INVESTIGATING THE MOVEMENT AND SEASONAL OCCURRENCE OF CETACEANS IN HAWAI'I USING SOUND

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

DECEMBER 2015

By Alexis B. Rudd

Dissertation Committee:

Whitlow Au, Chairperson
    Paul Nachtigall
    Marc Lammers
    Eva Marie Nosal
    Joseph Mobley
“I want my world to be a true one. I have faith in the scientific endeavor to the degree that I believe that the more we know, the more we care.”

-Kenneth Norris

Le mieux est l'ennemi du bien.

-Voltaire

If you can't explain what you're doing and why you're doing it to any intelligent layman, that really means that you don't understand it yourself.

-David Allan Bromley
President, American Physical Society (1997)
DEDICATION

This dissertation is dedicated to my parents,
Jerry and Valerie Rudd,

and to my husband, Andrew Titmus.
ACKNOWLEDGEMENTS

This research was primarily supported through grants from the U.S. Office of Naval Research (Grant No. N000141210285). Additional assistance for these projects was provided by Young Brothers Shipping Company, NAVFAC, Guidestar Engineering, the Hawaiian Superferry and the Moir Scholarship for Outstanding Outreach.

No PhD is completed alone, and I could not have done this without the help and support of many individuals.

The most time-intensive part of my dissertation is based on research done with the Young Brothers Shipping Company. The sailors, stevedores, and management that assisted in this project are too numerous to list. Steve Roundtree was instrumental in making the project happen. Randy Lau was essential in organizing the logistics of the project. Eddie Magaoay helped with hydrophone deployment design. Captains Mike Semien, Rudy Kok, Richard Sachs, Art Takushi, Dave Judkins, Jeb Baker, Lance Laybourn, Bill Shamburger, and Ron Bluelow were kind enough to allow me to tag along on their ships. The crew members who assisted me are too many to name, but included Chris Kojima (who takes amazing whale videos), Mike Klaussen, Wendell Kam, Jeremy King, and Sammy Pedro. In addition to the folks at Young Brothers, I also need to thank Julie and Mike Oswald for all their hard work creating TRIA and ROCCA and for integrating them into PamGUARD. They are also two of the nicest people in existence. I would like to thank David Mellinger for his patience and help with Ishmael programs, and Adam Frankel for his general programming assistance, friendliness, and ability to think creatively about difficult problems.
I could not have done the work on DIFAR localization without the exertions of the wonderful team from Guidestar Engineering led by Siebert Murphy and including James Graham, Don Smith, and Neil Baitcher, and Gloria Koch. Multiple Marine Mammal Research Lab members were also involved in the project; Michael Richlen, Lee Shannon, and Alison Stimpert. The project was sponsored by the US Navy, and specific guidance and management was provided by Chyau Shen, Peter Woodside, and Donald Statter. Other help onboard the R/V Miriam and at the shore stations was provided by Patrick Lusk, Katie Leecorchick, Sharon Wright, Katie Koslucher, Donna Dunn, Patricia Guy Hugo Molina, and Roy Yumori. Permitting help for the at-sea demonstration test was provided by David Manery, David Alvarico, Lance Hayashi, and Travis Araki, Donald Hubbard, Jayne LeFors, Dan Quinn, Audrey Baker, and Steve Lau.

I would like to thank Dave Matilla for his words of wisdom about continuing through adversity. Joshua Drew was an incredible mentor and provided invaluable help with writing and editing. Miriam Goldstein and Rob Williams served as role models. Jim Darling’s stories and writing were an inspiration. James Mead reminded me why I loved science in the first place. Shiela Conant has been an inspiration. I hope that someday I can be half as cool as she is. Wu Jung Lee walked with me on the dark paths of bioacoustics and was not afraid. There is no way I could have written this dissertation without the help of Alex Verstak and Anurag Acharya. Thank you for making me much more than 10% more efficient. Florence Welch, Paul Epworth and Kid Harpoon provided words of wisdom when I needed them most.

I could not have completed the last few years of my PhD if I had not had the opportunity to work as a Frank M. Cushing Marine Policy Fellow, and I owe a debt of gratitude to Frank
Cushing’s family and to the policy team, especially Hannah Dean, Kc Cerveny, Kevin Wheeler, and Dr. Robert Gagosian at the Consortium for Ocean Leadership for their support.

I owe a debt of gratitude to Senator John Thune and the staff of the Senate Oceans and Surface Transportation Subcommittees. Adrian Arnakis, Fern Gibbons, Wendy Lewis, Robert Donnell, and Ross Dietrich showed me immense kindness and support while I was writing up this thesis. Adrian Arnakis and Fern Gibbons were instrumental in improving my writing process, and Wendy’s competitive nature spurred me forward. I also am thankful for Darren Lerner, Cindy Hunter, Una Chang, Maya Yamamoto, and Julia Galkiewicz from the Hawaii Sea Grant and the National Sea Grant Fellowship offices for the amazing learning opportunities that I have had as a Knauss fellow. My fellow Sea Grant fellows Meagan Dumphy-Daly, Patrick Drupp, and Carolyn Doherty have been especially understanding during my hermitage.

It is impossible to express the importance of the mentorship and friendship of the Marine Mammal Research Lab during the last 7 years. Roland Aubaer was my technical guru in the topics of soldering, epoxy and philosophy. I would especially like to thank Michael Richlen and Lee Shannon for their help with the DIFAR project, Jessica Chen for taking such good care of the Hikianalia recorder after I left Hawaii, and Alison Stimpert, Aude Pacini, and Michael Richlen for being such tireless mentors.

Finally, I would like to thank my Hawaii Ohana; David Sischo, Matthew Lam, Matt Lurie, Lindsay Young, Eric VanderWerf, Sheldon Plentovich, Pollyanna Fisher-Pool, Michael Richlen, Amber Inwood, Koa Inwood, and Lulu Fisher-Pool. I love you guys.
ABSTRACT

This dissertation tests two methods to obtain information of the distribution and movement of cetaceans. The first method uses vessels of opportunity as platforms to conduct acoustic surveys between the main Hawaiian Islands, with the ultimate goal of providing a method that can be used in future studies to contribute to mapping distribution and habitat modeling of data-poor cetacean species in the areas of the ocean which are infrequently surveyed. The distribution of a well-studied species, the humpback whale *Megaptera novaeangliae* was mapped and analyzed in relation to remotely sensed data on ocean depth, sea surface temperature, sea surface height, wind speed, chlorophyll-A, and surface currents. The results agreed with previous research on humpback whales, indicating that acoustic surveys from vessels of opportunity are a viable method for collecting distribution data on cetaceans. The predicted species of odontocete whistles collected during vessel of opportunity surveys was determined using the Real-time Odontocete Call Classification Algorithm, and analyzed in respect to remotely sensed data. The sighting rate for odontocete surveys in this study is comparable to that of previous survey methods, and cryptic species are identified at a higher relative rate than when using visual sighting methods. The biases inherent in concentrating survey effort primarily in the calm waters on the leeward sides the Hawaiian Islands are discussed, as well as the drawbacks of relying on visual sighting methods for detecting species with low visual detection probability. In addition, the potential impacts of anthropogenic noise and ship strikes from commercial vessels are discussed during the case study of a high-speed craft. This dissertation also discusses a second methodology involving the use of DIFAR
sonobuoys to track multiple singing humpback whales, with the end goal of learning more about the function about humpback song. This method is also applicable to other cetacean species.
# TABLE OF CONTENTS

Acknowledgements ......................................................................................... v
Abstract ........................................................................................................... ix
List of Tables .................................................................................................... xiii
List of Figures ................................................................................................... xiv

Chapter 1: Introduction .................................................................................... 1
  Intent of this dissertation .............................................................................. 1
  The Utility of Acoustics to Study Living Organisms ..................................... 2
  Visual vs. Acoustic Survey Methods ........................................................... 3
  Cetacean Sound Production ......................................................................... 5
  Cetacean Hearing ........................................................................................ 6
  Cetacean Communication ........................................................................... 7
  Species Life Histories ................................................................................ 9
    Short-Finned Pilot Whale *Globicephala melas* .......................................... 10
    False Killer Whale *Pseudorca crassidens* ............................................... 11
    Spinner Dolphin *Stenella longirostris* .................................................... 12
    Striped Dolphin *Stenella coeruleoalba* .................................................. 13
    Pantropical spotted dolphin *Stenella attenuata* ...................................... 15
    Rough-toothed dolphin *Steno bredanensis* ............................................. 16
    Bottlenose dolphin *Tursiops truncatus* .................................................. 17
  Implications for Anthropogenic Impacts ..................................................... 19
  Anthropogenic Noise From Commercial Ships .......................................... 20
  Methods for Measuring Ship Noise ............................................................ 26
  Objectives of this dissertation ................................................................... 28
  Works Cited .................................................................................................. 29

