes of Hawaiian coral reef fishes during a series of underwater detonation training events. Finally, Chapter Six summarizes the findings of the four data chapters, discusses the conservation and management implications of the work, and suggests potential future research directions.

Research Significance

Accomplishing the work presented in this dissertation was challenging due to the close and intimate coordination required between the researchers and United States military special operation forces, biologists, and policy makers responsible for environmental monitoring of Naval activities. Access to underwater training ranges is difficult, and explosive events are inherently hazardous. This research is at the intersection of environmental concerns and maintaining military readiness; these two realms can be extremely difficult to reconcile. Information gathered during these studies may be used by biologists and the U.S. Navy to help understand the biodiversity present at Hawaiʻi’s underwater detonation range, and potentially mitigate the negative impacts of explosions on the local marine ecological system.
CHAPTER 2: ACOUSTIC SOUNDSCAPE ANALYSIS

Introduction

Sound is the most efficient way that an organism can interact with its environment in the water (Au and Hastings, 2008; Lythgoe, 1988). Light travels considerably less effectively than sound; sound is propagated in water five times more quickly than in air (Michelsen, 1978). Sound can be used for navigation, identification of conspecifics, social interactions, threat and mating displays, hunting, foraging, predator avoidance, and orientation to suitable habitat (Hopp et al., 2012). The life history traits of many marine organisms include long periods of drift in the pelagic environment that can last days or even months (Shanks, 2009). As an organism matures, it becomes critical that suitable habitat for settlement and development is located.

A variety of different cues can assist a pelagic larval organism in finding the appropriate substrate to settle, including ocean currents and olfaction (Atema et al., 2002; White et al., 2010). Acoustic cues are becoming more widely understood to play an important role in assisting marine organisms in settlement (Slabbekoorn and Bouton, 2008). Different coastal habitats exhibit different acoustic signatures (Radford et al., 2010), and vary due to abiotic components, including weather, waves, and seismic activity (Duennebier et al., 2012) as well as the biologically generated sounds of the ecosystem (Staaterman et al., 2013). Of conservation concern are the anthropogenic noises that now are part of the acoustic soundscape of many habitats. For example, preliminary investigations indicate that pelagic larvae of reef fishes and crustaceans likely use the sounds of coral reefs as settlement cues (Jeffs et al., 2003; Montgomery et al., 2006; Simpson et al., 2004; Tolimieri et al., 2000). However, the typical sounds that reefs produce do not seem to travel far through the water column, so may be more important in localized habitat selection (Kaplan and Mooney, 2016). Some larval fishes have been shown to be able to differentiate acoustically between seagrass, mangroves and reefs (Huijbers et al., 2008) as well as between different sites on the same reef (Piercy et al., 2016). In addition, juveniles (not just larval fish) likely use some acoustic cues to find suitable habitats (Radford et al., 2011). However, there is still much to be learned about sounds as marine settlement cues.

Passive acoustic recording is becoming an increasingly cost effective technically advanced empirical way of measuring sound in marine ecological systems of interest (Au and Lammers, 2016; Richardson et al., 2013; Au et al., 2012; Zimmer, 2011). Abiotic, biotic, and anthropogenic sounds from different marine habitats can be recorded, cataloged and subjected
to a variety of human, manual, and automated analytical methods (Geyer et al., 2016; Sanchez-Gendriz and Padovese, 2016; Wiggins et al., 2016). Additionally, acoustic recordings provide the ability to collect comprehensive, long term, empirical, high fidelity time series datasets that can be archived. The files can be subject to later analyses and comparisons made across time and locations, including analyses by tools and algorithms that have not been developed yet (Eldredge et al., 2016; Farina and James, 2016; Martin and Popper, 2016; Sueur and Farina, 2015).

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 (Figure 2.1). 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 (Figure 2.2). 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 (Figure 2.1). The range is located entirely within the Pearl Harbor Defensive Sea Area established by Executive Order 8143 on May 26th, 1939.

This study aims to obtain long term baseline acoustic soundscape information from Pu’uloa UNDET range, on a temporal scale looking for diel and seasonal patterns. In addition, it aims to determine the sound pressure level in terms of acoustic energy in 1-2 kHz bands. To date, no attempt has been made to conduct fine scale habitat studies at this location.

**Methods**

*Study Area Overview*

The Pu’uloa UNDET Range site is located west of the mouth of Pearl Harbor off the Island of O’ahu, Hawaiʻi centered approximately 21 degrees 17 minutes 29 seconds north latitude, 157 degrees 59 minutes 14 seconds west longitude (Figure 2.1). 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 algal 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/ fossil 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 (Ross, pers.comm.; Friedlander and Parrish, 1998).

Ecological Acoustic Recorders

The instruments used to collect long-term passive acoustic data for this study were Ecological Acoustic Recorders (EARs) developed jointly by 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 16-bit analog to digital conversion board. The EARs at the Pu’uloa range are programmed with an analog-to-digital sampling rate of 40 kHz on a 10% recording duty cycle of 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 2.1). As noted in the table, 1 EAST experienced an analog to digital converter board (ADC) failure and no data were collected.

When active, the EAR records sound information on a 2 GB compact flash memory card. Once this card is full, the on-board hard drive activates and the files are written to a laptop. 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 were 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 as shown in Figure 2.3 (Lammers et al., 2008). Two EARs were deployed adjacent to the UNDET range at 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 2.1).

Characteristics of the Sensor Technology SQ26-01 hydrophone and EAR energy detectors are shown in Figure 2.4:

• Response Sensitivity of −193.5 dB
• Flat (within 1.5 dB) received voltage response from 1 Hz to 28 kHz
• “Wideband” event detector from 20 Hz - 20 kHz
• “High Frequency” detector in energy band from 10 - 20 kHz
**EAR Deployment and Recovery**

EAR deployments were supported by scuba dive teams from Mobile Diving Salvage Unit (MDSU) ONE. Figure 2.1 shows the deployment locations of the two EARs used in this study. EAR1 was located adjacent to a hard bottomed sea floor coral reef environment, and EAR2 was deployed on a sandy bottom. The bottom depth at both locations was approximately 65 FSW, along the 60 FSW isobaths delineated on DMA chart 19366 (Figure 2.1). EARs were placed approximately 1,000 ft. (300 m) outside the nearest border of the range to ensure the devices were an adequate distance away from potential detonation sites to avoid damage to the delicate instrumentation by underwater shockwaves. This distance was calculated by using Navy EOD diver safe swimmer exposure threshold curves determined by the Explosive Ordnance Disposal Tactical Decision Aid (EOD TDA) Program, while allowing the maximum opportunity to record detonation sounds. Weighted buoy lines were deployed on GPS marks. Divers used salvage lift bags to lower the concrete anchors to the bottom. Then, the EAR unit was secured to the anchor with cable ties. Upon completion of the deployment, divers reacquired and recovered the EAR units for data retrieval, refurbishment, and re-deployment.

**Soundscape Characterization**

A total of 397,919 30 second or 60 second passive acoustic recordings (files) were collected at the Pu‘u‘ula Pu‘uloa UNDET range. Table 2.1 shows the specifics of each deployment. The duty cycle was modified from one minute of recording every hour to 30 seconds of recording every 5 minutes after the initial deployment. Due to an analog to digital converter (ADC) circuit board failure, EAR data from the first deployment EAR 1 EAST were lost and no files were recovered.

EAR files recovered were run through a custom written Matlab (Mathworks, Inc) program. The root mean square (RMS) sound pressure level in dB was calculated using the following equation.

\[
SPL = M_r - G + 20 \log \frac{1}{T} \sqrt{\int_0^T p^2(t) dt}
\]

Where:  
- \(M_r\) is the hydrophone sensitivity in dB/v  
- \(G\) is the system gain in dB  
- \(p(t)\) is the instantaneous acoustic pressure  
- \(T\) is the time duration of the file
The overall mean of these individual file means was taken to obtain meta-information on different temporal scales. Parameters, such as day, month, or hour were set and the outputs of the means and standard deviations were recorded into spreadsheets. Graphs were generated to visualize trends in mean RMS sound pressure levels over time.

Then, Root mean squares of the sound pressure levels were also calculated for energy in specific frequency bands (0-2, 2-4, 4-8, 8-16 and 16-32 kHz) and graphed to visualize the distribution of energy across frequencies.

Results

The average daily RMS SPL measurements for the EAR deployments over the entire data collection period for both sites are shown in Figure 2.5. The eastern EAR, deployed adjacent to coral reef habitat, consistently recorded a higher level of sound than the western EAR (by approximately 8 dB) which was deployed on a sandy bottom. The noise over the entire site varied between 115-126 dB re 1 uPa for both deployments.

The daily mean RMS SPL ranges consistently between 122-126 dB for the East EAR, and 115-120 dB for the West EAR. The sounds produced by snapping shrimps (Family Alpheidae) were the dominant biological component to the sound field; the shrimp population produces sound continuously all day. The lunar pattern can also be seen in the full energy band in the eastern location, indicating the strong contribution of snapping shrimp to the overall soundscape in the coral substrate site adjacent to Tripod Reef (see Figure 2.5). It should be noted that there are jumps in SPL in between different deployments of 1-2 dB in the long-term dataset.

Figure 2.6 shows monthly SPL mean at the site. The results were relatively consistent with little SPL variations from month to month. The diel variation of the sound field for each deployment of the dataset averaged per hour is shown in Figures 2.7 through 2.11. The sound field shows a strong diel pattern, with sound levels increasing at night. The magnitude of variation was on the order of 4 dB higher at night the eastern EAR next to the coral reef, and approximately 3 dB higher nightly for the western EAR over the sandy bottom. Interestingly, there is a small (1 dB) but easily noticed and consistent spike of the sound field amplitude at the 19:00 hour, the loudest level recorded on both EARs. The hourly sound field adjacent to the
coral reef was approximately 8 dB louder than over the sandy bottom, confirming at this scale the observation made in the daily sound level measurements.

Figures 2.12a-r show mean SPL by energy bands 0-1.25kHz, 1.25kHz-2.5kHz, 2.5-5kHz, 5-10kHz, and 10-20kHz for each deployment either by date (a,c,e,g,i,k,m,o,q) or hour (b,d,f,h,j,l,n,p,r). Diurnal patterns can be seen in all bands except for the lowest (0-1.25kHz) band, showing an increase in energy during night hours. A lunar cycle was most obvious in the 2.5-5kHz band at the eastern location (Figures 2.12c,g,k,o) and can also be seen in the full energy band shown in Figure 2.5.

In the full band, and in the 0-1.25kHz and 1.25-2.5kHz bands, there is approximately a 1-3 dB difference in sound pressure levels that indicates humpback whale (*Megaptera novaeangliae*) season is identifiable in the spectra and whale song represents an observable contribution to the acoustic environment in the vicinity of the Pu`uloa range. The west EAR showed several energy spikes that may indicate transit of small fishing and recreational boats with higher frequency cavitation from their propeller against the backdrop of an overall quieter environment than the eastern location.

**Discussion**

Long term soundscape information from the Pu`uloa EAR deployments indicated the environment is quite noisy, with high average RMS SPLs. For comparison, sound level data collected with EARs from Kane`ohe Bay and Waikiki Marine Life Conservation District off Waikiki beach are shown in Figure 2.13 (Lammers et al., 2008). RMS SPLs for these areas average 108 dB and 112 dB respectively, both substantially lower than sound levels at Pu`uloa.

Results indicated a difference of up to 8 dB between the two EAR locations, despite the fact they were deployed within a couple thousand meters of each other along the 60ft isobath. This finding indicates that local sound levels, even in close proximity, can vary greatly and may have implications for ecological characterizations and management at smaller scales than most studies to date have explored.

The eastern EAR location was consistently louder, due largely to proximity to coral reef habitat and the presence of snapping shrimps. Snapping shrimps (Alpheidae) are the primary source of biological noise in many nearshore marine habitats, including coral reefs (Au and Banks, 1998; McWilliam, 2016). Biological sounds recorded on the UNDET range included snapping shrimp, reef fish, humpback whales, and odontocetes. Anthropogenic sounds recorded included small boat noise, shipping traffic, echosounders, various types of SONAR,
mechanical transient noise, and explosions.

The 1-2 dB jumps in SPL in between different deployments in the long-term dataset may possibly be explained by slight differences in EAR hydrophone calibration or internal electronic noise in the EAR circuitry. EAR instruments were alternated back and forth between both sites to account for any variety in instrumentation. One of the of the two study EARs is currently deployed, so a side by side comparison to determine the origin of the 1-2 dB variation cannot be conclusively determined.

Soundscapes at Pu`uloa displayed a diel pattern with consistently higher noise levels recorded at night. Fish vocalizations are often found to be louder at night in nocturnal fish species, since these species do not have as many additional visual cues with which to communicate (Ruppe et al., 2015). At the ecosystem level, the diel noise pattern observed is consistent with other nearshore reef habitats where snapping shrimps and reef fish are present (Lammers et al., 2006a; Lammers et al., 2008).

Events such as explosive sounds, boat noise, sonar pings and other anthropogenic sounds are transient and contribute intense acoustic energy, but for only a short time compared to the mean acoustic contribution of snapping shrimp. Even natural sounds from rain, high surf and storms are short lived compared to aggregate snapping shrimp sounds. Mean sound levels at the western site were more variable than at the eastern site, possibly due to a lower amount of snapping shrimp habitat, and therefore more obvious contributions of transient noises, such as vessel traffic or humpback whale song.

Teasing out energy from full band into biologically relevant energy bands revealed diurnal patterns present with increased energy present during night hours in all but the lowest (0-1.25kHz) energy band. The sounds at this energy level may abiotic in origin, such as rain and waves. The 2.5-5kHz band seemed to show a distinct lunar pattern; this is likely due to snapping shrimp. The pattern is most obvious at the eastern site, in closer proximity to the reef where more snapping shrimp are present. The lunar pattern can also be seen in the full energy band, indicating the strong contribution of snapping shrimp to the overall soundscape. Some studies have indicated that soundscapes, particularly ones dominated by snapping shrimp, may be driven by lunar cycles (Radford et al., 2008b; Staaterman et al., 2014).

During months from November to April, humpback whales are present in the Hawaiian Islands. A 1-3 dB increase in sound pressure levels at the 0-1.25kHz and 1.25-2.5kHz bands during these months indicate an observable contribution from humpback whale vocalizations to the soundscape near the study site.
The similarities in soundscape patterns to other reefs indicate that Tripod Reef’s close proximity to an underwater detonation range is not observably affecting the soundscape. While it not possible to conclusively determine if the detonations are negatively affecting the acoustics of the reef, it is possible to say that the acoustics of Tripod Reef resemble the soundscape patterns of other similar reefs. Many other factors are likely influencing the acoustic composition. A detailed, full spectrum ecological analysis and benthic habitat mapping were not the focus of this effort, but could be conducted in the future.