Chapter 2: Use of a Novel Method to Study a Well-Known Species: Distribution and Relative Abundance of Humpback Whales in the Main Hawaiian Islands ............... 46
  Introduction .................................................................................................. 46
  Methods ....................................................................................................... 52
    Data collection ......................................................................................... 52
    Acoustic Analysis .................................................................................... 57
    Satellite Data ............................................................................................ 59
    Statistics .................................................................................................. 60
  Results ........................................................................................................... 62
  Discussion .................................................................................................... 69
    Comparison with Previous Research ...................................................... 69
    Future Work ............................................................................................ 74
  Works Cited .................................................................................................. 76

Chapter 3: Relative Abundance and Distribution of Odontocetes in the Deep Water Channels of the Main Hawaiian Islands ......................................................... 93
  Introduction .................................................................................................. 93
  Methods ....................................................................................................... 98
    Data collection ......................................................................................... 98
Acoustic Analysis and Whistle Classification ................................................. 104
Satellite Data ................................................................................................. 107
Statistics ....................................................................................................... 108
Results .......................................................................................................... 110
Discussion .................................................................................................... 119
Addressing Biases in Survey Effort ............................................................... 119
Distribution of Odontocete Species ............................................................... 125
Future Work ................................................................................................. 130
Works Cited ................................................................................................. 131

Chapter 4: Underwater Sound Measurements of a High-Speed Jet-Propelled Craft:
The Implications of this Ship Type for Large Whale Ship Strikes .................. 148
Abstract ........................................................................................................ 148
Introduction ................................................................................................... 149
Materials and Methods .................................................................................. 150
Results ............................................................................................................ 154
Discussion ...................................................................................................... 157
Acknowledgements ........................................................................................ 165
Works Cited ................................................................................................. 166

Chapter 5: A Portable Method for the use of DIFAR Technology to Study behavior and
Relative Movement of Marine Mammals ........................................................ 171
Introduction ................................................................................................... 171
Materials and Methods .................................................................................. 176
  Equipment .................................................................................................... 176
  Preliminary Deployments .............................................................................. 178
  Data Analysis for Localization .................................................................... 179
Results ............................................................................................................ 183
Discussion ...................................................................................................... 186
Works Cited ................................................................................................. 187

Chapter 6: Conclusions .................................................................................. 191
  Filling Gaps in Information on Distribution, Behavior, and Abundance ...... 191
  Summary of Conclusions and Results ......................................................... 191
  Future Work ............................................................................................... 193
  Works Cited ............................................................................................... 195
List of Tables

Table 2.1: Results of the 2 block stepwise binary regression model explaining whale locations ................................................................................................................................................................................................. 67

Table 3.1: Summary of times, number of cetacean species encountered, coverage, and of four sources of potential information on marine mammal distributions in Hawaii ....................... 98

Table 3.2: Species detected, with breakdown of visual IDs and total detections .................. 113

Table 3.3: Results of the 2 block stepwise binary regression model explaining dolphin locations .............................................................................................................................................................. 117

Table 4.1: Comparison between Alakai Speed, SPL, Distance (m) at which the ship is audible above ambient noise, and closure time ........................................................................................................ 163
List of Figures

Figure 1.1: Current estimate of biologically important area for *Globicephala macrorhynchus* ................................................................. 10
Figure 1.2: Current estimate of biologically important area for *Pseudorca crassidens* ................................................................. 11
Figure 1.3: Current estimate of biologically important area for *Stenella longirostris* ................................................................. 13
Figure 1.4: Distribution of several species, including *Stenella coeruleoalba* ................................................................. 14
Figure 1.5: Current estimate of biologically important area for *Stenella attenuata* ................................................................. 15
Figure 1.6: Current estimate of biologically important area for *Steno bredanensis* ................................................................. 16
Figure 1.7: Current estimate of biologically important area for *Tursiops truncatus* ................................................................. 18
Figure 2.1: Global coverage of the oceans by commercial shipping ................................................................................. 49
Figure 2.2: Map of Young Brothers routes used to collect data for this survey ................................................................. 53
Figure 2.3: A stationary EAR resting on the ocean floor near coral ................................................................................. 54
Figure 2.4: Schematic of towfish depth at zero and underway [above 4 mph] ................................................................. 55
Figure 2.5: Recording Equipment Setup .................................................................................................................. 56
Figure 2.6: Example spectrogram of short periodic flow noise caused by surface interference ................................................................................. 58
Figure 2.7: Number of hours of effort surveyed per week throughout the survey ................................................................. 62
Figure 2.8: Spectrogram of humpback whale calls recorded on February 8, 2012 ................................................................. 63
Figure 2.9: Percent of total of survey effort vs. time of day ................................................................................................. 64
Figure 2.10: Distribution of effort by depth ................................................................................................................ 65
Figure 2.11: Seafloor depth distribution of location of humpback whale sightings ................................................................. 65
Figure 2.12: Detections per hour of effort in each category of the Beaufort wind scale ....................................................................................... 66
Figure 2.13: Box-plot comparisons of bathymetry and satellite data from humpback locations and sub-sampled survey effort ....................................................................................... 68
Figure 3.1: Map of Young Brothers routes used to collect data for this survey ................................................................. 99
Figure 3.2: A stationary EAR resting on the ocean floor near coral ................................................................................................. 100
Figure 3.3: Schematic of towfish depth at zero and underway [above 4 mph] ....................................................................................... 101
Figure 3.4: Recording Equipment Setup ................................................................................................................ 102
Figure 3.5: Example spectrogram of short periodic flow noise ................................................................................................. 104
Figure 3.6: Spectrogram of a bottlenose dolphin whistle, showing the ten variables that were measured from each whistle ....................................................................................... 106
Figure 3.7: Number of hours of effort surveyed per week throughout the survey ................................................................. 110
Figure 3.8: Spectrogram of humpback whale calls recorded on February 8, 2011 ................................................................. 111
Figure 3.9: Percent of total of survey effort vs. time of day ................................................................................................. 111
Figure 3.10: Distribution of effort by depth for all transects ................................................................................................. 112
Figure 3.11: Depth distribution of dolphin detections by species ................................................................................................. 114
Figure 3.12: Detections per hour of effort in each category of the Beaufort scale ................................................................. 115
Figure 3.13: Isolated Average RMS SPL vs Wind Speed and vessel speed ................................................................................................. 116
Figure 3.14: Box-plot comparisons of bathymetry and data from odontocete locations and survey effort ....................................................................................... 118
Figure 3.15: Box-plot comparisons of isolated average RMS SPL data from odontocete locations and survey effort ................................................................. 118
Figure 3.16: Decreases in detection probability g[0] on the survey line for visual line transect surveys for seven of the six species detected in this study .................. 120
Figure 3.17: Generalized ambient noise spectra attributable to various sources ...... 121
Figure 3.18: Covariates of Beaufort sea-state plotted against unadjusted, ungrouped perpendicular sighting distances for sea turtles .............................................. 123
Figure 4.1: Map showing the locations where the radiated noise was measured ...... 151
Figure 4.2: Examples of received sound pressure levels as a function of time for the hydrophone at the 10 m depth ........................................................................ 155
Figure 4.3: The broadband (022 kHz) sound pressure levels of the ship noise as a function of speed and aspect of the Alakai .......................................................... 156
Figure 4.4: The frequency spectra of the radiated noise from the Alakai traveling at 37 knots, integrated over 1 s, as measured by the hydrophone at a depth of 10 m for the bow aspect (front of the ship), the beam aspect (perpendicular to the ship), and the stern (back of the ship) .................................................................................. 157
Figure 4.5: Comparison of noise measurements from the Alakai and other ships of similar speeds and SPLs .................................................................................. 160
Figure 4.6: Estimated range in km at which the received sound of the Alakai would be louder than ambient noise of humpback whale song during whale chorusing in peak humpback season for whales located at a depth of 3 m and 10 m ...................... 161
Figure 4.7: Closing time (defined as difference between the time when the time the sound of the ship is louder than the ambient noise during peak chorusing and the time when the ship would arrive at that location) for the Alakai at 12, 24, and 37 knots and at depths of 3 m and 10 m ............................................................................. 164
Figure 5.1: Geometry of a two-hydrophone array with a sound-producing animal at position s(x,y) ................................................................................................. 172
Figure 5.2: Localization with a linear array of three hydrophones. From Au and Hastings 2008 ............................................................................................................. 173
Figure 5.3: Inside of a DIFAR sensor ..................................................................... 175
Figure 5.4: Modified DIFAR Sonobouy, showing (clockwise from top right) the hydrophone, the battery pack, and the float and radio antenna ............................ 177
Figure 5.5: Location of test DIFAR sonobouy deployments in Yokahama Bay .......... 178
Figure 5.6: Cross-correlations between two matching calls ..................................... 180
Figure 5.7: Example of the cross correlation values between one call from Sonobouy 1 and all the calls from Sonobouy 2 ................................................................. 181
Figure 5.8: Example of how the locations of whales are determined using only the calculated bearing toward the whale sound from the DIFAR Sonobouy ............... 181
Figure 5.9: Theoretical example of an ambiguity surface for DIFAR data. This ambiguity surface was generated using the deployment locations of the two sonobouys and an estimated TDOA for an animal calling at this location ........................................ 183
Figure 5.10: Spectrogram of humpback whale calls from on-board recordings on Sonobouy 1 ................................................................................................. 184
**Figure 5.11:** Recordings of humpback whale calls, showing the difference in signals recorded on the Omnidirectional, North/South, and East/West components of the DIFAR array. ............................ 184