Future research

A number of sources of anthropogenic and biological sounds could be quantified to determine their net contribution to the total sound field at Pu`uloa. A specific search for mid-frequency sonar signals and broad spectrum, high energy, highly impulsive detonation signatures could be undertaken to measure each sound types net contribution to the total soundscape. Counts of small vessel noise could also be made to determine how often these craft transit the restricted area of the UNDET range.

Passive acoustic instruments are currently collecting data at three additional sites in and around Pearl Harbor: off Ford island, near the entrance channel, and recording underwater construction activities such as cutting, grinding, welding, and hydraulic tool use at ALFA docks. Quantifying the acoustic characteristics of construction sounds is particularly interesting, because these sounds are present commonly during underwater construction activities. In addition, a device has been deployed with a Mobile Diving Salvage Unit (MDSU) during a six month long western Pacific operational deployment with the intention of opportunistically recording sounds created by routine multi-national underwater training activities. All these data will provide valuable insight into the underwater acoustic environment.

There is great potential in acoustic monitoring of nearshore areas as we learn more about the sounds of the ocean. Continuing work to acoustically quantify “healthy” reefs and “unhealthy” reefs has significant conservation implications; higher quality reefs have been shown to have louder and richer acoustics than degraded reefs (Harris et al., 2016; Piercy et al., 2014). This pattern holds for other nearshore ecosystems as well: in mangrove habitats, soundscapes diminish when the habitat is degraded (Butler et al., 2016). Work is also ongoing to connect primary productivity (chlorophyll a) levels and soundscapes of coral reefs (Fisher-Pool et al., 2016).
Studies such as those referenced above may help researchers clarify exactly what larval fish and crustaceans are cuing in on for settlement. Correlating sound types and levels with actual recruitment numbers would also be valuable. Anthropogenic noises may be masking vital underwater acoustic settlement cues, just light pollution affects seabird and sea turtle visual cues (Longcore and Rich, 2004). The relationship of anthropogenic sounds in the ocean is complex, even on small scales. For example, a study of the effect of small boat noise on a single species (the singing fish, *Porichthys notatus*) found the boat noise indirectly benefited the fish by decreasing predators in the area, but also negatively impacted the fish by increasing stress and metabolic costs (Cullis-Suzuki, 2015). While much progress has been made in understanding how anthropogenic sound affects marine ecosystems, it is still a nascent field; though one with great potential for ecology and conservation.
### Tables

**Table 2.1.** Summary of EAR collection effort from July 2010 to June 2013. Asterisk indicates EAR ADC board failure with no data collected for 1 EAST deployment.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Location</th>
<th>Start Date</th>
<th>End Date</th>
<th>Duty Cycle</th>
<th>Sample Rate</th>
<th>Total Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 EAST</td>
<td>21N 17.449, 158W 00.365</td>
<td>08 JUL 10</td>
<td>14 SEP 10</td>
<td>60 s / 3600 s</td>
<td>40 kHz</td>
<td>0*</td>
</tr>
<tr>
<td>1 WEST</td>
<td>21N 17.376, 157W 58.691</td>
<td>08 JUL 10</td>
<td>22 SEP 10</td>
<td>60 s / 3600 s</td>
<td>40 kHz</td>
<td>1,826</td>
</tr>
<tr>
<td>2 EAST</td>
<td>21N 17.449, 158W 00.365</td>
<td>15 NOV 10</td>
<td>20 APR 11</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>44,855</td>
</tr>
<tr>
<td>2 WEST</td>
<td>21N 17.376, 157W 58.691</td>
<td>15 NOV 10</td>
<td>28 MAY 11</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>55,968</td>
</tr>
<tr>
<td>3 EAST</td>
<td>21N 17.449, 158W 00.365</td>
<td>01 DEC 11</td>
<td>08 MAY 12</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>45,805</td>
</tr>
<tr>
<td>3 WEST</td>
<td>21N 17.376, 157W 58.691</td>
<td>01 DEC 11</td>
<td>14 MAY 12</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>47,552</td>
</tr>
<tr>
<td>4 EAST</td>
<td>21N 17.449, 158W 00.365</td>
<td>14 MAY 12</td>
<td>03 DEC 12</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>58,443</td>
</tr>
<tr>
<td>4 WEST</td>
<td>21N 17.376, 157W 58.691</td>
<td>07 JUN 12</td>
<td>03 DEC 12</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>51,612</td>
</tr>
<tr>
<td>5 EAST</td>
<td>21N 17.449, 158W 00.365</td>
<td>06 DEC 12</td>
<td>07 JUL 13</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>58,938</td>
</tr>
<tr>
<td>5 WEST</td>
<td>21N 17.376, 157W 58.691</td>
<td>06 DEC 12</td>
<td>09 JUL 13</td>
<td>30 s / 300 s</td>
<td>40 kHz</td>
<td>60,357</td>
</tr>
</tbody>
</table>
Figure 2.1. Pu`uloa UNDET Range (Purple dashed square danger area is approximately 1 square mile) west of the mouth of Pearl Harbor, with approximate location of EARs annotated. Source is DMA Chart 19366.
Figure 2.2. UNDET Training on Pu`uloa Range, showing detonation plume from surface firing device, and “steam cauldron” from underwater explosive shockwave reflecting off of the water’s surface.

Figure 2.3. EAR deployment, showing the shallow water EAR configuration used at Pu`uloa.
Figure 2.4. Schematic diagram of EAR (Lammers et al. 2008)
Figure 2.5. Daily sound levels taken from East and West EARs over the entire study period.
Figure 2.6. Monthly sound level means taken from East and West EARs over the entire study period.
Figure 2.7. Diurnal pattern of EAR Deployment 1 showing hourly sound level means over the entire deployment period.
Figure 2.8. Diurnal pattern of EAR Deployment 2 showing hourly sound level means over the entire deployment period for both locations.
Figure 2.9. Diurnal pattern of EAR Deployment 3 showing hourly sound level means over the entire deployment period for both locations.
Figure 2.10. Diurnal pattern of EAR Deployment 4 showing hourly sound level means over the entire deployment period for both locations.
Figure 2.11. Diurnal pattern of EAR Deployment 5 showing hourly sound level means over the entire deployment period for both locations.
Figure 2.12a. Mean SPL of full band and by energy bands for deployment 1 of the West EAR by date.

Figure 2.12b. Mean SPL of full band and by energy bands for deployment 1 of the West EAR by hour of the day.
Figure 2.12c. Mean SPL of full band and by energy bands for deployment 2 of the East EAR by date.

Figure 2.12d. Mean SPL of full band and by energy bands for deployment 2 of the East EAR by hour of the day.
Figure 2.12e. Mean SPL of full band and by energy bands for deployment 2 of the West EAR by date.

Figure 2.12f. Mean SPL of full band and by energy bands for deployment 2 of the West EAR by hour of the day.
Figure 2.12g. Mean SPL of full band and by energy bands for deployment 3 of the East EAR by date.

Figure 2.12h. Mean SPL of full band and by energy bands for deployment 3 of the East EAR by hour of the day.
Figure 2.12i. Mean SPL of full band and by energy bands for deployment 3 of the West EAR by date.

Figure 2.12j. Mean SPL of full band and by energy bands for deployment 3 of the West EAR by hour of the day.
Figure 2.12k. Mean SPL of full band and by energy bands for deployment 4 of the East EAR by date.

Figure 2.12l. Mean SPL of full band and by energy bands for deployment 4 of the East EAR by hour of the day.
Figure 2.12m. Mean SPL of full band and by energy bands for deployment 4 of the West EAR by date.

Figure 2.12n. Mean SPL of full band and by energy bands for deployment 4 of the West EAR by hour of the day.
Figure 2.12o. Mean SPL of full band and by energy bands for deployment 5 of the East EAR by date.

Figure 2.12p. Mean SPL of full band and by energy bands for deployment 5 of the East EAR by hour of the day.
Figure 2.12q. Mean SPL of full band and by energy bands for deployment 5 of the West EAR by date.

Figure 2.12r. Mean SPL of full band and by energy bands for deployment 5 of the West EAR by hour of the day.
Figure 2.13. Diel Patterns and RMS SPL for Kane`ohe Bay (top) and Waikiki Marine Life Conservation District, showing soundscape level averages of 108 dB and 112 dB respectively (Lammers et al. 2008), both below levels found at the Pu`uloa detonation sites.
CHAPTER 3: MARINE MAMMAL HABITAT USE NEAR AN UNDERWATER DETONATION RANGE

Introduction

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; Ketten, 1995; Lammers et al., 2003; Nachtigall, 1980; Roitblat et al., 1995; Yuen et al., 2005). 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 have negative effects on marine mammals (Carrington, 2013; Govoni et al., 2008; Ketten, 1995; Mohl et al., 1999; Parsons et al., 2008).

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 for classifying effects of impulsive sounds on marine mammals. Acute anthropogenic noise that could result in 1) mortality, 2) permanent damage to the animal’s sensory system (permanent threshold shift), 3) temporary degradation of the animal’s sensory systems (temporary threshold shift), 4) negative behavioral response, or 5) have no observable effects (Nowacek et al., 2007; Southall et al., 2007).

Regarding underwater explosions, the parameters that determine which of the above effects an explosive event will have on a cetacean 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 consequence criteria based on the 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 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 net explosive weights. Based on additional research, NOAA published a comprehensive guide in 2015 on the acoustic
levels believed to cause permanent and temporary threshold shifts in marine mammals (NOAA, 2015).

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, such as a temporary moratorium on the use of non-electric, non-command time delay firing systems. 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 required 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 (500kg HBX-1 at 1.7km, peak pressure 70kPa).

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 or 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 SPL measurements taken at 2 km from the site saturated the recording system. The sound “clipped” above 170 dB re 1μ Pa, indicating the sound pressure level (SPL) was greater than that level at 2km from the source. 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 by relating impulse pressure and distance from the detonation to percent individuals killed (Govoni et al., 2008). It is impractical, arguably unethical and currently illegal to do similar controlled exposure experiments on 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 inference, 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 (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).

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.

The most common marine mammal species in the shallow waters of the Hawaiian archipelago is the spinner dolphin (Lammers, 2004; Lammers et al., 2006b). 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) studied the 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 commonly encountered, but showed no specific site preference. Overall, spinner dolphins
preferred nearshore environments, transiting along the 20m isobath during the day, particularly the early afternoon, time periods normally associated with resting (Lammers, 2004; Norris et al., 1994). Figures 3.1 and 3.2 duplicated directly from Lammers (2004) graphically represent the proportion of encounters based on total number of observations. Pods of animals were intentionally sought out; the low number 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 high frequency of sightings in this area.

The implications of these findings for the Pu`uloa UNDET range are twofold. Firstly, the 20m (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 multiple locations along the south shore. Benoit-Bird and Au (2003) found a strong association with the location of spinner dolphin pods based on the location of their prey species, but this was 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.

The objective of this study was to use passive acoustic data to determine odontocete patterns of occurrence through tracking and identifying social whistle behavior on the Pu`uloa UNDET range, where there is increased anthropogenic noise at potentially injurious levels due to routine military operations, including explosions and sonar events.

**Methods**

*Study Area and Ecological Acoustic Recorders*

For a detailed description of the location and background information of the study site, Pu`uloa UNDET range, please see the methods section of Chapter 2 of this dissertation. The parameters and deployment history of the Ecological Acoustic Recorders (EARs) used to collect these data are also detailed in Chapter 2.

*Data Analyses*

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

All the data were analyzed with an automatic odontocete whistle detector written in MATLAB for the Marine Mammal Research Program (MMRP) at the Hawai`i Institute of Marine Biology (HIMB). This whistle detection program, findWhistles.m, searched individual files in the dataset 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.

Manual examination of the files that were flagged by the detector was conducted visually and aurally by human analysts. Detonations at the Pu`uloa range are only conducted during working hours (0800-1600) so files were sub-setted 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 that were recording during working hours were reviewed manually; a total of 133,715 files were reviewed by human analysts searching for whistles.

Files were converted from a .bin recording format to a .wav format using Triton (Ver. 181 2012). A team of 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 an 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 © (1992-2016).

Files were visualized in spectrogram mode (time on the X-axis, frequency on the Y-axis, and intensity indicated by color). The spectrogram parameters in Adobe Audition were a Blackmann-Harris windowing function, resolution band of 2048, and a window width at 50%. Simultaneously, the analyst listened (using high quality Bose AE2 headphones) for any sounds in addition to standard background noise (primarily snapping shrimp) such as odontocete whistles, humpback whale vocalizations, explosions, sonar, vessels, and any unidentified sounds.

Observations were cataloged into a spreadsheet of results, and an experienced researcher was consulted on any sounds that could not be identified easily. Files that were positively identified as containing odontocete whistles were confirmed by a second researcher. In addition, three files (approximately 15 minutes) before and after each whistle positive file were re-checked for the presence of whistles.
To determine any relationship between whistle positive files with time and/or location, 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.

Opportunistically, a singing humpback whale (*Megaptera novaeangliae*) was recorded during a detonation event. An analysis was conducted to determine what effect, if any, the recorded detonation may have had on the singing behavior of the humpback whale. To evaluate whether the humpback whale increased the intensity of its calling behavior after the detonation vice before, an investigation of signal to noise ratios for the five most obvious song units (short, low frequency downsweep or “F” type calls) was conducted. A low-pass filter with a corner frequency of 4 kHz was applied, then start and stop times were identified manually for each of the five whale calls captured on the 30 second acoustic file. Additionally, start and stop times were identified for the two noise windows [A,B] for each whale call. The window “A” an interval before and after each call to determine background noise, and “B” is the window that includes the call and the background noise inside it. The Root Mean Square (RMS) Sound Pressure Levels (SPLs) were then calculated for each of the five whale calls. Next, each of the ten noise windows (two for each whale call) were split into sub-windows of the same length as the respective whale call. The sub-windows were overlapped in such a way that adjacent sub-windows shared all but one sample. The RMS level in each noise sub-window was calculated, as well as the Signal to Noise Ratio (SNR, in decibels) for the whale call and each of the noise sub-windows: 10*\log_{10}(\text{RMS}_{\text{Signal}}/\text{RMS}_{\text{Noise}}). A two dimensional histogram was plotted to show the variability in calculated SNR level for each call across all noise sub-windows. For each histogram column, the mean and standard deviation for the SNR values in that column were calculated.

Results

**Automated detection**

In order to avoid false alarms from the background noise, the threshold of the whistle detector algorithm had to be set so high that odontocete whistles were masked, and not discernible. This algorithm did not detect any whistles because the high sound level of snapping shrimp and the low sound level of the odontocete vocalizations resulted in a low signal to noise ratio. Shown in Figure 3.3 is an example of a spectrogram that contains dolphin whistles. The figure illustrates the difficulty of detecting whistles at this location with an automated algorithm.
The whistle is received at similar sound levels to snaps from shrimp, therefore not
distinguishable from shrimp to the detector above the background noise.

**Manual odontocete whistle detection**

Due to the lack of success with the automated algorithm, a manual detection was
determined to be necessary. Of the 133,715 files manually examined, 804 files (0.6%) were
found to contain odontocete whistles. Figures 3.3 and 3.4 show examples of spectrograms that
include whistle signals (Figure 3.4 in the presence of sonar) that were 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 3.5). Month was also significant in the
model, though less strongly than location (p<0.012), with more occurrences in late
summer/early fall (Figures 3.6 and 3.7). Time of day (hour) was not significant (p>0.6) 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 3.8 and 3.9). Two of the four interaction coefficients tests were significant:
month x hour (p<0.03) and location x hour (p<0.005). It should be noted the residuals for this
model were relatively high, indicating the data did not fit the statistical model particularly well.

**Humpback whale acoustic behavior during detonation event**

Humpback whale songs were detected by the EARS during calving season in Hawai‘i,
from approximately November to May (NOAA, 2013). A literature search revealed no specific
studies investigating humpback whale song variation in the presence of detonations.
Fortuitously, an explosion was recorded at Pu‘uloa on 11 FEB 2011 coinciding with a singing
humpback whale emitting stereotyped calls (Figure 3.10). The explosion occurs 21.5 s into the
file. For reference, Figure 3.11 shows an example of a singing humpback whale with no
detonation recorded from a different portion of the dataset. The similar song patterns in the two
files indicate no major interruption occurred in normal singing behavior due to the detonation.

Figure 3.12 shows the explosion waveform and five humpback whale calls, with start
and end times for each signal and noise window, and a spectrogram for whale calls and the
explosion in the frequency range of the whale calls.
The humpback whale song was primarily recorded in frequency bands 1 kHz and below. Figure 3.13 show variability in calculated SNR levels between whale calls, noise windows, and noise sub-windows. Each window is the total time of interest, and the sub-windows “A” and “B” are the parts containing and not containing a call. Mean and standard deviation for SNR values for each call:noise window combination are included. Based on the analyses above, and human visual and auditory inspection, there seems to be no observable or consistent difference in amplitude before, during and after the detonation. Specifically, in windows 4 and 5 the signal to noise ratios are lower; had the whale increased his sound output the ratios would have been higher. It appears from the spectrogram and the comparison of signal to noise ratios from the sub-windows before and after “A,” and during “B” that the overall increase in energy may be due to the additive effect of the reverberation of the wave instead of a louder source level from the animal.

Discussion

Automated 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, which might be applicable to other nearshore locations. 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 (Volphiliere, pers. comm.). Since humpback whale songs are high energy below 2 kHz, and odontocete whistles have a wide range of frequencies, automated detection may ultimately prove ineffective - the background may simply be too noisy.

Manual odontocete whistle detection

Spinner dolphins have demonstrated a preference for transiting the coastal areas of leeward O`ahu along the 20m isobath (Lammers, 2004; Lammers et al., 2006b). Since the 20m 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 likely not commonly frequented by odontocetes. These findings are consistent with observations from acoustic recording studies in other areas around the Hawaiian Islands; fewer vocalizations were detected in areas off Kauai.
where there is a large transit distance from the shore to the 1km isobaths (Howe, unpublished data). Off O`ahu, there is a comparatively long horizontal transit from the potential shallow water resting area at Pu`uloa out to the coastal shelf where nightly feeding begins (Benoit-Bird and Au, 2003) as compared to other sites investigated with higher detections (Howe, unpublished data). Figure 3.14 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 detected by 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 coral reef (U.S. Government, 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. Areas with sandy bottoms are known as preferred resting habitat for spinner dolphins (Danil et al., 2005; Norris and Dohl, 1980; Norris et al., 1994). 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 from the resting habitat out to 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 other words, the odontocetes may have been on the east side just as often, they were just not detected as easily. Third, it is possible that spinner dolphins signal less while over a noisy habitat.

Month was a significant variable in the model, with a higher percentage of whistles detected in the late summer and early fall than during other times of the year. This pattern is not easily explained, and is likely due to numerous factors, such as optimal foraging or characteristics of dolphin reproduction. In past studies of Hawaiian spinner dolphins, locations of pods could be correlated with presence of prey species, but prey species distribution was not predictable (Benoit-Bird and Au, 2003). Similarly, not much is known about the seasonality of spinner dolphin reproduction; studies have indicated Hawaiian spinner dolphin calves are born year round (Barlow, 1984) while others suggest two calving peaks per year in November and March (Ostman-Lind et al., 2004). In a study of captive spinner dolphins in Hawai`i, the hormones estradiol and progesterone peaked in late summer and early fall, indicating ovulation in females (Wells, 1984). Abiotic factors, such as weather, could also be directly or indirectly
influencing the monthly variation of acoustic activity detected in the model. Overall, not enough is known about spinner dolphin life history traits, foraging behavior, and movement patterns in this area to speculate what this monthly pattern may mean, or if it will continue over larger time scales.

There was no statistical relationship between time of the day and the presence of whistles, at least during the working hours analyzed (0800-1600). This may indicate there is no set daylight hour transit pattern used by coastal odontocetes in the area, which is consistent with the findings of Lammers (2004) and Lammers et al. (2006b). As the daytime hours (corresponding to the normal training hours on the range) analyzed are associated with times when the animals are 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 dataset 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 that 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 90% of animals that are vocalizing. This is an inherent constraint of using duty cycling as a method of sample collection, as it gives a smaller sample size than continuous recording (Thomisch et al., 2015). Another limitation is that files were classified with presence/absence of whistles. It was not determined if a file included multiple whistles if the whistle all came from a single animal or from multiple animals transiting together.

Another critical consideration 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 and therefore they may not be vocalizing frequently. Based on behavioral observation of spinner dolphins in other parts of the main Hawaiian Islands (Brownlee and Norris, 1994), resting spinner dolphins do not vocalize often or at all. However, transiting spinner dolphins do, and visual observations (Shannon, pers.obs.) of these animals indicate they are transiting the Pu‘u‘u‘aloa range when they are detected.

While it is important to note that the absence of vocalizations does not 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 and the low numbers of visual sightings of coastal odontocetes from past studies off southern O`ahu suggest a low number of animals in the area.

*Humpback whale acoustic behavior during detonation event*

The humpback singing recorded before and after a detonation with no apparent interruption in song is noteworthy. Detonations are performed an average of 15 days a year, and to capture one together with humpback vocalizations during one of the passive acoustic cycles was quite fortuitous. Although of interest, this interpretation is based on this single example. Range, bearing, and received level of explosion intensity at the animal’s location cannot be determined from this sample. If the opportunity arises to collect additional samples, more substantial conclusions could be drawn.

While the apparent lack of behavioral response in this single file of a humpback singing during a detonation event is illuminating, it is anecdotal and limited in scope. However, it is valuable, as mysticete hearing, vocalization, and acoustic behavior in general are even more challenging to study than in odontocetes (Au et al., 2006; Stimpert et al., 2007). Fristrup et al. (2003) reported on humpback whale songs off of Hawai`i measured in response to acoustic broadcasts ("pings") from the U.S. Navy SURTASS Low Frequency Active sonar system, and found songs that overlapped with pings did not differ in length from those in the control period, although the longest songs were sung 1-2 hours after the last ping; the variation in humpback song length remains unexplained. However, Risch et al. (2012) reported reduction in humpback whale song concurrent with low frequency active acoustic pulses of an Ocean Acoustic Waveguide Remote Sensing (OAWRS) experiment to image fish shoals approximately 200 km away from the animals.

Reports on the effect of anthropogenic noise on blue whales (*Balaenoptera musculus*) have found a range of behavioral changes. Blue whales called consistently more during days when ambient noise was increased due to seismic survey operations in the St. Lawrence Estuary, Canada (Di Iorio and Clark, 2010). In contrast, a different study of blue whales found they were less likely to produce calls when mid-frequency active sonar was present (Melcon et al., 2012). The blue whales also demonstrated other behavioral changes, such as cessation of deep foraging dives, increased swimming speed, and a shift in direction away from the source of the sound (Goldbogen et al., 2013). The frequencies of mid-range sonar are well above the range in which blue whales produce sound, yet still seem to be causing behavioral changes. Some cetaceans change their acoustic signature; the average vocalization frequency of the Sri
Lankan pygmy blue whale subspecies decreased over the course of a decade (2002 to 2012; from 107 Hz to 100 Hz) despite the lack of corresponding change in the ambient soundscape (Miksis-Olds and Nieukirk, 2016).

This pattern has been detected in other mysticetes as well. North Atlantic Right Whales (Eubalaena glacialis) may have limited communication due to anthropogenic ship noises that have masking effects (Hatch et al., 2012). Parks et al. (2016) found that North Atlantic right whales increased their call amplitude linearly as the background noise increased. In addition, North Atlantic Right Whales showed decreased levels of stress hormone metabolites when ship traffic (and thus underwater noise) was decreased in the Bay of Fundy, Canada following the events of September 11, 2001 (Rolland et al., 2012). Fin whales (Balaenoptera physalus) change their vocalizations and behavior when exposed to seismic survey noise (Castellote et al. 2012b).

The study at Pu‘uloa range did not focus on mysticetes; however, the opportunistic detection of a humpback whale singing during a detonation was an unexpected discovery. When literature research was conducted to determine the implications of this finding, it became clear that different animals in different locations had a wide variety of responses to impulsive events, and in some cases were not observed to react at all. Expanding on the findings to date in this particular area of study will require significant investments of time and resources in order for any conclusions to be scientifically and empirically valid.

**Future Directions**

For this study, analysts did not attempt to identify the species of odontocete vocalizing in 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 higher frequency vocalizations than bottlenose dolphins, and false killer whales have the lowest frequencies of the three (Lammers, pers.comm.). 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 a similar program for species identification (Barkley et al., 2011; Lin and Chou, 2015; Oswald et al., 2007).
While this study did not focus on sonar events, they were recorded and detected by the explosive event detector. Some files contained by sonar and whistle signals. Figure 3.4 represents a spectrogram of operating sonar identified by the explosion event detector. This spectrogram contains multiple short duration frequency modulated (FM) odontocete whistles repeated at rapid intervals within the first 15s of the recording period. Future analyses could include looking at differences between whistle signals when sonar is present or absent, as well as if the sonar begins mid-file, if the whistle signature exhibits any noticeable changes.

Passive acoustic monitoring has limitations, but also much potential as the technology improves, for both the recorders themselves and tools available for analysis. Directionality of whistle has been found in spinner dolphins, and seems to be 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 (*Physeter macrocephalus*) (Nosal and Frazer, 2007; Nosal and Frazer, 2006), though a lower budget technique using a single hydrophone may be 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 autonomous hydrophones in an array to study odontocete vocalization distance and direction.

Valuable information can be obtained through the use of 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 of odontocete habitat usage could be made between Pu`uloa and 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 illuminating comparisons and help determine which factors influence odontocete habitat choice (Howe, unpublished data).
Figures

Figure 3.1. Occurrence of spinner dolphins off the leeward coast of O`ahu from 0700 to 0959 as observed by Lammers 2004.

Figure 3.2. Occurrence of spinner dolphins off the leeward coast of O`ahu from 1000 to 1159 as observed by Lammers 2004.
**Figure 3.3.** Example of spectrogram containing dolphin whistles nearly concealed in background noise (masking).

**Figure 3.4.** Dolphin whistles in presence of sonar.
Figure 3.5. The total number of whistle positive files detected for the east and west EARs on Pu`u`uola UNDET range.

Figure 3.6. The percent of files with positive whistle detections by month from the EAR location on the eastern edge of the UNDET range.
Figure 3.7. The percent of files with positive whistle detections by month from the EAR location on the western edge of the UNDET range.

Figure 3.8. 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 3.9. The percent of files with positive whistle detections by hour (0800-1600) from the EAR location on the western edge of the UNDET range.
Figure 3.10. Humpback whale singing in the presence of a detonation, which occurs at 21.5s.

Figure 3.11. Humpback whale singing without a detonation in the background.
Figure 3.12. The explosion waveform and five humpback whale calls, with start and end times for each signal and noise window (above). Spectrogram for whale calls and explosion in the frequency range of the whale calls (below). The detonation occurs immediately following call/window 3.
Figure 3.13. Variability in calculated SNR levels between whale calls, noise windows, and noise sub-windows. Mean and standard deviation for the ratios between SNR values for each call:noise window for each call. The detonation occurs immediately following call/window 3.
Figure 3.14. 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 Hawai`i School of Ocean and Earth Sciences, NOAA.
CHAPTER 4: DETONATION OBSERVATIONS IN NEARSHORE HABITATS ASSOCIATED WITH NAVY USE

Introduction

Most studies investigating the effects of military-associated anthropogenic noise have concentrated on deep sea or open ocean propagation of sound and its effect on marine mammals such as echolocating odontocetes, and mysticetes emitting social calls (Au, 2015; Finneran and Jenkins, 2012; Goldbogen et al., 2013; Urick, 1983). Special operations units conduct shallow water live fire explosives training and comparatively little attention has been given to the impact on nearshore marine ecosystems from these underwater detonation events. Operational use of explosives underwater is an extremely perishable skill that requires a great deal of training to attain and maintain proficiency for a wide variety of mission sets. One of the sites of these training operations is Pu`uloa Underwater Detonation (UNDET) range (see Chapter 2, for range location and description).

Use of explosives underwater includes salvage techniques for cutting metals, punching holes in steel beams to allow attachment of lifting shackles, and the destruction of underwater obstacles to facilitate refloating of grounded ships. It also includes explosively setting anchors, remote precision cutting of wire and anchor chains under tension, and other salvage operations. In addition, attack charges are used by combat swimmers such as Navy SEALS, and specialized explosive charges for the render safe and disposal of naval mines and other underwater ordnance are utilized by Explosive Ordnance Disposal (EOD) units. Training for these various missions requires proficiency in multiple types of underwater charges of varying geometries and varying explosive weights from a few ounces for linear cutting charges up to 20 lb. charges of bulk explosives. 20 lbs. is the range net explosive weight (NEW) limit at the study site (Shannon, pers. obs.).

At the Pu`uloa UNDET range these charges are typically set on the seafloor, requiring a double strand of detonating cord (‘det cord’) to transmit the explosive force from the detonating device at the surface to the charge below. Typical detonating cord contains 50 grains per foot of pentaerythritol tetranitrate (PETN) with a detonation velocity of over 26,000 feet (8,000 m) per second. Bulk charges usually consist of Composition C-4 plastic explosive. C-4 is comprised of 91% cyclo-trimethylene trinitramine (RDX) with a detonation velocity of 8,000 m/s typically packaged in M112 charge blocks weighing 1.25 lbs. each.
Charge initiation is usually accomplished by one of five methods: MK 67 Remote Firing Device (RFD), Nonel® shock tube, electric wire, non-electric time fuse, and M147 digital time delay firing device (TDFD). The first three methods are “command” detonation, meaning the demolition team has exact control of the time of firing. The last two methods are time delay firing, meaning the charges will detonate at a specific time interval after activation of the firing device (e.g. ten minutes for safe separation) and time countdown cannot be safely stopped.