**Figure 5.12:** Relative GPS movements of Sonobouy #1 during the five hour testing period signals recorded on the Omnidirectional, North/South, and East/West components of the DIFAR array. .............................................................. 185
CHAPTER 1. INTRODUCTION

Intent of this Dissertation

Effective management of protected species requires not only good research, but also clear communication of that research. To that end, this dissertation has been written with a minimum of jargon wherever possible. In addition, although it is a dissertation in the zoological sciences, it uses concepts from both physics and electrical engineering. As a whole, the aim of this dissertation is to examine methods of collecting acoustic data that are novel, inexpensive, and may provide solutions to vital gaps in understanding of the distribution and behavior of marine mammals. New, economical methods do not always meet the ideal standard for data collection. However, the use of these methods does help make incremental steps toward better understanding of the natural world and the impacts of human activity. This dissertation will discuss the strengths and weaknesses of the methods used in this dissertation, as well as relate how these methods complement those that are currently considered to be the gold standard. In Chapter Two, gaps in current understanding of marine mammal distribution will be discussed and a new acoustic survey method will be presented with the potential to help in filling these gaps. In Chapter Three, this survey method is used to examine the distribution of odontocetes in a region where previous survey efforts have been temporally and spatially biased. In Chapter Four, the conservation implications of using commercial vessels as platforms of opportunity to collect acoustic survey data are examined. Finally, in Chapter Five, a method using sonobuoys to solve some of the problems of using line and bottom mounted arrays to localize cetaceans is
discussed. All but Chapters One and Six have been written and are presented as individual manuscripts to be published separately.

The Utility of Acoustics to Study Living Organisms

Lack of information on the behavior and distribution of a species can lead to inadequate ecosystem and wildlife management policies. Increased knowledge about the movement and temporal distribution of highly mobile pelagic predators has led to many improvements in management, including the protection of important breeding, resting, and foraging areas and the establishment of international management strategies. Among the many challenges to conservation is the fact that we lack basic knowledge about many of the world’s organisms. Studies have examined the risk factors that make species more likely to become endangered, such as habitat loss, invasive species, and pesticide exposure (Wilcove et al. 1998). However, if virtually nothing is known about habitat use and behavior, the status of a species can be almost impossible to determine. When species are cryptic¹ or in inaccessible areas, visual methods are not an efficient method of locating them. Organisms that exist in environments where vision is not a reliable method of locating each other commonly use other strategies. For example, forest birds use song to locate and communicate with each other, bats and cetaceans use clicks and calls, and dogs use chemical cues (Bradbury and Vehrencamp 2011). Even in the clearest water, visual distance is limited to hundreds of feet, compared to on land where it is often

¹ The Merriam-Webster Dictionary defines cryptic as “serving to conceal (cryptic coloration in animals).” The opposite of cryptic is “obvious.”
possible to see objects tens of miles away. As a result, underwater organisms often rely on senses other than vision to interact with their environment. Sound travels farther and faster underwater than it does in air (averaging 1530 m/s in water vs. approximately 340 m/s in air), and many marine organisms have come to use sound for crucial biological functions such as navigating, communicating, and foraging for food. Underwater sound is important to a wide variety of animals, from sea slugs (Nedelec et al. 2014) to dolphins (Au 1993). Juvenile fishes, lobsters, and crabs use reef sounds to orient themselves and find suitable habitat to settle and grow (Montgomery et al. 2006) Commercially important fishes, such as croakers (Ramcharitar et al. 2006) and groupers (Schärer et al. 2012) use sound to communicate during reproduction, and marine mammals share information and find food using calls and echolocation (Au and Hastings 2008).

Sound can also be used to gain information about animals that are hard to study visually. Sound is especially useful, since it can travel over long distances, is easy to record autonomously, and can give many clues about the behavior of the animals producing it. Acoustics can be used to get information about animals that are difficult to study visually, and that information can be used to improve management and conservation. These methods can be used in the study of multiple spatial scales, as well as used in conservation.

**Visual vs. Acoustic Survey Methods**

One fundamental aspect of ecology is the description of the processes that determine the distribution and abundance of organisms. Ideally, these descriptions would be based on accurate measures of population size and distribution over time. However, with cryptic species,
this can be extremely difficult to do visually. Cetaceans, for example, are mobile within three dimensions, and spend the majority of time underwater. For example, Barlow (Barlow 1999) estimated the visual detection probability of four of the longest diving whales (pygmy sperm whales (*Kogia* spp.) and beaked whales (*Mesoplodon* spp., *Ziphius cavirostris*, and *Berardius bairdii*)) between 0.35 and 0.95 percent. These low detection probabilities make visual searches for these species extremely inefficient. Acoustic methods can also increase the efficiency of line-transect surveys by increasing the strip width. One study that highlighted this increase in strip width examined distributions of the curassow (*Cracidae*), one of the most threatened birds of the neotropics. In the lowland wet forest, visual observations of these occur when the bird is about 10 m from the observer. In contrast, the booming vocalizations of these birds can be detected from more than 100 meters away. This increase in detectability leads to an increased transect strip width. In addition, the distribution of acoustically detected curassows within distance categories allowed robust distance-sampling detection function models, while the distribution of visually detected birds does not (Jimenez *et al.* 2003). Acoustic monitoring can also be useful for animals that are not often considered as cryptic, but which are difficult to survey visually because of a large range and the difficulty in surveying this range. African forest elephants in Kakum National Park and Assin Attandanso Forest Reserve range over 366 km². These elephants cannot be surveyed via airplane because of tree cover, but their low-frequency calls travel long distances. Thompson *et al.* (2010) used acoustic recorders to estimate elephant numbers using known calling rates. These estimations agreed with estimations from two other methods (dung counts and mark-recapture), and also gave information about the distribution of elephants through time. In this example, automated acoustic recorders also allowed data to
be recoded remotely without humans present. On land or underwater, acoustic methods can increase the effectiveness of survey methods, both in conjunction with visual surveys or where they are ineffective.

**Cetacean sound production**

When using sound to study cetaceans, it is important to have an understanding of the mechanisms used by the animals to produce those sounds. Odontocete sound production can be separated into two functional categories based on use, communication and echolocation (Cranford 2000). Clicks (short, impulsive, and broadband) are generally used for finding and capturing food, while calls and whistles are used for communication (Herman and Tavolga 1980). There are some exceptions to this rule, most notably sperm whales, which use sequences of clicks for communication (Watkins and Schevill 1977). For odontocetes, both clicks and whistles originate at a structure located in the forehead area known as the phonic lips. Air is pushed past the phonic lips, causing them to vibrate, much like the lips of a human playing a trumpet (Cranford et al. 1996). The vibrations from the phonic lips are transmitted and directed by the tissues in the animal’s head. The skull, the nasal air sacs, the connective tissue, and the melon all play an important role in focusing sound (Cranford 2000). Clicks are directed forward into a distinctive beam of sound (Au et al. 2008). Whistles and calls, which have been less well studied, are less directional than clicks, but still may convey directional information to conspecifics (Lammers and Au 2003, Branstetter et al. 2012). Humpback whale calls have also been shown to be directional (Au et al. 2006).
Cetacean Hearing

Differences in the physics of air and water have necessitated adaptations in the hearing mechanisms of animals that rely on underwater sound for biological function. Underwater sounds must have a pressure 61.5 dB higher in water than in air to have the same intensity for animals that hear in both air and water (Ketten 2000). The physics of sound in water are similar to those in body tissues (Reysenbach and Haan 1957), making the ear canal a poor route for underwater sound reception. Externally, cetaceans only possess a small external opening, and the ear canal is generally less than 3 mm in diameter and often completely blocked with waxy deposits (Ketten 2000). In odontocetes, sound travels through the tissues of the head to the ears, via either the acoustic fats in the lower jaw (Norris 1968, Brill et al. 1988, Brill et al. 2001, Cranford et al. 2008) or via other parts of the head (Mooney et al. 2008, Pacini 2011, Mooney et al. 2014). For mysticetes, the path of sound transmission may be via fat lobes near the ears (Yamato et al. 2012), or skull vibration (Cranford and Krysl 2015). The similarity in ear morphology between mysticetes whales and elephants suggests that they may be similarly capable of infrasound hearing through bone conduction (O’Connell et al. 1997). Estimates of the hearing of whales and dolphins are based on either audiometric data, recordings of phonations, or biometrics (Ketten 2000, Nachtigall et al. 2000, Tyack and Clark 2000). Audiometric data is generally collected through the use of auditory evoked potentials, which are very small electrical voltage potential recorded in response to an auditory stimulus. These can be recorded via electrodes placed directly in the brain (Johnson 1967), but are more commonly recorded from less invasive suction cup electrodes placed on the head (Pacini et al.)
Audiometric data is available for approximately 14 species of small odontocete, including the bottlenose dolphin *Tursiops truncatus*, Rough-toothed dolphin *Steno bredanensis*, beluga whale *Delphinapterus leucas*, killer whale *Orcinus orca*, false killer whale *Pseudorca crassidens*, Rissos’s dolphin *Grampus griseus*, and harbor porpoise *Phocoena phocoena* (Thomas *et al.* 1988, Popov and Klishin 1998, Klishin and Popov 1999, Szymanski *et al.* 1999, Nachtigall *et al.* 2000, Cook *et al.* 2005, Popov *et al.* 2007, Southall 2007, Houser and Moore 2014, Mooney *et al.* 2015), as well as for the Blainsville’s beaked whale (*Mesoplodon densirostris*, Pacini *et al.* 2011). Data suggest that odontocetes have a 10 to 12 octave functional hearing range and that most species have a maximum sensitivity above 30 kHz (Ketten 2000). However, some species can hear as high as 130 kHz (Supin and Popov 1990). These values are consistent with the peak frequencies of the signals these species produce (Ketten 2000). No audiograms have yet been collected for a mysticetes species. However, based on vocalizations, they are likely to have a hearing sensitivity with peak frequency spectra between 0.012 and 3 kHz (Ketten 1994, 1997, 2000). New estimations of humpback whale hearing are based on measurements of the basilar membrane of the inner ear (Houser *et al.* 2014), and are discussed further in Chapter Two.

**Cetacean Communication**

Although marine mammals produce sounds for use in foraging and navigation, the sounds discussed in this dissertation, odontocete whistles (Herman *et al.* 1980) and humpback calls (Payne and McVay 1971), are used for communication. Communication requires one animal to produce a signal, which the receiving animal then uses to make a decision about how
to respond (Bradbury and Vehrencamp 1998). Wilson (1976) defined animal communication as any exchange in which at least one of the participants benefitted from the information transfer. Using this definition, communication can also involve the detection of predators, and many prey species of killer whales have been shown to respond strongly to killer whale calls (Barrett-Lennard et al. 1996, Deecke et al. 2002, Wilson and Dill 2002, Cummings 2006). Most research on cetacean acoustic behavior has studied intraspecific communication, which includes contact calls and recognition signals, advertisements of fitness, and threats and fighting assessments (Tyack et al. 2000). Contact calls allow members of the group to maintain contact and reunite with each other, which is especially important for maintaining bonds between mothers and calves (Tyack 2012) and social bonds (Ford 1989, Weilgart and Whitehead 1997). Although many odontocetes use whistles for communication, many do not, including several species of porpoise (members of family Phocoenidae, as well as Phocoena phocoena and Phocoenoides dalli), the Commerson's dolphin Cephalorhynchus commersonii, Hector’s dolphin Cephalorhynchus hectori, pygmy sperm whale Kogia breviceps, and sperm whales Physeter macrocephalus (Au et al. 2008). The behavioral role for humpback song is not fully understood, but may act as a spacing mechanism (Tyack 1981, Helweg et al. 1992, Frankel et al. 1995). Chapter Five discusses a method that may be used to shed some light on the function of humpback song.
Species Life Histories

The research for this dissertation focuses on the calls and whistles of six different species of the order cetacea. One of these species, *Megaptera novaeangliae* is from the sub-order Mysticeti and the family Balaenopteridae, while the remaining six species (*Globicephala melas, Pseudorca crassidens, Stenella longirostris, Stenella coeruleoalba, Stenella attenuata, Steno bredanensis, and Tursiops truncatus*) are from the sub-order Odontoceti and belong to the family Delphinidae. *Globicephala melas* and *Pseudorca crassidens* also belong to the sub-family Globicephalinae (LeDuc *et al.* 1999).

All cetaceans have a relatively long life span, ranging from twenty to more than one hundred years in some cases. The southern resident killer whale J2 is estimated to be 103 years old. All cetaceans give birth in the water, generally to one offspring after relatively long gestational period of between eight months and one year. Newborn marine mammals are precocial, and are able to swim almost immediately following birth (McBride and Kritzler 1951). While some species breed seasonally (Chittleborough 1958), tropical species often breed year-round (Whitehead and Mann 2000). The life histories of the five species of odontocete listed above are presented in the following paragraphs. Chapter Three will further discuss their distribution and feeding ecology in Hawaii. The life history of humpback whales *Megaptera novaeangliae* is included as part of Chapter Two.
Short-Finned Pilot Whale *Globicephala macrorhynchus* (Gray, 1846)

Adult short-finned pilot whales can be up to 5.5 m long (for females) and 7.2 m long (for males) and can weigh up to 3600 kg. Males also have a more bulbous head shape, which can often appear to be square, as well as a large, falcate dorsal fin. Pilot whales are highly social, and are occasionally seen in groups of several hundred. This may contribute to frequent mass strandings. Current estimates of distribution in Hawaii is summarized in Figure 1.1. They have been known to live to at least sixty-three years (Jefferson *et al*. 2008). Studies of the stomach contents of stranded animals show that they eat both squid and mesopelagic fish (Seagars and Henderson 1985). Females become sexually mature at eight to nine years old, and males at thirteen to seventeen (Benirschke and Marsh 1984). Audiograms of stranded and recovered pilot whale showed that the best hearing for this species is between 11.2 and 50 kHz, with maximum sensitivity at 40 kHz (Pacini *et al*. 2010). The International Union for Conservation of Nature (IUCN) last categorized this species as data deficient in 2011.

![Figure 1.1: Current estimate of biologically important area for *Globicephala macrorhynchus* based on photo-ID, vessel-based survey data, satellite tag data, and expert judgement. From Baird *et al*. (2015).](image)
False Killer Whale *Pseudorca crassidens* (Owen, 1846)

Along with pilot, killer, pygmy killer, and melon-headed whales, the false killer whale is commonly referred to as a blackfish. They are long and slender (6 m for males and 5 m for females, weighing up to 907 kg). They are typically found in groups of 10-60 animals. Both males and females reach sexual maturity at about eight to fourteen years. They eat large fish, and have been photographed preying on mahi mahi and tuna (Baird 2002). Current estimates of distribution in Hawaii is summarized in Figure 1.2. Audiograms obtained through evoked auditory potential indicate that this species is most sensitive to sound frequencies between 16 and 22.5 kHz, with a peak sensitivity that has been measured at 22.5 kHz (Yuen *et al.* 2005). However, this animal was has demonstrated high frequency hearing loss, and other measurements have included highest sensitivity between 16 and 64 kHz (Thomas *et al.* 1988). False killer whales were categorized as data deficient by the IUCN in 2008.

*Figure 1.2:* Current estimate of biologically important area for *Pseudorca crassidens* in the main Hawaiian Islands based on vessel-based survey data, satellite tag data, genetic analysis, photo-id data, and expert judgement. From Baird *et al.* (2015).
**Spinner Dolphin *Stenella longirostris* (Gray, 1828)**

Spinner dolphins occur throughout the world in subtropical and tropical oceans and along coasts. In addition to four known subspecies, the Hawaiian spinner dolphin is recognized as a race (Perrin 1975). Research on Spinner dolphins dates back to the 1960s, when William Perrin first estimated that approximately 250,000 dolphins were being killed as bycatch in the tuna fisheries of the eastern tropical pacific (Perrin 1969). They have small, slender bodies typically 1.39-2.04 m long and 55-65 kg for females and 1.6-2.08 long and 66-75 kg for males (Norris *et al.* 1994). The Latin name *longirostris* refers to their long, thin beak. Males reach sexual maturity at nine to twelve years, while females reach it at about four to seven years with a gestation length of 10.6 months (Perrin *et al.* 1977, Jefferson *et al.* 2008). The common name of the spinner dolphin refers to their frequent behavior of leaping up to three meters high and spinning as many as seven times before splashing back into the water (Hester *et al.* 1963, Norris *et al.* 1994). Spinner dolphins typically spend the daytime resting in shallow, sandy bays, before moving offshore in the afternoon, where at dusk and dawn they will feed on small mesopelagic fish, squid, and shrimp (Jefferson *et al.* 2008). In Hawaii, they follow the mesopelagic boundary community as it rises and migrates onshore through the night (Benoit-Bird and Au 2003).

Current estimates of distribution in Hawaii is summarized in Figure 1.3. Hearing measurements are not currently available in the published literature for this species, although evoked auditory potentials have apparently been measured for a stranded individual (Mann *et al.* 2010).

*Stenella longirostris* was categorized as data deficient by the IUCN in 2012.
Figure 1.3: Current estimate of biologically important area for *Stenella longirostrus* in the main Hawaiian Islands based on vessel-based survey data, genetic analysis, and expert judgement. From Baird *et al.* (2015).