Figure 4.1 shows a typical configuration for a training charge set on the Pu`uloa range, with several smaller charges detonated at once, connected by a ‘det cord’ ring main line. Note that all initiating devices are “primed” from the surface. No blasting caps are used underwater. Once placed on the bottom, the charges are connected by swimmers above the water via ‘det cord’ to the firing devices/ initiating systems.

The Pu`uloa range has been used for decades to conduct Navy EOD explosives training (MacDowell, pers. comm.). An exact record of the use of explosives at the range has not been kept, as there was no formal requirement to do so before 2009. After a dramatically reduced period of use of over 10 years, the UNDET range saw an increase in activity beginning in 2005 (Shannon, pers. obs). This increase was due to renewed emphasis on UNDET training for combat salvage divers stationed at Mobile Diving Salvage Unit (MDSU) ONE to meet required operational capabilities.

According to the Commander, Third Fleet Staff, from August 2011 to October 2013 there were 65 UNDET requests at the Pu`uloa range. Of these requests, only 37 detonations were executed. The maximum charge size allowed on the range is 20 lbs. net explosive weight TNT or equivalent, but anecdotally the charge net explosive weight was usually 7-12.5 lbs.

*Underwater shock wave physics*

At source level, explosive shock waves travel at 3-5.5 times the speed of sound in water (Urick, 1983). At a given distance (depending on the composition of the charge and propagation loss in the environment) these shock waves slow to a point where the energy begins to act as broadband acoustic signals, or regular sound waves. Propagation of high frequency acoustic components of the detonation the waves, regardless of speed, follows a multi-ray path model. This means that the sound radiates out as if in discrete rays, each individually subject to forces that may change their speed and direction independently of the others. In deep water, this means that the high frequency rays “bend” according to Snell’s Law.
of Refraction, deflected by changes in water density caused by temperature and salinity differences (Erbe, 2011).

In shallow water, the waves generated by an explosion reflect off the hard boundaries created by the surface and the bottom, causing time of arrival differences to any given receiving point; the point first receives a direct wave, followed by a number of reflected waves or pulses. The direct pulse or wave will not be delayed by more than the distance between the explosion and the receiver divided by the speed of sound in water. Figure 4.2 depicts the direct, surface reflected, and bottom reflected ray paths from a simulated ship shock trial, illustrating the principle. With respect to ray paths, the actual pressure wave over time is composed of direct rays and many different reflected rays that increase the total magnitude of acoustic energy passing through a given point (e.g. the hearing system of a marine mammal). The greater the distance from the source, the longer it takes for all of the wave energy to pass through that point.

Figure 4.3 shows the simulation of a mid-water explosive wave propagating from a detonation point at 1.4m depth over a 2.2m hard bottom. Note at this point in time, the charge simulation exhibits spherical spreading since it has not yet contacted the low density reflective boundary at the surface (air/water interface), or the high density reflective bottom. Figure 4.4 shows the same event stepped forward in time approximately 1ms, clearly showing the reflected components of the wave after interaction with the shallow water bottom and surface.

In Figure 4.5, the graph shows an actual detonation waveform with simulation overlay; pressure in pounds per square inch (psi) is graphed over time in milliseconds (ms). Surrounding the waveform plot in Figure 4.5 are inset simulation plots of the direct shock wave, bottom reflected wave, negative pressure cavitation, and collapse of the cavitation bubble correlated with wave travel past a set point indicated by a black dot. Note that the illustrations in both 4.3 through 4.5 are modeling the point of detonation as a mid-water explosion, while most detonations at the Pu‘uloa range are on the bottom.

Most available literature regarding shock wave propagation comes from studying deep water high net explosive weight charges (thousands of lbs. NEW) (Christian, 1967; Urick, 1983; Urick, 1971) with different properties than the relatively small (20 lbs) charges detonated on the bottom at Pu‘uloa. Waveform parameters have been estimated for explosives detonated at depths of 20m-200m; however, in these experiments the ocean depth was 600m so there was no interference from bottom-reflected energy (Chapman, 1985; Chapman, 1988). The direct measurement of shallow explosive acoustic source energy levels is challenging because of the
confounding measurements from the energy reflected from bottom and the surface of the water (Buck, 1974; Gaspin et al., 1979).

Adding to the complexity of determining the energy levels a marine mammal would encounter from a detonation is the fact that pressure levels will vary based on depth: pressure levels are higher deeper in the water column due to the increasing water pressure, and the combined pressure front of direct and bottom-reflected waves. Figure 4.6 shows U.S. Navy diver safe swimmer distance curves for a 25 lb. charge of TNT at 60 FSW dependent on swimmer depth. The curves show increasing pressure exposure with respect to depth, mitigated by distance. While pressure wave propagation is site specific and not easily explained by simple propagation models, in general it can be inferred that a marine mammal exposed to impulse pressure at deeper depth is likely to experience greater deleterious effects than one at shallower depth due to the shock wave convergence and higher pressures.

Madsen et al. (2006) reported that due to convergence zone and shadow zone effects during seismic surveys with air gun arrays, increasing depth and distance did not correlate with increasing sound exposure to diving sperm whales (*Physeter macrocephalus*). However, more shallow water studies like the current effort at Pu`uloa range are needed to confirm these effects and create effective mitigation policy in these areas. In fact, there is evidence that explosive charges near or on flat surfaces such as those at the Pu`uloa range on the bottom may propagate shock and sound quite differently than explosions at the surface or in the mid-water column (Krieger and Chahine, 2005).

The first aim of this study was to create and test an automated detection algorithm that could identify the days and times of sound files containing detonations from tens of thousands of acoustic recordings in order to reduce human manual analysis time. The second aim was to characterize the types of impulsive sounds associated with military detonation training at Pu`uloa UNDET range, and determine how explosive training may affect the soundscape of the local marine ecosystem.

**Methods**

*Study area and Ecological Acoustic Recorders*

For a detailed description of the location and background information of the study site, Pu`uloa UNDET range, please see the methods section of Chapter 2 of this dissertation. The
parameters and deployment history of the Ecological Acoustic Recorders (EARs) used to collect these data are also detailed in Chapter 2.

**Automated detonation detection**

EAR files used in Chapter 3 were also screened for this study. A total of 397,919 passive acoustic files, each file containing 30 seconds or 60 seconds of acoustic data were collected 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, data from the first deployment of EAR 1 EAST were lost and no files were recovered.

A custom MATLAB program was written to search the recordings for explosive-like broadband sounds characterized by large deviations in sounds pressure level (SPL) from background pressure and a near instantaneous rise time. The explosion detector algorithm first performed a low-pass filter operation and then threshold detection. This threshold value was determined by examining the characteristics of previously recorded detonation files from the Pu`uloa range from 2011 (as discussed below), to ensure the other environmental factors were the same. The algorithm was site-specific to avoid too many false positives or misses. If the calculated energy over a 0.125 second window surpassed the set threshold, the algorithm indicated that a possible explosive sound was detected. The file name was stored so that the file could be retrieved and examined visually for verification. Flagged files were then reviewed visually and aurally to verify the presence of a detonation.

**Surface recordings of explosions from small craft**

In addition to explosion events being detected from the passive acoustic files, four separate detonation events were recorded with surface recording equipment on the Pu`uloa UNDET range. One event was recorded on 27 October 2011, and three were recorded on 02 November 2011 (Figure 4.7). Data were collected using a Navy F-42C transducer (specifications in figures 4.8 and 4.9) at a depth of 3 meters and recorded on an M-AUDIO MicroTrack 24/96 digital recorder.
MicroTrack settings for UNDET monitoring were as follows:

- L/M/H set to “L”
- Ph PWR “Showing RED”
- Input monitor “ON”
- 27dB TRS Boost “off”
- Encoder “WAV”
- Sample rate “44.1”
- Bits “24”
- Channels “Mono”
- Version: Firmware – 1.4.5, Bootloader – 1.04

Analysis

Waveform analysis of the detonation files recorded by the F-42C system was conducted in MATLAB by inputting each unfiltered waveform for the detonation then splitting the waveform into 44100 sample (1 s) windows with 44000 samples (0.9977 seconds) (fSampling=44100 Hz) of overlap between adjacent windows. Then the RMS (Root Mean Square) SPL, SEL, and peak waveform value in each window was calculated. Then, the vector of RMS, SEL, and peak SPL values were divided into super-windows of 2205 values (equal to 5 s worth of 1s windows) with 2105 values (~= 4.7732 s worth of 1s windows) of overlap between super-windows. For each super-window, histograms of RMS, SEL, and peak values calculated from the 1s overlapping windows within the 5 s super-window were plotted. For visualization purposes, only the mean and standard deviation values for 1 out of every 5 super-windows was plotted. Y-axis limits were set to show background noise fluctuations, rather than detonation values.

Results

Automated detonation detection

The explosive event detector algorithm accounted for multiple variables that may have reduced its accuracy. For example, if snapping shrimp produced sounds very close to the hydrophone, they may have produced acoustic intensities at the same level of a small explosion several hundred of meters away. Sonar sounds produced by fishermen and Navy ships, boat sounds, lightning strikes, and other events also have been misinterpreted as detonations by the program. Of the 397,919 files examined, 362 files were highlighted as containing possible explosive events. Therefore, 99.9% of the files were automatically eliminated.
Of the 362 files detected by the automatic explosion detector, 22 contained sonar signals, and 6 contained explosive events (Table 4.1). The remainder of the highlighted files contained boat sounds or other impulsive mechanical transient noises. Table 4.2 lists details of files containing explosions. Also noted in Table 4.2 are coincidences of dolphin whistles within 5 hours before or 5 hours after each detonation. There are not enough whistles present in the files immediately surrounding detonation events to draw any conclusions about behavioral changes. No single files contained both whistles and explosive events.

Figure 4.10 shows an example of a detonation file recorded by an EAR at Pu`uloa. The spectrogram is depicted above the waveform, showing reverberation and differing arrival times for multiple components of the wave. The detonation files collected at Pu`uloa saturated the EAR system, which is a common problem in recording high intensity impulsive sounds such as a detonation with a single hydrophone while trying to simultaneously record biological background sounds in the field. The un-calibrated waveform in Figure 4.10 gives a representation of the total energy, although the magnitude of the clipped peaks could not be determined.

For comparison, Figure 4.11 shows the spectrogram and waveform of a sonar signal also identified by the detection algorithm. This signal also saturated the EAR due to the fact that these EARs are programmed with a gain increase of 47 dB. It is interesting to note the profile in the sonar waveform shows a high amount of energy over a longer time interval than the impulsive detonation sound. SEL/ energy flux densities cannot be estimated from these files due to clipping, resulting in an inability to estimate the total magnitude of the high amplitude signals.

Surface recordings of explosions from small craft

Figure 4.12a-d depicts four waveforms collected from detonations in October and November 2011. As listed in Table 4.3, each recording was taken at a different range and bearing to the detonation charge. Charges were of varying sizes, all placed on a flat sandy bottom but in close proximity to other bathymetric features. Although the waveform amplitudes are clipped at peak impulse pressure on all recordings, it is obvious that the characteristics of the waveforms vary significantly, indicating differences in reverberation and total energy for each shot. This variability is likely due to the different recording distances from the shot, as well as the reverberate environment and charge size.
Figure 4.13 shows that there was no visually notable drop in amplitude of biologically generated noise immediately after the detonation. Figures 4.14a-d quantifies these data, and shows histograms of the RMS, SEL, and peak SPL (mean and standard deviation) values for each of the four explosions. The symbols indicate the mean and unit standard deviation bounds for one out of every 5 histogram super-windows. It should be noted that the explosion values are not shown (denoted by a red line in each figure) because they are well above the maximum y-axis value on each plot. These plots of means and standard deviations do not appear to show changes to the biological noise levels surrounding the detonation events. Rise in sound level on Figures 4.14c and d at 150s and 120s respectively are explained by the small boat engine from the surface support craft investigated the results of the detonation.

Discussion

Automated detonation detection
The explosive event detector identified six explosive events. The log of charges actually detonated on the Pu‘u‘uoa range (obtained from U.S. Navy Third Fleet staff) during the data collection period indicates a total of 38 detonations occurred. Given that the recording interval was only 30 seconds every 300 seconds, this result means that 16% of the detonations conducted were recorded while sampling 10% of the time – a result aided by random chance, but encouraging. Additionally, the explosive detector picked out certain high energy broadband sonar events as well. The successful testing of this algorithm on recording from Pu‘u‘uoa indicate its use can be expanded and applied to detect anthropogenic impulsive sounds from passive acoustic recordings at other sites.

Surface recordings of explosions from small craft
The data indicated that the dominant source of biological acoustic noise, snapping shrimp (Family Alpheidae) did not seem to change observably following the detonations. An interesting and unexpected result of close analysis of the explosive events was the variation in wave forms of the four different explosions (Figure 4.9 and Table 4.3). The regulatory significance of this finding is that the idealized spherical or cylindrical propagation loss model may not apply in the shallow waters of this location. If spherical or cylindrical spreading applied, the exact same waveform (scaled for distance and charge) would be observed.
Traditional free-field and open water propagation models in a simplified sea do not closely fit actual propagation in the environment (Madsen, 2005), although these models are currently being used to estimate sound exposure on marine organisms in the absence of more accurate models. Spreading loss and propagation of sound from detonation events vary by location and day, and are influenced by water depth, charge size, bottom type, charge depth, charge shape, and other factors.

Research on mapping sound propagation on underwater detonation ranges to provide better models of sound attenuation at distance is currently ongoing. Analyses and modeling of underwater explosions have been conducted at Silver Strand Underwater Detonation Range, Coronado, California (Soloway and Dahl, 2015) and Virginia Capes Underwater Detonation Range, Virginia Beach, Virginia (Soloway and Dahl, 2014). Working in conjunction with the Applied Physics Laboratory at University of Washington at the Puʻuloa range in May 2016 as part of a separate study with a controlled experimental design, three replicates of three different charge sizes at a known GPS point were completed over two days. The method employed included multiple instruments including a nine hydrophone vertical array.

The results from the sound wave propagation analyses from the APL-UW array study at Puʻuloa seem to be different than the models published from Silver Strand and Virginia Capes (Soloway and Dahl, 2015; Soloway and Dahl, 2014). The sound wave propagation at Puʻuloa is lower by 30 dB compared to the other shallow water study sites (Figures 4.15 and 4.16). This could be caused by different substrate characteristics at the sites, or could be due to inaccurate information on charge sizes at the other sites, because the Silver Strand and Virginia Capes studies were opportunistic and feedback from the military personnel to the research team was not as precise.