**Striped Dolphin *Stenella coeruleoalba* (Meyen, 1846)**

The striped dolphin has a shorter beak than the spinner dolphin, as well as distinctive dark gray stripes originating from the beak and runs the length of the body. Striped dolphins can be as long as 2.56 m, with a maximum weight of 156 kg. Males are somewhat larger than females. Sexual maturity occurs between ages seven to fifteen for males and five to thirteen for females. Gestation lasts twelve to thirteen months, and individuals of this species may live as many as fifty-eight years. *Stenella coeruleoalba* is widely distributed through the Indian, Pacific, and Atlantic oceans (Jefferson *et al.* 2008). Striped dolphins are a deep-water species that is seen rarely in Hawaii, although they have documented by Baird (2013) off the Kona coast of the Big Island of Hawaii (Figure 1.4). This species preys on many types of small fish, from the midwater to the benthopelagic. Striped dolphins may be able to dive to depths of 200-700 m.
Current estimates of distribution in Hawaii is summarized in Figure 1.4. Striped dolphins can hear frequencies ranging from 0.5 to 160 kHz, with a maximum sensitivity at 64 kHz and a range of maximum sensitivity between 29 to 123 kHz (Kastelein et al. 2003). *Stenella coeruleoalba* was categorized as least concern by the IUCN in 2008.

**Figure 1.4:** Distribution of several species, including *Stenella coeruleoalba*, from 13 years of small boat effort, with effort tracklines in gray and the 1,000 and 2,000 m depth contours (black dashed lines).

From Baird et al. (2013).
Pantropical spotted dolphin *Stenella attenuata attenuata* (Gray, 1846)

At birth, pantropical spotted dolphins are dark gray with white bellies, and develop spots as they mature to adulthood. The amount of spotting for offshore spotted dolphins *S. a. attenuata* is sometimes nonexistent, especially in comparison with coastal *S. a graffmani*. They range in size from 1.6 to 2.4 m for females and 1.6 to 2.6 m for males, with a maximum recorded weight of 119 kg. *Stenella attenuata* are distributed throughout the offshore coastal zones of the Pacific, Atlantic, and Indian oceans. Current estimates of distribution in Hawaii is summarized in Figure 1.5. Sexual maturity for females is reached at age 9 to eleven in females and twelve to fifteen in males. Gestation takes about 11.5 months, with a two to three year gap between calves. This species breeds year-round (Jefferson *et al.* 2008). Prey is generally squid and mesopelagic and epipelagic fish (Wang *et al.* 2003). Hearing measurements are not currently available in the published literature for this species, although evoked auditory potentials have been measured for an individual stranded Atlantic Spotted dolphin *Stenella frontalis* (Mann *et al.* 2010). *Stenella attenuata* was categorized as least concern by the IUCN in 2012.
Rough-toothed dolphin *Steno bredanensis* (Cuvier, 1828)

The rough-toothed dolphin looks almost like a modern ichthyosaur, with its long beak and conical head shape. Individuals of this species are generally dark gray, with a white or pinkish belly, and are often highly scarred with scratches and cookie cutter shark bites. Adult *Stenos* are about 2.65 m long, and weight up to 155 kg. Females are slightly larger than males (Jefferson et al. 2008). Very little is known about reproduction in this species, but estimated sexual maturity for males has been estimated at fourteen years for males and ten years for females (Sakai et al. 2011). Rough toothed dolphins prey on both cephalopods and fish, including mahi mahi (Pitman and Stinchcomb 2002). Current estimates of distribution in Hawaii is summarized in Figure 1.6. Auditory evoked potential measurements of live-stranded rough toothed dolphins resulted in potential hearing thresholds between 5 and 80 kHz (Cook et al. 2005). *Steno bredanensis* was categorized as least concern by the IUCN in 2012.
Bottlenose dolphin *Tursiops truncatus* (Montagu, 1821)

Of all cetacean species, the bottlenose dolphin is one of the most thoroughly studied, both in captivity and in the wild. The offshore ecotype is larger and more robust than the smaller Atlantic coastal ecotype. It is a dark gray, with a lighter belly. When fully grown, they range from 1.9 to 3.8 m long, with a maximum weight of about 650 kg. Females are slightly smaller than males. Males live to forty to forty-five years of age and females to more than fifty years. Females are reproductively mature at five to thirteen years, and males at nine to thirteen years (Jefferson *et al.* 2008). Gestation lasts about twelve months, and calves stay with their mothers for one and a half to two years (Cornell *et al.* 1987, Jefferson *et al.* 2008). Bottlenose dolphins feed opportunistically on many types of prey, including fish, squid, crustaceans, and
shrimp (Wells and Scott 1999). Current estimates of distribution in Hawaii is summarized in Figure 1.7. The hearing of bottlenose dolphins is probably the best studied of all cetaceans, with the first behavioral audiograms dating back to Johnson (1967) and indicated a maximum sensitivity near 50 kHz and a maximum sensitivity range between 15 and 110 kHz. More recent studies involving multiple animals have collected auditory evoked potentials that indicate a hearing range between 8 and 152 kHz, with the best sensitivity at 45 kHz (Popov et al. 2007). *Tursiops truncatus* was categorized as least concern by the IUCN in 2012.

![Figure 1.7](image)

**Figure 1.7:** Current estimate of biologically important area for *Tursiops truncatus* in the main Hawaiian Islands based on vessel-based survey data, satellite tag data, genetic analysis, photo-id data, and expert judgement. This species has also been found west of Kauai. From Baird et al. (2015).
Implications for Anthropogenic Impacts

One of the many contentious anthropogenic impacts facing management of the species listed above is the issue of mid-frequency navy sonar. Known frequency and source levels for these sound sources span from 0.1 to 8.2 kHz and 229 to 299 dB (Dolman 2008). These source levels are well within the range currently believed to cause temporary threshold shift (Fritts and Rodda 1998) and permanent threshold shift (PTS) in cetaceans (Southall 2007). TTS results in a temporary loss of hearing, while PTS results in total loss of hearing at some range of frequencies. Studies of TTS have been performed in two species of small odontocetes: the bottlenose dolphin and beluga whale (Nachtigall et al. 2003, Mooney et al. 2009, Finneran and Schlundt 2010, Popov et al. 2011), but TTS for mysticetes has not been experimentally demonstrated. However, mysticetes are the most likely to be impacted by low frequency sound exposure (Ketten 2004). Marine mammals rely heavily on sound for communication and foraging, and sudden or gradual hearing loss may adversely affect behavior and physiology (Richardson 1995). Near shore mid-frequency sonar activity has been associated with mass strandings and non-stranding mortalities of beaked whales and other cetaceans (Parsons et al. 2008). As concern over the effects of noise on marine mammals has increased, several lawsuits have been brought against the US Navy to prevent or mitigate their use of sonar. The National Resources Defense Council (NRDC) has filed several suits to this effect (2003, 2007, 2008b). In Hawaii, federal court injunctions in 2008 and 2015 required additional mitigation during Undersea Warfare Exercises (USWEX) around the Hawaiian Islands (2008a, 2015). These suits and the various mitigation measures represent a considerable monetary and public relations cost to the US Navy, resulting in a search for more accurate and cost effect methods of
mitigation. The U.S. Navy currently uses three main strategies for avoiding impact on marine mammals: 1) spatial or temporal avoidance; 2) changes in procedure such as “ramp up” of sonar source level over time; and 3) monitoring for marine mammals at the surface (Dolman 2008).

During the 2006 Rim of the Pacific (RIMPAC) exercises, the Navy attempted to mitigate sonar impacts in space by banning active sonar within 25 km of the 200 m isobaths surrounding the islands. The exceptions to this ban were three “chokepoint” exercises that occurred in the deep-water channels between islands (Dolman 2008). It is possible that at least one of these chokepoint exercises occurred in the Kaiwi, Alenuihāhā, or Kaʻieʻieʻiewaho Channels, which separate Oahu and Molokai, Maui and the Big Island of Hawaii, and Oahu and Kauai, respectively. The US Navy National Defense Exemption defines areas with rapid depth changes, channels and embayments, and surface ducts as areas of increased risk to beaked whales (Dolman 2008). The Alenuihāhā and Kaʻieʻieʻiewaho clearly meet some of these criteria. Since these channels are used for active sonar exercises, more detailed information on the distribution of sensitive species through space and time would be helpful to mitigate risk of anthropogenic noise.

**Anthropogenic Noise from Commercial Ships**

Chapters Two and Three of this dissertation discuss the use of an acoustic survey method for collecting distribution data on cetaceans in difficult to access areas of the ocean by using commercial shipping as a platform of opportunity. Incidental noise from shipping is the
most pervasive source of chronic ocean noise, although other sources, such as sonar, oil and gas exploration, are very noisy over shorter time periods (Arveson and Vendittis 2000, Wittekind 2014). Therefore, it is important to consider the impacts of these potential research platforms on the acoustic environment and on cetaceans specifically. The issue of shipping noise is discussed in greater detail in Chapter Four, where sound measurements are made for an exceptionally quiet ship. For the purposes of this dissertation, anthropogenic noise is categorized into two main types based on their duration and intensity: short duration but high amplitude, which will be referred to as “acute,” and long duration of low amplitude, which will be referred to as “chronic.” Acute noises occur over a period of seconds to months, and include activities such as underwater explosions, sonar, and construction. Chronic noises occur over a much longer time scale, over the span of years and decades. As the number of individual ships rises, so does the cumulative level of underwater sound, which has been doubling every decade since the 1960s in some locations (McDonald et al. 2006). Most noise from shipping is low-frequency sound between 20 and 200 Hz and low frequency sound travels farther than high-frequency sound in both water and air. Because low-frequency sounds can spread long distances, the impacts of shipping noise are not localized to a particular region, or to the area in which a particular vessel is traveling. Instead, low frequency sounds can spread over long distances; even crossing entire oceans. The result of this spread is an ocean-basin scale increase of ocean noise, even in the deep seas. (Andrew 2002, McDonald et al. 2006, Jensen et al. 2009). Ships can also produce substantial noise at higher frequency, affecting an even wider range of marine biota at closer range (Hermannsen et al. 2014).
The majority of underwater noise from commercial ships comes from propeller cavitation. Propeller cavitation occurs when a propeller spins quickly enough that the pressure on the water near the leading edge of the propeller blade gets so low that the water vaporizes, forming a bubble of gas. As the bubble moves past the propeller, the water pressure increases back to normal, and the bubble implodes upon itself with an audible snap (Brennen 2013). Like the sound of many clapping hands accumulating to create applause, the combined sound of thousands of collapsing bubbles is very noisy. In addition, the force from these implosions can eventually eat into nearby ship surfaces, especially the propeller itself, causing pitting and necessitating expensive repairs (Blake and Gibson 1987). Propeller cavitation does not occur until vessels reach a certain speed (called the “cavitation inception speed”). Some vessels, such as scientific research vessels, have been specifically designed to cavitate at a higher speed, which means they can go faster before becoming noisy due to cavitation (Bahtiarian and Fischer 2006). This modified scientific research vessel has been designed specifically to avoid producing sound in the sensitivity range of fish during NOAA stock assessment surveys, but also reduces noise in the estimated hearing range of large mysticetes whales (Ketten 2000, Houser et al. 2001, Houser et al. 2014).

Background noise has an obscuring effect on biological sound; as the amplitude of noise increases, it reduces the distance over which other sounds can be used for basic life functions, and, if loud enough, will conceal those sounds completely. This disruption of hearing through interference of background noise is called “masking,” because of the way noise obscures biological signals. Increasing levels of noise in the ocean have correlated with many marine animals producing louder or higher frequency calls (Scheifele et al. 2005, Miksis-Olds 2006,
Parks et al. 2007). These changes have been hypothesized to be associated with biological costs, including reduced sound transmission distances, and the possibility of additional risk of predation, greater energy use, and loss of information (Wale et al. 2013, Read and Jones 2014, Simpson et al. 2015). Reduced transmission distances mean that animals must be closer together to communicate about the location of food, predators, or each other. Having to make louder noises to be heard over the ambient ocean noise may increase predator ability to find prey animals, thereby reducing prey population sizes. Some researchers argued that expending a greater amount of energy to make sounds means less energy is available for other activities, such as growth and reproduction (Weilgart 2007), while others conclude that the energetic cost of sound production is negligible in comparison to the high metabolic rate of cetaceans (Jensen et al. 2012). Studies with terrestrial mammals have shown that vital information about age, health, and fitness can be conveyed via acoustic signals (Bradbury et al. 1998, Reby and McComb 2003, Fischer et al. 2004, Hardouin et al. 2007, Charlton et al. 2009, Taylor et al. 2010, Charlton et al. 2011). The inability to pass on the correct information about where food or other animals are located can therefore have harmful consequences (Lusseau et al. 2009, Barber et al. 2010, Hatch et al. 2012). Noise can also have health impacts on animals, increasing their levels of stress hormones and possibly decreasing their long-term survival (Rolland et al. 2012). With multiple pressures (e.g. ocean warming, acidification, and pollution) already affecting ocean organisms, chronic ocean noise may add to the stress load on these organisms, and may decrease their resiliency to other (more difficult to mitigate) pressures.

Policy changes to address increasing underwater noise have begun to occur in the U.S. and internationally. NOAA has held meetings discussing the impact of shipping noise on marine
mammals since 2004. In 2010, Dr. Jane Lubchenco (then Administrator of NOAA and Under Secretary of Commerce for Oceans and Atmosphere), wrote a memorandum to the President’s Council on Environmental Quality stressing concern for the impact of underwater sound on marine mammals, and committing the agency to improve mitigation by, in part, developing a plan for estimating sound budgets and establishing a baseline level of sound in the oceans. As a result, NOAA convened two working groups in 2011 to map underwater sound fields and cetacean distribution and density throughout the U.S. territorial sea and exclusive economic zone and to identify biologically important habitat. Their products, which continue to be expanded and improved, have been made available via the Internet to regulators and the public, and in 2014 an international workshop was held to build capacity for similar efforts in other regions. As of 2015, the White House Office of Science and Technology Policy’s Subcommittee on Ocean Science and Technology’s has formed a Task force on Ocean Noise and Marine Life to improve agency coordination regarding management of ocean noise and filling data gaps.

Outside the U.S., the European Union's Marine Strategy Framework Directive, which aims to protect the resource base upon which marine-related economic and social activities depend, includes the acknowledgement that “chronic exposure to noise can permanently impair important biological functions and may lead to consequences that are as severe as those induced by acute exposure” (Tasker et al. 2010). Additionally, noise-related resolutions and statements of concern have been issued by various international groups, including the United Nations (UN), the European Parliament, the International Council for the Exploration of the Sea (ICES), the Convention on Biological Diversity (CBD), and the International Whaling Commission
(IWC). International agreements containing specific language limiting underwater noise include the UN Convention on the Law of the Sea (UNCLOS), the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic (ACCOBAMS), and the Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS). The latter three intergovernmental bodies, together with the Convention on Migratory Species (CMS), have formed an ocean noise-working group to, among other efforts, begin implementing regional noise management plans.

In April 2014, the International Maritime Organization (IMO), the specialized United Nations agency responsible for the safety and security of shipping and the prevention of marine pollution by ships, released voluntary guidelines (IMO 2014) for underwater noise recommending the use of new standards for measuring underwater noise (ISO 2012). Beyond governmental entities, the commercial shipping industry is also becoming increasingly aware of and concerned about this issue, as evidenced by the long involvement of the Chamber of Shipping of America in domestic and international ocean noise policy formulation. Multiple ship classification societies, such as Det Norske Veritas and RINA, have begun offering a quiet ship certification; and at least one prominent green certification company, Green Marine, has begun developing noise performance indicators for ports, shipping lines, and other industry partners.
Methods for Measuring Underwater Ship Noise

There are three main methods for measuring underwater noise from ships. These methods fall into two central categories: measurements of ships in very controlled situations and measurements of ships at sea. First, controlled measurements of ship noise are made at ship modeling basins, which are physical basins or tanks used to carry out hydrodynamic tests with ship models (Wittekind 2014). This method allows for extremely accurate measurements of noise, under precisely controlled conditions for water temperature, salinity, and sound speed. However, this method can also be costly, time-consuming, and only allows measurements under specific conditions. Measurements in the modeling basin are limited to flow and propeller noise, since the model basins do not hold full-scale ships with all associated machinery. Any such measurements are scaled approximations of the real ship that are not directly applicable to real ships. Underwater noise measurements made at sea can occur under more realistic conditions, but the environment in which the measurements are taken is much less controlled. In the open ocean, density differences in water at different depths can change the path of sound (Jensen 1994). Thus, to obtain an accurate measurement of the source level of a sound, it is necessary to have current accurate measures of temperature and salinity at depth. Two main methods have been used to measure ship noise at sea; an opportunistic and a directed field measurement. The first, opportunistic, method determines the location of moving ships using the Automatic Identification System (AIS), a publicly available automatic GPS tracking system used on civilian ships and by vessel traffic services. At the same time as they are tracked, underwater sound from these ships is recorded using an underwater hydrophone.
that is mounted to the ocean floor or to a buoy. Estimated source levels of the ship can be calculated using the known location from AIS and the sound recording (McKenna et al. 2012, McKenna et al. 2013). This method allows for data collection on many ships traveling under a range of speeds and conditions, and also can be performed while ships are underway. However, there is a large degree of inaccuracy associated with the limits in accuracy for positional GPS and the need to add in measurements of sound speed. This inaccuracy can be mitigated if GPS locations are averaged over many measurements, but obtaining multiple measurements requires cooperation from the shipping company, and obtaining this cooperation can be difficult, as is further discussed below. The 2008 underwater sound measurements of a ship outlined in Chapter Four have these same inaccuracies, although location data was collected via onboard ship GPS rather than AIS. A second method, which was originally standardized by the Acoustical Society of America and the American National Standards Institute (ANSI/ASA 2009) has been adopted by the International Standards Institute (ISO 2012), requires that ships maneuver on a specific course relative to an underwater hydrophone array at specific speeds and ship machinery conditions. This method is easier to standardize for comparison of multiple ships, but is somewhat limited by its requirement that measurement of ship noise interrupt regular sailing schedules. Commercial ships that are not actively moving goods incur the loss of unused capital, which is one reason why shipping companies minimize time spent idle in port (Strandenes 2004, Hummels 2007). Although collecting ship noise measurements using the ISO standard is ideal, obtaining voluntary cooperation from shipping companies is difficult in light of the time and costs incurred. Due to the reluctance of commercial shipping entities to incur these costs, opportunistic ship noise measurements will continue to be an important, although
potentially flawed, method of estimating the noise from individual ships. One possible solution to this problem would be to investigate the magnitude of error between the opportunistic and directed field measurement standards and to incorporate this error into opportunistic ship noise measurements.