The study of shallow water acoustics is a complex field. Modern equipment, signal processing and increased effort have led to a greater understanding of acoustics in shallow water environments. However, highly variable factors such as sea state, salinity changes, bottom composition that can vary by location, time, and point of measurement make predictive models difficult to construct. This is compounded by the fact that the chemical process of a detonation occurs at such a rapid pace that it is difficult for mechanical instruments to measure and characterize accurately, and the boundary between near field and far field acoustics becomes even harder to delineate when characterizing the behavior of a shock wave through its transition into sound energy in the water. Caution should be taken when trying to generalize acoustic and shock propagation across sites, and when possible, detailed studies of each area
should be accomplished, and data archived for additional analyses when advances in
technology enable more precise measurements and conclusions.
### Table 4.1. Results from automated explosion event detector.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Total Files</th>
<th>Candidate Files</th>
<th>Explosion</th>
<th>SONAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 WEST</td>
<td>1,826</td>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2 EAST</td>
<td>44,855</td>
<td>16</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2 WEST</td>
<td>55,968</td>
<td>143</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3 EAST</td>
<td>45,805</td>
<td>31</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3 WEST</td>
<td>30,997</td>
<td>54</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>4 EAST</td>
<td>45,924</td>
<td>20</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4 WEST</td>
<td>51,612</td>
<td>16</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>5 EAST</td>
<td>58,938</td>
<td>29</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>5 WEST</td>
<td>60,357</td>
<td>52</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Data Set</td>
<td>File</td>
<td>Date</td>
<td>Time of day (hr mn:sec)</td>
<td>Whistle Detections Same Day</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>-----------</td>
<td>-------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>1 WEST</td>
<td>00000194</td>
<td>16JUL10</td>
<td>1217:02</td>
<td>NO</td>
</tr>
<tr>
<td>2 WEST</td>
<td>00002355</td>
<td>23NOV10</td>
<td>1519:02</td>
<td>YES</td>
</tr>
<tr>
<td>2 WEST</td>
<td>00025354</td>
<td>11FEB11</td>
<td>1154:03</td>
<td>NO, Singing Humpback Whales</td>
</tr>
<tr>
<td>3 EAST</td>
<td>00014098</td>
<td>19JAN12</td>
<td>1050:02</td>
<td>YES</td>
</tr>
<tr>
<td>4 EAST</td>
<td>00018736</td>
<td>18JUL12</td>
<td>1320:02</td>
<td>NO</td>
</tr>
<tr>
<td>4 WEST</td>
<td>00038021</td>
<td>17OCT12</td>
<td>1225:03</td>
<td>YES</td>
</tr>
</tbody>
</table>
Table 4.3. Recordings of UNDET data from surface deployed F-42C Transducer on Pu`uloa Range. Water depth is listed in feet of sea water (FSW).

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Shot Position</th>
<th>Boat Position</th>
<th>Water Depth</th>
<th>Shot Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>02NOV11</td>
<td>1129</td>
<td>21 N 17.832, 157 W 59.386</td>
<td>21 N 17.797, 157 W 59.734</td>
<td>35 FSW</td>
<td>7 X M112 Blocks, 150’ Det Cord</td>
</tr>
<tr>
<td>02NOV11</td>
<td>1205</td>
<td>21 N 17.832, 157 W 59.386</td>
<td>21 N 17.728, 157 W 59.703</td>
<td>35 FSW</td>
<td>2 X M112 Blocks, 150’ Det Cord</td>
</tr>
</tbody>
</table>
Figure 4.1. UNDET “Shot Plan” from MDSU ONE training, October 2011.
Figure 4.2. Diagram of direct and reflected ray paths from a mid-water explosive charge to a point "P" showing time of arrival delay (U.S. Government, undated).
Figure 4.3. UNDET simulation showing depth of bottom, location of surface depth charge, and PSI for an idealized detonation prior to contact with the surface or bottom. (US Government, undated).
Figure 4.4. UNDET simulation showing depth of bottom, location of surface depth charge, and PSI for an idealized detonation after the shock wave reflects off the surface and bottom, with the low pressure area shown behind the shock front. (US Government, undated).
Figure 4.5. Pressure wave over time data graph (with simulation overlay in color below) correlated with wave travel past a set point indicated by a black dot on the simulation overlay. Reds and yellows indicate high pressure fronts, white indicates negative pressure (U.S. Government, undated).
Figure 4.6. Safe swimmer distance curves for a 25 lb. charge of TNT at 60 FSW dependent on swimmer depth. Graph from Explosive Ordnance Disposal Tactical Decision Aid (EOD TDA) computer program.
Figure 4.7. Satellite image of Pu’uloa UNDET range, showing EAR locations and one UNDET monitoring event using a hydrophone and recorder from a RHIB. Map from Google Earth.
Figure 4.8. Basic specifications for the F-42 transducer series (from Naval Research Laboratory Underwater Sound Reference Detachment Catalog, 1991). An F-42C transducer was used for these recordings.
Figure 4.9. Free Field Voltage Sensitivity for the F-42 transducer series (from Naval Research Laboratory Underwater Sound Reference Detachment Catalog, 1991). An F-42C transducer was used for these recordings.
Figure 4.10. EAR file containing an explosion showing spectrogram (top) and waveform (bottom). Waveform was saturated peak to peak during the impulse pressure, clipping the signal. Note reverberation adding to the total energy of sound exposure.
Figure 4.11. EAR file containing a mid-frequency sonar signal showing spectrogram (top) and waveform (bottom). Waveform was saturated peak-to-peak, clipping the signal. However, SEL of this signal may be greater than impulse sound from detonation shown in Figure 4.7.
Figure 4.12a-d. Four separate UNDET waveforms recorded on the Pu`uloa range, showing different propagation patterns. Waveforms are shown in chronological order, amplifying information is found in Table 4.3.
Figure 4.13. Although un-calibrated, this waveform appears to show no drop in snapping shrimp noise after a detonation on the Pu`uloa UNDET Range.
Figures 4.14a-d. Histograms of the RMS (top), SEL (middle), and peak (bottom) values for each of the four explosions; the symbols indicate the mean and unit standard deviation bounds for one out of every 5 histogram super-windows. It should be noted the explosion values at the red line are not shown because they are well above the maximum y-axis value on each plot.
Figure 4.15. Peak Energy recorded in May 2016 from the Pu`uloa UNDET range (solid line) as compared to measurements at other sites (dashed line), from Dahl et al. (2016).
Figure 4.16. SELs recorded in May 2016 from the Pu`uloa UNDET range (solid line) as compared to measurements at other sites (dashed line), from Dahl et al. (2016).
CHAPTER 5: ACUTE BEHAVIORAL RESPONSE OF REEF FISHES TO UNDERWATER DETONATION

Introduction

Acoustic recorders can provide a wealth of information on the soundscape, but they still have a number of limitations. Recorders cannot easily distinguish between individual species of odontocetes, or individual species of reef fishes reliably; visual confirmation is required. Marine mammals can be sighted when they return to the surface to breathe, but species of fishes and invertebrates are significantly more difficult to study when attempting to use a combination of acoustic and visual methods. Additionally, the impacts of sounds on odontocetes, mysticetes, and pinnipeds have been studied extensively because it is clear how critically important sound is to these species. Special considerations are also afforded these mammalian taxa from the Marine Mammal Protection Act, and listing under the Endangered Species Act. In the past, the impact of sound energy on reef fish and invertebrates has not been a focus of research efforts due to the difficult nature of such studies, as well as the fact few of these species are listed as Endangered. The importance of sound to fishes and invertebrates is an area of emergent study (Hawkins et al., 2015).

Mortality and injury of underwater organisms due to underwater detonations can be mitigated if the explosion occurs at a safe distance. Studies such as Yelverton et al. (1973), in which mammals and birds were subjected to detonations in a controlled experiment, catalogued physiological effects of detonations to develop exposure curves based on detonation magnitude and distance from the explosion. From Yelverton et al. (1973), Goertner (1982) curves that predicted safe distances for a variety of marine mammal species were developed. Similar curves have been developed to mitigate damage and mortality to fish within the context of commercial blasting and in underwater construction for dams and piers (Goertner, 1978; Govoni et al., 2008; Yelverton et al., 1975;). For example, Govoni et al. (2008) created mortality curves of larval fish subjected to detonations related to overpressure levels, which are rapid increases in water pressure surrounding the organism.

Explosive shockwaves cause damage to living organisms due to changes in the density of the medium as the shockwave passes through the body (a type of impedance mismatch). For terrestrial organisms, there is a change in density when the shockwave moves from air into the mostly liquid body and then through to the air cavities within the body (Stuhmiller et al., 1996) and then leave again through the opposite side. Disturbance of structures and tissues
caused by the wave as it travels through differing densities of living material is the cause of
injury for blast mortality in living organisms (Clemedson and Pettersson, 1955). Most of the
tissues of underwater organisms are of similar density as the water around them, but in teleost
fish, the swim bladder is filled with gas (Hastings and Popper, 2005). The primary change in
density that causes blast damage in these fish is the density change from liquid to gas in the
swim bladder. Evidence suggests that the larger an animal’s swim bladder, the more damaging
the effect of the shockwave (Coker and Hollis, 1950; Goertner et al., 1994). The swim bladder is
highly vascularized, so as the shockwave passes into the swim bladder, it ruptures the vessels
and affects the fish’s ability to maintain buoyancy (Coker and Hollis, 1950; Govoni et al., 2003;
Yelverton et al., 1973). When a fish cannot control its buoyancy, it floats upward, which causes
the gasses in the swim bladder to expand according to the ideal gas laws (Goertner, 1978;
Govoni et al., 2008; Keevin and Hempen, 1997; Sailer et al., 1993; Yelverton et al., 1975;
Yelverton et al., 1973) leading to death.

Most studies on the effects of anthropogenic sound energy on aquatic and marine
organisms have examined fatality and obvious gross anatomical damage (Goertner, 1982;
Ketten, 1995). Even mortality studies that account for non-immediate mortality are rare (Govoni
et al., 2008). Keevin and Hempen (1997) provide a literature review of the effects of
underwater explosions on numerous taxa, including fish. The majority of studies involve
exposure of fish to seismic survey air guns, and focus on how the acute anthropogenic sounds
relate to catch rates of commercially valued fish (Wardle et al., 2001; Wiggins et al., 2016).
Those that have investigated fish behavior have come to varying conclusions. Santulli et al.
(1999) found biochemical indicators of stress in European sea bass (Dicentrarchus labrax)
caused by seismic survey air gun acoustic waves; the biochemical stress measures returned to
normal parameters within 72 hours. Wardle et al. (2001) studied fish behavior response to
seismic air guns using underwater cameras, and found that after an involuntary C-start escape
reflex (a startle response, where the animal quickly turns its head toward an escape direction,
causing the body to bend in a C-shape, then propels forward), fishes returned to their normal
behaviors soon after. Pearson et al. (1992) found that rockfish (Sebastes spp) showed intra-
and inter-species variation in alarm response to air gun stimuli such as schooling together at
different depths and changing behaviors.

In addition to physical movement responses, sound energy exposure may affect the
hearing and vocalization (this term refers to all sound production) levels of fishes. Most of these
studies, again using seismic survey air guns, have focused on captive fishes’ hearing thresholds
(McCauley et al., 2003; Popper et al., 2005). In a study by Popper et al. (2005), two of three freshwater fish species exhibited temporary threshold shift in their hearing when exposed to seismic air guns, and then returned to normal levels within 24 hours. However, another study found permanent hearing loss in fishes exposed to high intensity sounds apparent as ablated hair cells in the sensory tissue (McCauley et al., 2003). To date, very little is known about vocalization rates of fishes before and after exposure to anthropogenic noises.

When studying underwater detonations (as compared to air guns), we are limited to anecdotal observations of how these phenomena may be affecting animals. Controlled experiments involving exposure are difficult and may be considered ethically dubious. No direct observations have been made of fish behavioral responses to sub-lethal acoustic energy from a detonation that have also been correlated with the charge weight, depth, location, and distance from the fish community. The aim of this opportunistic study was to visually and acoustically quantify the behavioral response of Hawaiian reef fishes to an underwater detonation at a sub-lethal distance and determine the feasibility of collecting data as the acoustic energy increases from a sub-lethal to lethal levels.

Methods

On April 13th and 14th 2016, US Army Seventh Engineer Dive Company conducted routine underwater demolition training operations at Pu`uloa Underwater Detonation (UNDET) range, located west of the mouth of Pearl Harbor of the Island of O`ahu, Hawai`i. Six training detonations were conducted at N 21.28817 deg, W 157.98567 deg. Three charges were detonated per day between the hours of 0900-1500. Charges consisted of 8.54 kilograms net explosive weight (NEW) constructed from ten M112 demolition charges. Each M112 block is composed of 0.57 kilograms of composition C4 plastic explosive. C4 is 91% RDX (Cyclotrimethylenetrinitramine) by weight with the remainder being inert binding and plasticizer compounds. The charges were detonated on the seafloor at a depth of 11 meters; the bottom type consisted of a thin veneer of sand over fossilized limestone.

A Wildlife Acoustics Songmeter SM3M autonomous acoustic recorder configured with one HTI standard SPL hydrophone and one HTI high SPL hydrophone was deployed on the deck of a sunken U.S. Navy tugboat (YTB) at GPS position N 21.28528 deg, W 157.99000 deg in 14 meters of water. Concurrently with the deployment of the acoustic sensor, two GoPro Hero 4 Black Edition HD cameras were deployed and secured to the wreck to record the fishes in the vicinity of the deck of the tugboat. This wreck is used as an underwater range for diving.
and salvage training and has been in place since 2010. The structure has the expected pioneer coral community growth of *Pocillopora*, *Porites*, and *Leptastrea* species present. It is the only raised substrate structure in the vicinity of this location for several square kilometers and aggregates multiple species of Hawaiian coastal reef fishes.

The tugboat wreck is located 520 meters southwest (approximately 236 degrees true bearing) from the UNDET site with the bottom of the seafloor at 24 meters and the main deck of the derelict vessel in 14 meters of water. The detonations occurred over a two-day period with three detonations per day. GoPros stopped recording after the first detonation each day due to limited battery life. This resulted in the first detonation of each day having two videos from intersecting angles. All six detonations were acoustically recorded. Because of the use of a dual hydrophone array, the full amplitude of all detonations was captured with no sound clipping or loss of signal in the high sound pressure level (SPL) hydrophone. Simultaneously, the standard hydrophone recorded the sounds of the biological community.

From the video, a human observer recorded the number and species to lowest possible taxonomic level of all reef fishes in the frame from both angles for a total of eight minutes, four minutes before and four minutes after each detonation, at five second intervals. The mean and standard error of the total fish per frame were calculated from all four videos and plotted to track community composition changes before, during, and after the detonations. The mean and standard error of the fish per frame in the five most common fish families were also graphed to illustrate differences in reactions between families.

Songmeter SM3M audio recordings from four minutes before and four minutes after each detonation were evaluated aurally by human researchers using Bose Quiet Comfort 15 noise cancelling headphones and visually using the program WaveSurfer to quantify the number of reef fish vocalizations from the 0 to 3 kHz band in five second intervals. This frequency band has been associated with reef fish vocalizations (Tricas and Boyle, 2014).

**Results**

The soundscape as measured by the SM3M's standard hydrophone is shown in Figure 5.1, and a zoomed in section detailing frequencies up to 5 kHz is provided as Figure 5.2. The negative time values are the time prior to the arrival of the detonation and the positive values represent the time after the arrival of the detonation at time 0. The arrival of the detonation saturated the standard hydrophone channel but the high gain of the channel was necessary in
order to detect fish vocalization. Three separated fish vocalizations can be seen prior to the
arrival of the detonation and a number of closely clumped fish vocalizations can be seen about
2 seconds after the arrival of the detonation.