Objective of this dissertation

The objectives of this dissertation are to:

1. Test two novel methods of collecting acoustic data on sounds produced by cetaceans:
   a. A method using commercial ships as vessels of opportunity to collect acoustic data on transects between the main Hawaiian Islands.
   b. A method using DIFAR to concurrently localize multiple humpback whales.

2. Examine how the distributional data collected via one of these methods relates to current knowledge on the temporal and spatial distribution of cetacean species in Hawaii.

3. Examine the relationship between distributional the remotely sensed oceanographic data for cetacean locations and the remotely sensed oceanographic data for the entire survey.

4. Examine the ecological and conservation impacts of using commercial ships as an opportunistic research platform, using a case study as an example.
Works Cited


"Odontocete cetaceans around the main hawaiian islands: Habitat use and relative abundance from small-boat sighting surveys." *Aquatic Mammals* 39 (3):253-269.


32


IMO, I.M.O. 2014. Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life. In *MEPC.1/Circ.833*.


group 11 report underwater noise and other forms of energy." European Commission
Joint Research Centre/ICES Report EUR 24341.


wildlife abundance: Methodology for vocal mammals in forested habitats." African

Tyack, P. 1981. "Interactions between singing hawaiian humpback whales and conspecifics

10." The bottlenose dolphin:199.

whales." In Hearing by whales and dolphins, 156-224. Springer.

Wale, M.A., S.D. Simpson, and A.N. Radford. 2013. "Noise negatively affects foraging and

spotted dolphin, stenella attenuata, off the eastern coast of taiwan." ZOOLOGICAL


CHAPTER 2. A NOVEL METHOD FOR A WELL-KNOWN SPECIES: DISTRIBUTION AND RELATIVE ABUNDANCE OF HUMPBACK WHALES IN THE MAIN HAWAIIAN ISLANDS

Introduction

As human populations grow, anthropogenic impacts on the natural world grow with them. Baseline data is necessary to detect long-term changes in the natural environment, but maintaining long-term datasets also requires long-term commitments of resources. This is especially true for research on pelagic marine organisms. Total operating costs for research vessels managed by the University-National Oceanographic Laboratory System (UNOLS), the National Oceanographic and Atmospheric Administration (NOAA), and the National Science Foundation increased by nearly $100 million between 2002 and 2012 without a concurrent increase in the budgets of these agencies. Much of this increase is related to rising fuel prices; when fuel costs exceed the Office of Management and Budget’s prescribed fuel rate, agencies offset the costs by reducing days at sea (NOC 2013). With the current cost of a single day at sea for a UNOLS or NOAA ocean class ship at between thirty and forty thousand dollars (NOAA 2011), testing and standardizing alternative methods of collecting data at sea is becoming more critical. These alternative methods range from collecting oceanographic and biologic data from autonomous underwater vehicles and tagged marine mammals to using small boats and vessels of opportunity (Williams 2003, Fedak 2004, Wiggins et al. 2010, Block et al. 2011).

Visual cetacean surveys can be costly in terms of time and personnel, must be done during the daytime, are dependent on good weather, and do not work well for species that surface infrequently (Kinsey et al. 2000, Marques 2001). Many gaps in survey effort still exist;
only 25 percent of the oceans have been surveyed for cetacean abundance using visual line-transect methods, with an average of just 10% of a species predicted range covered by at least one survey (Kaschner et al. 2012). As recently as 2008, 38% of marine mammal species were considered to be data deficient (Schipper et al. 2008). The difficulties in surveying cetaceans means that declines that should result in a vulnerable listing may go undetected at least 70% of the time (Taylor et al. 2007). The difficulty of visual cetacean surveys has led to an increasing interest in the use of passive acoustic monitoring. For some species, especially those that are cryptic or with long dive times, acoustic detection rates are higher than or comparable to visual detection rates (Clark 1997, Akamatsu et al. 2001, Swartz et al. 2003). Barlow and Taylor (2005) were able to detect seven times more sperm whales with acoustic than visual methods.

Acoustic methods have been used multiple times to estimate distribution through space and time. Distribution and relative abundance of striped dolphins (Gordon 2000) and both a seasonal difference in acoustic encounter rate and a clustering of the whales around geographic features were found using acoustic methods (Oleson et al. 2007). Seasonal trends in humpback whale chorusing sounds agreed with known breeding periods (Au et al. 2000). Stationary hydrophones in the northwest Hawaiian Islands have revealed previously unknown distributions of humpback whales (Lammers et al. 2011) and show inshore movements of spinner dolphins corresponding to known diurnal behavior (Lammers et al. 2008). Acoustic methods, which work best for species that vocalize frequently, can be used autonomously, at night, and in poor visual conditions (Mellinger et al. 2007). Most long-term acoustic monitoring of cetaceans up to this point has been conducted using fixed passive acoustic recorders.

Since before Charles Darwin collected data from the HMS Beagle (1831-1836), scientists have used vessels of opportunity to collect biological data. Vessels and platforms of opportunity (VO/PO) allow the collection of data concurrently with commercial or other activities. Cetacean visual sighting and effort data has been collected from sailing, Coast Guard, fishing, shipping, and whale watching vessels (Consiglieri and Bouchet 1981, Brereton et al. 2000, Monestiez et al. 2006, Williams et al. 2006). Even without the use of traditional line-transect methods, opportunistic data can yield useful information on species distribution at a low cost (Evans and Hammond 2004). One of the longest running marine biology surveys from a platform of opportunity is the Continuous Plankton Recorder (CPR) program, which began collecting data in 1931. Weather, navy, hydrographic and research ships, ferries, and commercial ships from more than 30 nations have towed the CPR from a cable or rope as they transited the ocean (Reid et al. 2003). Of these, the most numerous are commercial vessels, the number of which have more than tripled over the past fifty years (Frisk 2012). Commercial routes not only cross the oceans thousands of times per year, but they cover areas of the oceans not normally covered by visual line transect surveys (Figure 2.1, Kaschner et al. 2012, Tournadre 2014). If only a fraction of these ships were used to collect biological data, it would still represent an important increase in information on distribution and relative abundance of data poor cetacean species.
In addition to directly determining distribution through surveys, there has been an effort to increase the use of habitat modeling to predict the distribution of cetaceans. The distribution of apex predators, such as cetaceans, is frequently correlated with habitat variables (Schneider and Piatt 1986, Piatt 1992). The variables used to characterize habitat generally include satellite-derived ocean surface (temperature, salinity, chlorophyll) and oceanographic (upwelling, fronts, eddies) data (Redfern et al. 2006). Habitat modeling is currently being used for identifying habitat of humpback whales, both in Hawaii and elsewhere in the Pacific (Gregr and Trites 2001, Johnston et al. 2007). Habitat modeling requires information on the relationship between species distribution and environmental variables, which is noticeably lacking for data-poor species.

This survey was designed primarily to test a new method of collecting multi-season distribution data for marine mammals with an autonomous acoustic recorder towed from vessels of opportunity. To assess the success of this method in comparison to traditional survey
methods, we examined the distribution of a relatively well-known species and the relation of this distribution to environmental variables. Humpback whales (*Megaptera novaeangliae*) are one of the most well-studied cetacean species in the Hawaiian Archipelago, with focused research on distribution dating back to the 1970s (Herman and Antinoja 1977, Wolman and Jurasz 1977). In 2008, the International Union for the Conservation of Nature listed the status of this species as of least concern, and noted that they are better studied than other balaenopterid species (Reilly *et al.* 2008). Humpback whales migrate seasonally to Hawaii, with peak abundance from February through March (Mobley *et al.* 1999), although they are known to be present from September through June (Thompson and Friedl 1982). Their distribution in the main Hawaiian Islands correlates with the shallow banks near islands, with most animals found in depths of less than 182 m (Mobley *et al.* 1999). Humpback whales also occur in the deep channels between the islands (Mate *et al.* 1998b, Cerchio *et al.* 1999), where they have been recorded singing (Frankel *et al.* 1995). Adult humpback whales are 11-17 m long, and weigh at least 40000 kg. Females are 1-1.5 m longer than males (Jefferson *et al.* 2008). Female humpbacks reach sexual maturity at about 5-7 years (Clapham 1992), and gestation lasts for approximately twelve months (Chittleborough 1958). Humpbacks migrate from breeding areas in Hawaii and the tropics to temperate and polar summer feeding areas (Jefferson *et al.* 2008). On the breeding grounds, male humpback whales engage in physical competition for females (Tyack and Whitehead 1983). In an additional breeding display, they produce sequences of calls (units) occurring in a regular sequence and patterned in time, which is called song (Clark 1990). Each song can last from five to twenty minutes, and song sessions can last for hours (Payne and McVay 1971). When multiple whales sing at once, as occurs throughout the breeding season,
this is called chorusing. The source level varies between units of a song, with values ranging from 151 to 173 dB re 1 µPa and frequencies ranging from a base of 200 Hz to harmonics of up to 24 kHz (Au et al. 2006). Singing peaks during the winter at the breeding grounds (Thompson et al. 1982, Au et al. 2000), but can also occur during migrations and in the northern feeding grounds (Mattila et al. 1987, McSweeney et al. 1989, Clapham and Mattila 1990, Brown et al. 1995). There is also a diurnal pattern to song, with more song occurring at night (Au et al. 2000). Males generally sing solitarily, although they often have a companion male or female (sometimes with an accompanying calf). Singers can be either stationary, with their head downward and their tail 7-15 m below the surface, or traveling (Tyack 1981, Darling et al. 1983, Baker 1984, Frankel et al. 1995, Darling and Berube 2001). No direct measurements of hearing (audiograms) have been collected from humpback whales to date because of the difficulty of accessing and administering a hearing test on a large marine mammal. Modeling of humpbacked whale hearing based on the basilar membrane predicts that their region of best hearing ranges from 700 Hz to 10 kHz, and they are most sensitive to frequencies from 2-6 kHz (Ketten 2000, Houser et al. 2001). Other methods, such as behavioral responses to sounds, body size, frequency range of sound produced and ambient noise levels, have also been used to estimate that mysticetes are probably most sensitive to sound from 10 Hz to approximately 10 kHz (Richardson 1995, Wartzok and Ketten 1999, Erbe 2002, Clark and Ellison 2004). In this text, a new study method using vessels of opportunity to collect marine mammal acoustic data will be tested and the results for temporal and spatial distribution from acoustic surveys conducted from a platform of opportunity will be discussed in comparison with the results of previous research and in the context of current knowledge of humpback whales in Hawaii. The objective
of this study is to determine whether this is a viable method to collect data on marine mammal
distribution for data poor species in poorly surveyed areas for possible use in management and
habitat modeling.