The waveform and frequency spectrum of one of the detonations is shown in Figure 5.3.
The peak SPL at the receiver for this signal was 214 dB re 1 µPa and the Sound Exposure
Level (SEL) was 185 dB re 1 µPa²/s. The first arrival shown in the left panel of Figure 5.3 was
most likely the substrate-borne component of the shock wave and the second cluster of signals
consisted of the waterborne components with surface and bottom reflected entities. The
pressure signature of the detonation is typical of a short pressure pulse as described by Urick
(1983). At varying ranges from the point of explosion, the detonation signature becomes
complicated by refraction and multipath-propagation in shallow waters once the waves interact
with the surface of the ocean and the substrate (Urick, 1983). The frequency spectrum of the
detonation at the location of the recorder suggest a low-frequency energy event with the energy
decaying rapidly after a frequency of about 10 kHz. Most reef fish hearing that has been tested
(primarily pomacentrid species) extends from 1 to 2 kHz with the lowest detection threshold of
about 80 dB re 1 µPa (Fay, 1988) so it is likely there is sufficient acoustic energy in the blast for
most fish at the study site to hear the explosive signal.

In Figure 5.4, the mean number of total reef vocalizations in five-second intervals
preceding and following the explosion (at time zero) is plotted. A spectrogram of the detonation
is shown in Figure 5.1. A noticeable increase in fish vocalizations occurred immediately after
the moment of detonation, increasing roughly twenty times the baseline rate. By 30 seconds
after the detonation, the fish 'chatter' returned to pre-explosion levels.

Figure 5.5 shows the mean number of total reef fishes, not separated out by species, in
the video frame in five second intervals preceding and following the explosion (at time zero).
The plot of total reef fish means show no easily identifiable trends that could be reasonably tied
to the effect of the explosion. Standard error bars are large, indicating the variability present in
the frame of the four videos analyzed. When fish of all species are included, the mean number
of fishes per frame was not significantly different pre- and post-explosion (p=0.96, see Table 1).

The mean number of reef fishes of the five most common fish families at the study site in
the video frame in five second intervals preceding and following the explosion (at time zero) is
shown in Figure 5.6. The results of unpaired t-tests for the mean number of fish per frame by
family pre- and post- explosion are shown in Table 1. Qualitative descriptions of each of the five
major families are as follows: Chaetodontidae, the butterflyfish, showed an increase in fishes around 40 seconds after the detonation, then a decline 80 seconds post explosion, and the number of butterflyfish seemed more variable after the detonation compared to the period before. Labridae, the wrasse family, showed an increase in fish number in frame immediately after the explosion, and more variability in number post-explosion than pre-explosion. Surgeonfishes, tangs, and unicornfishes in the family Acanthuridae also showed an increase in mean fish number immediately after the explosion, which declined back to pre-detonation levels after approximately 100 seconds. Balistidae, the triggerfishes, were more common in frame pre-explosion, and the Pomacentridae, the damselfish family, were more common in frame post-explosion. However, qualitatively these fishes did not show any noticeable differences that may have been caused by the detonation. The large increase in Pomacentridae at the end of the post-explosion period was caused by a large school of *Abudefduf abdominalis* (family Pomacentridae) traveling into, then eventually out of, the frame.

**Discussion**

The results in Figure 5.6 show the mean number of fish in the frame by family, illustrating that fish families reacted differently to the explosion, or did not seem to have any significant reaction that could be connected to the shockwave/sound of the explosion. An increase in fish in the frames after the explosion represent fish aggregating back to the tugboat from more open water areas in response to the stimulus, perhaps schooling together, decreasing distance from cover for refuge, or possibly competing for habitat space that was momentarily vacated as a result of the startle behavior. High variability in location of each individual fish after the explosion may indicate either disorientation or random movement. The major fish families analyzed seemed to show varying changes in abundance pre- and post-explosion. Whether or not this means some species are “affected less” by the explosion is unknown at this point. Overall, when the data were aggregated to look at all fish species together, no significant difference in mean fish per frame was detected.

While data were not collected on species that were out of the video frame, some interesting anecdotal observations were made. A whitetip reef shark (*Triaenodon obesus*) was observed under the hull of the tugboat at 1130; the final detonation was at 1122, which means this individual likely did not leave the area in response to any of the three explosions. Two green sea turtles (*Chelonia mydas*) were observed greater than 500 meters from the explosion on the surface with no apparent behavioral effects such as a startle response or immediate dive.
Most fish species, though not all, demonstrated a C-start escape reflex response to the shockwave force/sound. Of note, the arc eye hawkfish (*Paracirrhites arcatus*) did not exhibit a C-start response. While this species and its relatives were not numerous enough to be considered common and included as a line on Figure 5.6, their numbers were included in the total mean number of fishes in Figure 5.5. Within the field of view of the camera, individual arc eye hawkfish perched in separate colonies of *Pocillopora damicornis*. They seemed to exhibit some form of competitive or social behavior, transiting between individual coral sites approximately every 30 seconds and occasionally displacing each other. At the moment of detonation, none of these individuals showed any evidence of startle response or visual change in behavior.

Previous studies have observed a difference in fish reaction to acute anthropogenic noise inversely correlated with the degree of association with the benthos: more benthic fish seemed to have less of a response than fish that spend the majority of their time higher in the water column (Coker and Hollis, 1950; Goertner et al., 1994; Keevin and Hempen, 1997). Typically, benthic fish species such as the arc eye hawkfish have reduced or even vestigial swim bladders (McCune and Carlson, 2004), which may reduce their sensitivity to the violent particle motion created by underwater shock and noise. The observations of arc eye hawkfish in this study supported these ideas. Additional observations could be made that directly correlate swim bladder size and degree of behavioral response.

Acoustically, the increase in the number of fish vocalizations immediately following the explosion is a clear behavioral response to the shockwave/sound (see Figure 5.1). The rapid return (less than 30 seconds) of the community to baseline levels of vocalization may indicate a lack of temporary or permanent loss of hearing in these fishes. Rather, the fish vocalizations may be a behavioral alarm response.

**Future Directions**

Recording marine organisms in a natural environment during a detonation event is a challenging task. A research diver must be able to place and recover equipment in situ at a temporal and spatial scale relevant to data collection. Coordinating where and when a detonation might occur, deploying proper data collection equipment, and the timing of all operations related to the explosion is extremely challenging from a logistics standpoint. Very rarely do researchers have the full cooperation of entities conducting detonations in the water, whether for legal or illegal purposes.
One of the challenges encountered during this study was the number of uncontrolled variables in an open water environment. Fishes could move in and out of the frame freely at this study site. Different fish exhibit a variety of natural schooling and aggregation behaviors; some fish exhibit darting behavior forming loose and transient schooling aggregations, some fish such as ta`ape (*Lutjanus kasmira*) form large, tightly packed schools that move slowly, and others exhibit no observable social behavior of any type. The degree to which each individual or species exhibit site specificity was difficult to determine, with the possible exception of the arc eye hawkfish. The limited field of view and the limited amount of time at the study site due to the opportunistic nature of the observations made predicting these behaviors difficult.

Collecting visual data of behavioral responses of marine organisms to detonations requires the organisms to be observed in open water. Captive studies are not an ideal means of studying the effects of detonations on marine animals. The very nature of an underwater explosion, including the high instantaneous sound pressure levels, the reverberations of an aquarium environment, and the damage to the aquarium itself caused by a detonation (let alone the organisms living inside it) make captive studies challenging. No electromechanical transducer can accurately reproduce the effects of a chemical detonation, particularly on a small scale.

While not representative of actual detonations, there is some value in conducting studies using recordings of detonations played back on a transducer at sub-lethal levels near fish in a more controlled way. Fish behavior could be quantified with fewer variables and less risk. Additionally, the fish may respond differently to sounds played continuously and/or frequently. Finally, to get an idea of fish stress levels beyond behavioral response, a more controlled study with captive fish could allow for stress hormone measurements, as well as the possibility of habituation to acute acoustic events.

In addition, it is difficult to estimate the distance and angle of fish movement in a natural environment with a two-dimensional camera. If similar experiments were conducted in the future, including additional cameras and graduated high contrast scale bars that would allow precise measurements of distance traveled would improve the empiricism of movement estimates. Software analyses could also be used to determine the magnitude and direction of fish responses, or behaviors could even be measured in three-dimensional space using active imaging sonar.

The sounds classified as fish vocalizations in this study were too irregular to be anthropogenic, and were associated with frequencies commonly heard in reef fishes in Hawai`i
(Tricas and Boyle, 2014), so it is likely that the data reflect a true increase in fish vocalization immediately after detonation. However, it was not possible to differentiate visually or aurally between fish vocalizations, or classify them by species or even family. The sounds could not be localized with the tools used, and many species sound similar to each other. Future work quantifying the vocalizations of Hawaiian reef fishes, especially with automated software, could allow for a re-analysis of these audio files in the future and positively identify which species is making which sounds.

While this study is limited in scope with only a few replicates, to the authors’ knowledge, it is the first time analysis has been conducted where visual and acoustic behavioral response of fish have been correlated with multiple explosions of identical known charge sizes at the same known distance.
### Tables

**Table 5.1.** Comparison of mean fish before (n=44 time points) and after explosion (n= 44 time points) using an unpaired t-test.

<table>
<thead>
<tr>
<th>Family</th>
<th>Pre-explosion mean in frame &amp; SD</th>
<th>Post-explosion mean in frame &amp; SD</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chaetodontidae</td>
<td>5.05/1.13</td>
<td>8.07/2.45</td>
<td>7.41</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Labridae</td>
<td>9.34/ 2.92</td>
<td>13.9/5.15</td>
<td>5.16</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Acanthuridae</td>
<td>3.90/0.86</td>
<td>4.99/2.13</td>
<td>3.15</td>
<td>0.0022</td>
</tr>
<tr>
<td>Balistidae</td>
<td>1.51/0.84</td>
<td>1.01/0.55</td>
<td>0.33</td>
<td>0.0015</td>
</tr>
<tr>
<td>Pomacentridae</td>
<td>1.30/0.30</td>
<td>2.27/1.98</td>
<td>3.18</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total fish</strong></td>
<td><strong>37.19/6.75</strong></td>
<td><strong>37.11/9.16</strong></td>
<td><strong>0.046</strong></td>
<td><strong>0.96</strong></td>
</tr>
</tbody>
</table>


**Figures**

**Figure 5.1.** Spectrogram of the soundscape as measured by the Wildlife Acoustics Songmeter SM3M the standard hydrophone. Negative time represent the time prior to the arrival of the detonation and the positive values represent the time after the arrival of the detonation at time zero.

**Figure 5.2.** File showing 20 second period at 5kHz scale, showing vocalizations surrounding a detonation.
Figure 5.3. The signature of the detonation as measured by the high sound pressure level (SPL) hydrophone is shown in the left panel and the frequency spectrum is shown in the right panel. The peak SPL for this signal was 214 dB re 1 \( \mu \)Pa and the sound exposure level (SEL) was 185 dB re 1 \( \mu \)Pa\(^2\)s. The initial pressure pulse shown in the left panel was probably a substrate-borne component with the larger waterborne component following by approximately 24 ms. The waterborne component consisted of the direct arrival and multiple secondary arrivals from surface and bottom reflections.
Figure 5.4. Mean number of total reef vocalizations in five second intervals preceding and following the explosion (at time zero).
Figure 5.5. Mean number of total reef fishes in the video frame in five second intervals preceding and following the explosion (at time zero).
Figure 5.6. Mean number of reef fishes by family in the video frame in five second intervals preceding and following the explosion (at time zero).
CHAPTER 6: CONCLUSIONS

The work conducted in this dissertation represents a truly multidisciplinary study, and lies at the intersection of ecology, underwater shock physics, hearing by marine organisms, and policy. A variety of visual and acoustic methods were used to evaluate anthropogenic sounds in a nearshore coral reef ecosystem uniquely associated with U.S. military activity.

Many aspects of data collection were challenging, primarily because of the sensitive and potentially dangerous nature of specialized military training involving scuba diving and use of underwater explosives. These are inherently hazardous activities, involving a great deal of expertise and caution from highly trained professionals. Justifiably, access to the study area, Pu'uloa underwater detonation range, was tightly controlled and at no time did the potential to record novel scientific data outweigh concerns for the safety of all personnel that were on the detonation range. These factors made constructing ideal experiments with tightly controlled variables and large sample sizes impossible. Additionally, the complexity of data collection was compounded by the fact that the study site was an unpredictable nearshore marine environment. As a result, a large portion of this work was highly opportunistic, requiring flexibility to collect data that lend themselves to valid scientific conclusions.

In addition to these unique challenges, acoustics are inherently difficult to study in any shallow water environment due to the nature of shallow water physics and the interactions of abiotic and biotic variables. Automated analysis techniques that have yielded definitive results in open ocean or deep water environments proved ineffective due to highly variable noise sources such as wind, waves, and ubiquitous biological noises such as snapping shrimp and reef fishes. The varying bathymetry, surface wave conditions, and significant acoustic signal from the biotic community could not be controlled, and contributed to making these analyses difficult.

Despite these challenges, these studies report data and observations that have seldom if ever been successfully observed or collected from the field with this degree of precision. The findings of this dissertation represent the first time acoustic data on soundscapes, odontocete whistles and acute detonation events have been collected at an underwater detonation range in proximity to living coral substrate. This work required immense coordination and cooperation with the U.S. military, and represents a unique contribution to the field of warfare ecology.
The overall acoustic energy in the ocean has been steadily increasing (Ketten, 2012). Growing emphasis and attention has been given to both biological and anthropogenic acoustics on marine ecosystems. Advances in signal processing, the lowering of costs of computing power and exponential increases in technology make studying marine acoustics more practical and economical than ever before, and acoustic data are becoming accessible to collaborating scientists and agencies across the world. In this chapter, this research will be placed in a broader perspective and promising new directions of investigation will be discussed.

Application of Research & Future Directions

Soundscape Analysis

Chapter 2 described the soundscape of a nearshore reef ecosystem, and the soundscape for seasonal and diel patterns of sound pressure levels were analyzed. Results indicated a difference of up to 7db between the two EAR locations, despite the fact they were deployed within a couple thousand meters of each other along the same 60ft isobath. This finding indicates that local sound levels, even in close proximity, can vary greatly and may have implications for ecological characterizations and management at smaller scales than most studies to date have explored. Diel patterns, lunar cycles, and seasonality of humpback whale song were observable in the collected acoustic data when analyzed in aggregate, and when the frequency bands were isolated from full-band energy detection.

These files were archived, and later can be compared over longer time scales, or to different reef locations to track noise levels and identify other trends. As autonomous sensors become more “intelligent” and solid state electronics become more prevalent and affordable, it may be possible to deploy an autonomous system of acoustic recorders that can be networked, with precise timing mechanisms to enable the localization of sound to show not only what sounds are present, but also where are they coming from underwater, making it possible to determine directionality and movement patterns of vocalizing animals automatically. Currently, this can only be achieved using cable connected, permanently installed arrays. A multidisciplinary approach is important in the field, as scientists and engineers work together to integrate the latest technologies in battery storage and acoustic sensory systems to provide an economical way of recording and storing this information.

Parsing the soundscape to determine which species (or perhaps genus or family of animals) are contributing which sounds to the overall acoustic signature of the community would
provide a wealth of information about an area. Instead of relying solely on visual surveys from scuba divers to determine community composition, acoustic methods could be applied. If the acoustic contributions of keystone species were identified, the increase or decrease of those species in an area could be tracked, and used as an indicator of ecosystem health.

There are many challenges in quantifying a soundscape as “healthy” or “unhealthy.” Habitat patches are unique, and soundscape characteristics in one area may not be indicative of ecosystem state for another area with a different biotic community and abiotic conditions. In addition, seasonal and lunar cycle variation in soundscapes would have to be studied carefully before we can understand which sounds comprise a stable or unstable reef. Integrating visual, chemical, and physical oceanographic measurements of an area would provide the best overall understanding of ecosystem health.

Acoustic cues likely play an important role in the settlement of pelagic larvae of fishes and invertebrates (Jeffs et al., 2003; Montgomery et al., 2006; Simpson et al., 2004; Slabbekoorn and Bouton, 2008; Tolimieri et al., 2000). However, a recent study indicated the coral reef sound emissions (in terms of particle motion) do not travel far through the water column, so exactly how larvae actually choose settlement substrate is still unknown (Kaplan and Mooney, 2016). Identifying specific sounds that are conducive to larval settlement could allow us to “seed” a specific area with beneficial sounds. For example, if these existing sounds could be amplified over masking anthropogenic noises, or if a transducer broadcasting the larval settlement cue sound(s), the ecosystems could be “engineered” to give them a better chance of settlement and success.

Acoustics in the marine environment is important in the context of climate change. One of many concerns of warmer seas is that ocean acidification will change the soundscape. Snapping shrimp, the noisiest organism on the reef, were shown to snap less often and more quietly in a controlled environment with elevated CO2 levels compared to baseline levels, which may cause larval fish to orient away from a reef instead of toward it (Rossi et al., 2016a; Rossi et al., 2016b). Bivalves were shown to change their digging behavior based on the sound intensity of an area; as sound intensity increased, digging depth increased (Peng et al., 2016). As more studies are conducted, we are learning more about how important sound is to a wide variety species, and the many direct and indirect ways humans are influencing this aspect of marine life.
Chapter 3 determined that based on whistle-positive files of passive acoustic recordings, odontocetes do not appear to regularly traverse the area during hours when detonations may occur. The data indicated that dolphins do occur in the area, but based on when signals were detected, the analysis did not reveal any strong trends to give the U.S. military a confident recommendation that avoiding certain hours of the day or certain months of the year would significantly decrease their chances of accidentally harming a marine mammal near the UNDET range. While not statistically significant, the trend of more whistle detections during the morning hours may not outweigh other variables military personnel have to take into account when planning a detonation operation. Ocean currents and weather must be taken into account; one common weather pattern in the area is an increase in winds and sea state in the afternoon. This causes white caps, which makes visual detection of odontocetes nearly impossible.

Visual surveys for marine mammals prior to a detonation event are standard operating procedure on all U.S. military UNDET ranges, and the range must be declared clear before the operation is carried out. To make this determination with more certainty, it is recommended that a portable, reasonably priced hydrophone be provided to specifically trained personnel conducting the operation. This would allow confirmation that the range is acoustically clear. Eventually, improved recording devices and analyses to determine number of animals, distance from hydrophone, and direction of movement could give personnel an even clearer picture of the marine mammal distribution in the area, and explosions could be delayed until the animals are determined to be a safe distance away.

Military underwater detonations, seismic surveys, and civilian construction noises will continue to cause acute anthropogenic acoustic disturbances. A number of direct mitigation technologies have been developed to dampen and attenuate the energy released from underwater detonation, such as bubble curtains, foams, or coffercells (Buckstaff et al., 2013; Wursig et al., 2000). It is recommended that investments be made in the portability and cost effectiveness of these technologies, as they are currently expensive and specialized, and in need of more development.

The unsuccessful trial of an automated whistle detector in shallow water high-noise locations of Pu`uloa range, and the large scale labor intensive manual inspection of over 130,000 files visually and aurally which took over 3,000 labor hours to complete, highlights the
need to improve automated detection technologies. Advancements in signal processing technologies will improve automated whistle detectors, and possibly allow for more detailed information beyond reporting the presence or absence of whistles. When designing automated detection programs, it may be informative to incorporate site specific parameters, such as bathymetry, bottom type and background noise to quantify detector performance (Helble et al., 2013).

Another recommended future direction is to continue to expand on the work of Nachtigall and Supin (2013), who found that odontocetes are capable of modulating their hearing in anticipation of exposure to a loud noise. As researchers look into how this mechanism works and how to trigger it, it may be possible in the future to activate wild animals’ natural ability to mitigate harm to protect themselves. A lower energy level “warning shot” could be broadcast to help protect odontocetes from a soon to follow acute anthropogenic noise. Acoustics are already used as a deterrent in a different manner: active “pingers” are used by some fisheries to keep dolphins away from an area and reduce by catch (Dawson et al., 2013).

**Detonation Observations**

In Chapter 4, the waveforms of different underwater detonations were carefully analyzed, as well as the soundscapes of the community before and after the acute events. Studies of shallow water underwater detonations of operational explosive charges are not commonly conducted and provided interesting information on waveform variation. Many future studies could build off this work. For example, it is well understood that the propagation of shock wave acoustics in air can be effected by the geometry of the explosive. It is less clear how sound propagation from shaped charges underwater may differ. A shaped charge is an explosive charge formed in a specific geometry and detonated at a specific point to focus the effect of the explosive's energy. The Munroe effect involves forming a conical charge to generate an explosive jet by initiating the detonator from the apex end of a hollow cone void. This type of charge creates a significant downrange explosive effect, with less explosive force propagated omnidirectionally.

Underwater shaped charges have many applications for Explosive Ordnance Disposal (EOD) and underwater salvage operations. These charges are sometimes used for unit level training on the Pu’uloa UNDET Range. To date, all acoustic measurements of UNDET events on the Pu’uloa Range have assumed that the signatures recorded are from spherical charges, the work described in Chapter 4 of this dissertation included. It is possible that acoustic
propagation of shaped charge sounds underwater may in fact be directional. Opportunistic investigation in conjunction with U.S. military personnel to record detonations of multiple shaped charges oriented toward and away from hydrophones is ongoing. The collected recordings will be analyzed to determine if there are any measurable, significant acoustic differences that can be correlated to the shaped charge jet direction.

This study also field tested an automated blast detector algorithm, which detected acute anthropogenic noises successfully. Developing an automated blast detector is of interest to marine resource managers to confirm events of illegal fish blasting (also known as dynamite fishing or fish bombing) on Southeast Asian coral reefs (Woodman et al., 2003). While these recordings were analyzed after acoustic recorders were removed from the water, as technology improves, there is potential for data on blasts to be transmitted to law enforcement agencies in real time.

Fish Behavior in Response to Underwater Detonation

In Chapter 5, reef fish responses to underwater detonations at a non-lethal distance were quantified both visually and aurally, collecting key data on fish behavioral responses to acute anthropogenic noise. Fishes showed variable visual behavioral responses and increased vocalizations immediately after the detonations, but returned to pre-explosion sound levels in less than 30 seconds. Most studies have focused on marine mammals. Far fewer focus on how human generated noises affect fishes, the permanent and ubiquitous vertebrate members of the coral reef community. Having correlated visual and acoustic analysis provides an even more robust view of how fishes respond to acute anthropogenic noise. While visual counts from high quality video provide confident identifications, most fish sounds cannot be easily identified to species. Tricas and Boyle (2014) documented that 47% (45 out of 96) of resident fish species off Hawai‘i island make sounds. Fish vocalizations are a significant part of the marine soundscape and recent studies are working to better quantify their vocalizations (Fay, 2009; Mann et al., 2016). Just like with odontocete identification, fish identification from sound files will only continue to improve as baseline data, recording equipment, and computing technologies improve.

This was an opportunistic study; many variables had to fall into place to successfully deploy cameras and recorders at a safe distance from a coordinated detonation. If this work were repeated in the future, improvements and expansions could include high speed cameras to decrease visual distortion of the lens, improved battery life of cameras, a reference plate
within the frame, and more precise control of detonation timing. The Navy tugboat is a unique structure in the ecosystem; data from different locations and different distances would allow for a clearer picture of the effects of detonations on fishes at non-lethal ranges. As mentioned before, however, because of the ethical concerns associated with designing an experiment that intentionally destroys a coral reef, it is likely these types of observations will continue to be opportunistic in the future.

**Broader Scope**

*Effects of Anthropogenic Noise on Marine Life*

The research reported in this dissertation focused on quantifiable acoustic measurements of marine ecosystems and acute anthropogenic noises, especially detonations. Logistical and ethical constraints prevent studies to quantitatively measure how marine organisms are affected physiologically, behaviorally, and cognitively by explosions. Even studies done in the past, such as Yelverton et al. (1973) who subjected mammals and birds to detonations in a controlled experiment, was limited to cataloging physiological effects. Adding to the challenge of trying to quantify the effects of acute anthropogenic noises on marine organisms is those effects that are not obvious, including behavioral effects (Nowacek et al., 2007; Southall et al., 2007). In addition, neurofunction and cognitive tests cannot be conducted easily on non-human animals in the wild. Therefore, while significant strides have been made in measuring the anatomical and physiological responses to acute sounds, we cannot truly “get inside an animal’s head” and know how marine organisms are being affected (Nachtigall et al., 2000; Potvin, 2016).

Another challenge of mitigating the effects of anthropogenic noise (which is a broad categorization, including acute and chronic sounds of varying levels and frequencies) on marine organisms is that the effects vary from species to species, and likely within species (i.e. whale calf vs adult). Studies can take place to determine how particular sounds affect individual species. For example, a Risso’s dolphin (*Grampus griseus*) and a false killer whale (*Pseudorca crassidens*) were experimentally exposed to a low frequency 75 Hz that researchers were planning to emit to study ocean temperatures. The odontocetes were determined to likely not have the capacity to hear the sound, unless they dove down to 400m, so were unlikely to be negatively affected (Au et al., 1997).
The harbor porpoise (*Phocoena phocoena*) has acute high frequency hearing (Kastelein et al., 2012). To ascertain the animal's ability to hear impulsive sounds (such as detonations) at a distance, it is important to know its hearing threshold levels for broadband impulsive sounds. At present, it is unclear whether hearing thresholds for short narrow-band signals can be used to determine the audibility of broadband impulsive sounds across species. Kastelein et al. (2012) attempted to determine the hearing threshold of a harbor porpoise for an impulsive sound, and to compare it with SEL thresholds for short duration tones identified in previous studies. Based on the results of this study, it is possible to use this method to approximate hearing sensitivity of these animals to broadband detonations using tonal sounds as a proxy. However, the results of both Kastelein et al. (2012) and Au et al. (1997) cannot be applied across other species or across other sound levels. This inability to generalize adds yet another challenge to the already logistically challenging field of marine acoustics.

In this section, some marine organisms that were not assessed quantitatively in this study will be discussed, and some additional anecdotal observations will be reported. While anecdotes are not nearly as powerful as controlled scientific studies, they are worth reporting, as data from controlled studies are not always available or feasible to obtain.

**Hawaiian Monk Seals**

There have been at least two recorded sightings of the Endangered Hawaiian monk seal (*Monachus schauinslandi*) during underwater detonation training at Pu'uloa range. A seal was visually detected entering the training area after the first charge detonation on 19 OCT 2011. Training was halted, and the seal foraged opportunistically on fish that were stunned or killed during the event. Upon departure of the animal from the area, Mobile Diving Salvage Unit (MDSU) divers waited the appropriate time period required per mitigation procedures, then resumed training. Two more detonations were conducted. The seal was seen a few days later, apparently exhibiting no ill effects noted by the monk seal network (Uyeyama, pers comm).

Limited studies have been conducted on the hearing of Hawaiian monk seals; an audiogram on a captive individual revealed a narrower range of hearing than other pinnipeds, with highest sensitivity in the 12-28 kHZ range (Thomas et al., 1990). Additionally, very little has been documented of monk seal vocalizations underwater though anecdotally, they make a noise similar to a “foghorn” like that of many other seal species (Stirling and Thomas, 2003). During this research, no attempt was made to investigate the data set for seal vocalizations.
Sea turtles

A population of Threatened green sea turtles (*Chelonia mydas*) is resident in the vicinity of buoys 1 and 2, as well as buoys 3 and 4 that mark the Pearl Harbor entrance channel (see Figure 2.1). While site specificity of these individuals has not been studied, the area has been monitored for sea turtles routinely by Naval Facilities Scientific Diving Services. The highest density of the population is concentrated approximately 0.75 – 1.2 nautical miles (1.3 - 2.2 km) from the eastern edge of the range. The presence of this population in such proximity to the detonation range is notable, though not fully understood. This presence of green sea turtles indicates that the population is being exposed to high amplitude sounds but suggests that either the habitat benefits of this site outweigh the costs incurred, the population has become habituated to the presence of these sounds, or that the sounds cause no deleterious effects to the animals.

There have been no controlled studies conducted on sea turtle blast injury, or behavioral changes due to detonations, and only limited field observations (Viada et al., 2008). Madin (2009) suggested the skull anatomy of sea turtles indicate an internal structure that may provide shock-hardening and protection to the animals, and noted its features may inspire improved helmet designs in the future. While few studies have examined the effects of anthropogenic noise on sea turtles, many species of sea turtles tend to aggregate in areas of high human activity and disturbance (Morreale and Standora, 1998). In a controlled study, when exposed in outdoor enclosures to loud pulses, sea turtles exhibited changes in orientation and swimming patterns (O'Hara and Wilcox, 1990). However, they seem to be most sensitive to low frequency (100-1000 Hz) sounds (Bartol et al., 1999; Ketten and Bartol, 2005) including noise from recreational and commercial boats (Samuel et al., 2005). While available information regarding the hearing ability of various types of sea turtles indicates reception of low frequencies, the way they use and process sound information is unclear (U.S. Government, 2005; Samuel et al., 2005).

All sea turtle species became included in mitigation measures after an explosive event in 1986 in the Gulf of Mexico off of Texas that removed oil and gas platforms: 51 sea turtles (primarily Kemp’s ridley, *Lepidochelys kempii* which are critically Endangered) as well as 41 bottlenose dolphins were found dead on Texas beaches shortly after the explosions. While these deaths were likely a result of the underwater detonations, they cannot be directly attributed to the explosions (Klima et al., 1988; Viada et al., 2008). On Pu‘u‘uoa underwater
detonation range, green sea turtles have been observed, though not commonly. The mitigation measure (exclusion zone for “clear” range) is the same for both turtles and marine mammals.

**Corals**

Corals face a variety of complex, interacting anthropogenic disturbances (Richmond, 1993). Invertebrate species are not normally considered among the charismatic megafauna, and thus are often the most neglected species in the marine ecosystem, yet they are of profound importance and warrant further study. Keevin and Hempen (1997) produced a significant summary of explosive effects on marine organisms for the U.S. Army Corps of Engineers, that included studies dating back as far as 1907. Their chapter on invertebrates summarizes studies on the effect of explosive detonations on lobsters, shrimp, oysters, sea urchins, and chitons. Only one explosive study on coral was found (Brown and Smith, 1972) which reported broken staghorn coral (*Acropora palmata*) colonies and that the encrusting coral (*Millepora complanta*) suffered abrasion. However, Brown and Smith (1972) did not include sound pressure levels or distance from charges.

Following underwater detonation training events on 01 OCT 2013, Naval Facilities Scientific Diving Services opportunistically investigated the blast site and discovered living corals less than 6 m from the point of a 5 lb. and 17 lb. net explosive weight (NEW) detonation in 20 meters of seawater. These inspection dives occurred more than three weeks after the detonations. Eight replicate line point intercept transects were recorded and photographed out to 25 m from the blast site. No visible negative effects on the corals immediately attributable to the detonation were observed in a radius greater than 25 m. These initial findings are potentially significant to the Navy from a regulatory standpoint in light of the listing of 22 coral species in the Pacific as Threatened and 3 as Endangered under the Endangered Species Act (although none of the listed species are found in Hawai`i). Revisiting the site to evaluate the current condition and collect additional data would provide interesting information on any delayed coral mortality. Additionally, the sound pressure information recorded from the Larson-Davis 831 sound level meter and TC-4013 hydrophone must be calibrated to back calculate and estimate source levels of pressure in order to determine the actual acoustic energy generated at the site during the incident.

The vast majority of coral destroyed by underwater detonations globally is deliberately conducted by blast fishermen; destructive fishing practices, including blast fishing, continue to pose a threat to coral reef sustainability, in conjunction with numerous other threats (Pet-Soede
and Edrmann, 1998). Expanding work that measures the effects of blasts on coral, as well as the rate of recovery has shown that blast fishing reduces resilience to natural perturbations and areas often take a very long time to recover, if they ever fully recover at all (Fox et al., 2003; McManus et al., 1997). It is important to note that corals, even if they are not physically destroyed, can become stressed (Edge et al., 2013; Harriott, 1993). Different measures of stress in coral are being investigated, including cellular diagnostics (Downs et al., 2012).

**Pros and Cons of Acoustic Monitoring**

The field of underwater biological acoustics continues to grow, and has great potential as an ecological monitoring tool, both in association with the military and in civilian waters. Acoustic recorders can be left in place for long periods of time, which provides long-term data, as well as limits risk of injury to human divers, as it only requires a person in the water for initial deployment and collection. Recorders deployed remotely can provide data from deep water areas otherwise inaccessible. Remote regions of the planet only need to be visited to place (and at this point, recover) recording devices. For example, passive acoustic recorders were used in the Northwest Hawaiian Islands to characterize acoustic patterns on remote reefs, detecting parrotfish (Scaridae spp) scraping the reefs as well as odontocete whistles (Lammers and Munger, 2016). In addition, many acoustic monitoring projects are non-invasive: animals do not have to be trapped, handled, or tagged to collect data. Acoustic recorders are more economical than visual monitoring methods for a variety of reasons, including less underway ship time and lower labor requirements, and the cost of the instruments themselves is decreasing.

While this dissertation research focused on a marine setting, acoustic monitoring has applications across ecosystems. Acoustic methods have been used to measure biodiversity (Krause and Farina, 2016; Pieretti et al., 2011; Servick, 2014; Zhang et al., 2016) or estimate wildlife population sizes in terrestrial communities (Drake et al., 2016; Marques et al., 2013). In addition to blast fishing, passive acoustic monitoring has the potential to detect poaching or illegal logging (Sutherland et al., 2016).

Although acoustic monitoring has myriad benefits and application, aspects of both the recording devices and computer programs have room for improvement. Most passive acoustic recorders use duty cycles, not recording 24 hours a day. Of those that record continuously, few record continuously for long periods of time. This compromise is made due to limitations of both battery life and data storage, but these will become less limiting factors as technology improves.
Many different devices are used to collect acoustic data. There is a need for standardization not only of equipment, but also of analysis protocols and techniques (Sousa-Lima et al., 2013). Additionally, different research papers on biological acoustics report results in varying formats. A significant challenge when attempting to compare soundscapes is a lack of standard protocols, data analyses, and reporting (Erbe et al., 2016a; King, 2015). However, work is ongoing on how to handle and share massive acoustic datasets, particularly of marine mammals, among scientists and agencies (Dugan et al., 2016; Nichols, 2016). For example, NOAA is investing in a project to map anthropogenic noise and cetacean density and distribution worldwide (Harrison et al., 2016).

**Complexity of the relationship between military conflict and the environment**

The studies conducted for this dissertation on the Pu’uloa underwater detonation range represent a microcosm of a worldwide, ubiquitous intertwining between human conflict and anthropogenic impact on the biosphere. More than any other endeavor, warfare and combat between humans has the potential to immediately, drastically, and irreversibly alter ecosystems. Below I will discuss some case studies illustrating the interdependency between human conflict and the environment.

*Korean DMZ*

Warfare ecology is a complex subject that is just beginning to be studied (Machlis and Hanson, 2008). While the focus on this research has been on mitigating the environmental effects of military training, it should be noted that areas associated with the world’s militaries are not necessarily directly suffering from damage, and in some cases, this status provides protection for native species in that area. For example, militarily isolated disputed lands and restricted military training reservations have the potential to act as de facto nature preserves due to limited access by the general public.

This is the case of the Korean De-Militarized Zone (DMZ), where such a barrier has divided the Korean Peninsula and limited human encroachment on a small strip of mountainous land for over 60 years (Kun, 1998). The total size of the DMZ is 4 km wide, and 250 km long running the entire breadth of the peninsula from coast to coast. The area encompasses a wide variety of ecologically distinct habitats. Temperate forests, abandoned farmlands, wetlands, lakes, streams, mountains, rocky coastlines, dunes, scrub, grasslands, tidal flats and sea cliffs
are all found within its boundaries (Kim and Cho, 2005). Although all of these habitat types are not unique to the DMZ, the continuous, uninterrupted nature of the DMZ is unique on the peninsula. Current ecosystem-based conservation thinking places value on protecting areas encompassing many habitats such as the DMZ.

In the remainder of South Korea, development has fragmented habitats and reduced their level of ecosystem function (Kim and Cho, 2005). The rapid development of South Korea has caused the endangerment or extinction of almost 30 percent of the country’s mammals, 48 percent of reptiles, and 60 percent of amphibians (Easen, 2003). The environmental status of North Korea is unknown, but based on historical environmental policies of closed totalitarian regimes in the past, it is assumed that stewardship of the environment in North Korea is significantly limited. In the case of the DMZ, the restrictive nature of the region makes accurate biodiversity surveys of the flora and fauna difficult, which may cause problems in documenting conservation needs and assigning priority of effort.

The status of the DMZ as a protected area from human incursion is informal and temporary. Should conflict escalate between North and South Korea, or should the two countries become reunified in the future, the biodiversity in the DMZ may decline.

Guantanamo Bay, Cuba

The waters off of Guantanamo Bay, Cuba are another example of the de facto preserve affect. Coral reef ecosystems in the Caribbean have been in decline for decades due to climate change, marine pollution, and invasive species, among other factors (Adam et al., 2015; Hughes, 1994). This includes deteriorating reefs in the proximity of the industrial and commercial areas of Cuba (Alcolado et al., 1997). The coral reefs at Guantanamo Bay, Cuba, have not been suffering as significantly as comparable surrounding reefs, which is thought to be due to inaccessibility and underutilization. The area is restricted access and cannot be used for fishing or recreation (Department of the Navy (DoN), 2009). The coral reefs at Guantanamo have sometimes been used as a benchmark for what a healthy Caribbean coral reef should look like, and high species richness has been observed (DoN, 2005; DoN, 2007; DoN, 2012b).

However, protected areas (de facto or otherwise), particularly marine protected areas, do not occur in a vacuum, and there are early indications the Guantanamo coral reef ecosystems are becoming stressed. Nearby sewage effluent and agricultural runoff may be affecting the area, and an increase in algal cover has been reported (DoN, 2012b). Invasive lionfish (Pterois spp.) were observed in greater numbers in 2012 than in 2011 and are
anecdotally reported by Navy divers as being extraordinary common in areas under piers (DoN, 2012b).

Finally, unauthorized fishing has been anecdotally reported in off limits areas of Guantanamo Bay, as there are no full time game wardens providing enforcement. A similar situation was reported in Farallon de Medinilla (FDM) in the Mariana Archipelago: restricted access has resulted in an ecosystem that is relatively undisturbed, but there was strong evidence in 2012 the area has become subject to illegal spearfishing (DoN, 2013a).

Ship Groundings

Military and civilian vessels are constantly traversing our oceans. Despite advances in technology and reliance on that technology, the ever-increasing volume of ship traffic means that groundings and potentially oil spills will be an environmental concern for the foreseeable future. One potential application of acoustic technology that could help prevent some ship groundings would be to install transponders near the reef, which would alert echosounders that a ship was approaching a shallow water reef. When a naval ship runs aground, it is considered an acute impact of warfare ecology. Between 2005 and 2015, the USNS Niagara Falls, USS Guardian, and USNS Kocak all ran aground on shallow coral reefs in the Pacific. The United States Navy has the responsibility to document damage to the reefs, and potentially remit compensation to the nations to which the reefs belong territorially. In the case of the USS Guardian, the entire ship salvage operation centered around eliminating hazards to personnel and to the reef. This represents a situation where environmental concerns were integrated into the salvage plan from the very beginning.

Although documentation and payment for damage are critical steps, it is recommended that grounding sites be monitored more extensively in the future, and over the longer term. Like a forest fire taking an ecosystem back to the initial stages of secondary succession, tracking the trajectory of a grounding site once the ship is removed, and comparing that area to other locations would provide essential information on reef recovery. This could include passive acoustic recorders that could stay in place to track the impact of salvage operations as well as recovery. Active restoration efforts of varying scope may provide ways to speed up the recovery process at grounding “scars.” Some coral species came back after blast fishing relatively quickly (10-20 recruits per m² in 6 months) when substrate was provided (Fox et al., 2005).
Shifting Policies and Attitudes

The above examples, those discussed in the introduction and research chapters, as well as many others help shed light on the complex relationship between the military and the environment. Currently, the military is more interested than ever before in mitigating damage to and restoring already impacted ecosystems. In mid-2016, the Navy put a call out for researchers to help them understand the physiological impacts of detonations on marine mammals.

Military lands and waters are often restricted, which limits the number of people who can directly impact them. Strictly limiting recreational and commercial use of an area has many benefits, such as enhanced reproductive potential which supports fisheries in marine ecosystems, as well as maintaining biodiversity and ecosystem function (Bergen and Carr, 2003). Restricted areas once riddled with ordnance are being cleared, such as on Midway, Kahoolawe, and Vieques (Bossert, 2004; Hourdequin and Havlick, 2011). A natural area reserve on Maui is being temporarily closed to clear ordnance (Dawson, 2016).

Not only are current military forces restoring lands, they actively work to limit the environmental damage their activities may cause. For example, Navy ships must report any negative marine mammal encounters, and like commercial vessels, are working to understand and reduce marine mammal ship strikes (Jefferies and Moore, 2016; Jensen et al., 2004; Laist et al., 2001; Lammers et al., 2013). Beginning in 2014, the Navy has worked with non-profit conservation groups to relocate Laysan albatross (*Phoebastria immutabilis*) eggs from near airfields on the Pacific Missile Range Facility on Kauai to safer areas on the island as well as protected lands on O‘ahu (Powell, 2014).

All of these mitigation and restoration efforts are in stark contrast to the military policies and attitudes of past eras. Regarding Naval operations, communications from senior level admirals during World War II referred to oceans as flat terrain, and gave no consideration to differing depths of oceans or varying marine ecosystems. According to declassified documents regarding Naval strategy in the Pacific during World War II, specifically memoranda from Admiral Raymond Spruance, the ocean was viewed as a pathway to get from one place to another, as well as an unending source of fish to feed military personnel, with no other intrinsic value or importance.

In recent decades, there has been a growing understanding of the importance of the marine environment, from both a strategic and an economic standpoint of natural resources. In addition, the conservation movement, arguably spearheaded in the 1970s by efforts to “save the
whales,” gave the militaries and governments of the world no choice but to address the full spectrum of political, economic, and conservation concerns in the oceans they are responsible for, as well as in international waters. In present day in the U.S. military, all U.S. ships and bases are required to be in compliance with all international, federal, and local environmental regulations. The individual commander of the ship or the base is held personally responsible if any violations occur, and strict rules are in place to maintain compliance by all personnel. For example, due the protections afforded to the red-footed booby (*Sula sula*) under the Migratory Bird Treaty Act, the continuing policy at Marine Corps Base Hawai‘i Kaneohe Bay prohibits the act of even pointing a firearm at a red-footed booby at the colony living at the Marine Corps weapons range (MCB Hawai‘i, 2008).

**Final Reflections**

We are entering a century in which food, energy, and water are becoming increasingly scarce and contested. The government of China, as a matter of national strategy, is pursuing a policy of military and economic expansion in the South China Sea, asserting ancient territorial claims which have been contested, and in some cases refuted by the international community (Krepinevich, 2015). Ostensibly, these claims are about securing oil resources, but growing opinion indicates this is mostly likely about access to fishing grounds (Morton, 2016; Schofield et al., 2016). The protection of natural resources has been traditionally viewed as a constraint on military training, but securing these natural resources has increasingly become a focus of national security concerns (Shannon, 2015).

Humans have always waged war, and will continue to engage in armed conflict for the foreseeable future. Likely, warfare of some sort will continue for the entire existence of our species. Knowing this, we have a moral imperative to address the impact of warfare on our planet’s ecosystems and other inhabitants; we would be remiss if we do not act. Just as surely as there will always be wars, those wars will end, and a state of temporary stability will return. All stakeholders have to come to an understanding on economic and security issues involved in trying to conserve environmental resources before and during conflict, and speed restoration after the conflict ends.
LITERATURE CITED


DoN (Department of the Navy). (2009). U.S. Naval Station, Guantanamo Bay, Cuba Outdoor Recreation and Wildlife Instruction 1710.10A.


Naval Research Laboratory Underwater Sound Reference Detachment Catalog (1991). From the Naval Research Laboratory, Underwater Sound Reference Detachment, PO Box 56833, Orlando, Florida.