Methods

Data Collection

In order to test the objectives of this study, acoustic surveys were conducted using
barges of Young Brothers, the largest inter-island shipping company in Hawaii. This was
carried out concurrently with another study, the methods of which are in Chapter 3 of this
thesis. The shipping barges have a length of approximately 35 ft., and are towed on
approximately 500 m of metal cable by a tugboat. The barges leave Honolulu approximately
twice per week to three locations: Kawaihae on the Big Island of Hawaii, Nawilili on Kauai, and
Hilo on the Big Island (Figure 2.2).
Figure 2.2: Map of Young Brothers routes (shown in black) used to collect data for this survey. Channels of interest are labeled. Annual average offshore wind speed was modeled by the National Renewable Energy Laboratory at a height of 90 m and out to 50 nmi from shore (Schwartz et al. 2010). Average wind speed ranges from Beaufort Wind Scale (BF) 2 to 6. White areas indicate no data. Much of the marine mammal research in Hawaii has taken place in low wind areas to the west of the islands, indicated in blue above. A funnel effect between the islands results in especially high wind speeds in the Alenuihaha, Kalohi, and Pailolo channels (Chavanne et al. 2002).

The trip to Nawiliwili takes approximately 14 hours, and the trips to the Kawaihae take approximately 20 hours. In an average week, there are four trips for each route, two at night and two during the day. This survey used two of these routes: from Honolulu to Nawiliwili and Honolulu to Kawaihae, in order to cover all the deep water channels between the Hawaiian
Islands as well as for the practical reason of limiting equipment to the deeper harbors, where it was less likely to be damaged (Figure 2.4). Transects were conducted approximately every two weeks as ship availability allowed. The recording equipment for this project included a modified EAR (Lammers et al. 2008). The EAR is normally used as a stationary recorder, with the batteries, electronics, and hydrophones contained within one cylindrical unit (Figure 2.3).

![Figure 2.3: A stationary EAR resting on the ocean floor near coral.](image)

For these surveys, the electronics, batteries, and recording gear of the EAR were housed in a waterproof Pelican™ case on the deck of the barge, with an extended cable leading to the hydrophone at the end of the cable, which extended behind the barge into the water. The towline for the hydrophone could not be longer than 9 m, to avoid damage to the acoustic equipment. Harbor depth is 6 m and all towed equipment had to be lowered into the water within the harbor, because no crew was allowed on the barge during the channel crossings for safety reasons. The two-towfish system maximized the depth of the hydrophone while keeping the equipment light enough to be deployed by a single person and significantly reduced periodic broadband surface noise compared to a single towfish system or a weighted hydrophone (Figure 2.4).
Figure 2.4: Schematic of towfish depth at zero and underway (above 4 mph). The shallow towfish (A) has wings set at a steeper angle than the deep towfish (B), resulting in a deeper angle of dive.

The short (9 m) length of the cable necessitated the addition of a pre-amplifier. A custom-designed pre-amplifier was used between May 9, 2011 until March 20, 2012 for cost savings, and then was replaced with a MTI TBS-101B Differential Voltage Preamplifier to save time spent building custom preamplifiers during equipment repairs when the saltwater intruded on the equipment after damage to the cable by floating debris (on July 26, 2012) and during docking (on April 26, 2012). The pelican case was strapped through a metal eye on the deck of the barge (Figure 2.5), with the cable and towline (the strong rope which was used to minimize strain on the electronics cable) trailing into the water.
Figure 2.5: Recording Equipment Setup. The Pelican Case with recording equipment is strapped to the stern of the barge (A), while the cable and hydrophone trail into the water (B). One of two aluminum towfish stabilizes the towline (teal rope) and keeps the hydrophone at depth (C).

Two towfish were attached to the towline, at 6 m and 7.6 m from the connection to the barge. The towfish were constructed out of aluminum pipe and internal lead weight to stabilize the hydrophone cable and keep it as deep under the surface as possible. Wings angled downward at 30° caused the towfish to dive, while it was stabilized by a dorsal fin and internal lead weights. The hydrophone cable was secured to the towing line and connected to the electronics module on the barge. The system had a total (built in and system) gain of 30 dB. The EAR uses a Sensor Technology SQ26-01 hydrophone with a sensitivity of 193.5 dB re 1 V_{rms}/µPa and a flat response frequency (± 1.5 dB) from 1 Hz to 28 kHz. Sample rate was set at 50 kHz with a 67% recording duty cycle (recording for 120 s out of every 180 s) from May 9, 2011 to July 4, 2011, and a sample rate of 80 kHz and a recording duty cycle of 57% (recording for 120 s out of every 210 s) between July 5, 2011 and May 4, 2012. Sample rate was increased in the hopes of detecting high frequency beaked whale signals (Dawson et al. 1998, Johnson et al. 2004a, Zimmer et al. 2005) in the range from to 25-40 kHz for a concurrent study on odontocetes.

Surveys alternated between the Nawilwili and the Kawaihae routes and were conducted approximately every two weeks, as scheduling and berthing allowed. At the start of each survey, the recorder and GPS unit was turned on in Honolulu harbor by the acoustic technician. The time for the EAR recorder was synced to the satellite time for the GPS recorder. The GPS unit recorded the satellite time and the barge position every 30 seconds. On reaching the destination, the recorder was turned off, data were downloaded, and batteries were recharged or replaced while the barge was offloaded. The process was repeated on the survey back to Honolulu.

Acoustic Analysis

Due to the limitations on the length of the towline, some recordings contained short (~2 s) periodic surface flow noise (Figure 2.6). Since cetaceans occur at a lower density in the low-nutrient waters of Hawaii in comparison to higher productivity coastal areas (Barlow and Forney 2007, Allen and Angliss 2015, Waring et al. 2015, Bradford et al. in review), minimizing the number of missed calls (also defined by Mellinger et al. (2007) as false negative detections),
was a priority. Most autonomous detectors, such as PAMGUARD and ISHMAEL, are able to filter out narrowband noise, but do not function well with broadband noise (Mellinger 2001, Gillespie et al. 2008). To avoid false negatives, an acoustic technician visually and aurally searched through all data to detect humpback whale calls. Calls were saved as individual .wav files along with the date and time that they were recorded and the GPS location of the detection was determined by matching up the synced time. Following analysis by the technician, all acoustic data were high-pass (HP) filtered at 1000 Hz to remove low frequency ship noise and isolate periodic surface flow noise, and then the average root mean square (RMS) sound pressure level (SPL) across all frequencies was calculated for each file using the same methods as Lammers et al. (2008). This metric, which is a measure of the amount of flow noise in each file, shall hereafter be referred to as Average Isolated RMS SPL.

Figure 2.6: Example spectrogram of broadband periodic flow noise caused by surface interference.
Satellite Data

The five remotely sensed products used for this study were surface Chlorophyll-A, sea surface temperature (SST), surface currents, wind, and sea surface height (SSH). Bathymetric values were obtained from the Main Hawaiian Islands Multibeam Bathymetry and Backscatter Synthesis 50 m Bathymetry grid (SOESTa). Chlorophyll-A, which is used as a proxy for phytoplankton biomass, and SST were obtained from the NASA Aqua MODIS sensor with a spatial grid resolution of 0.025 degrees (equivalent to approximately 2.8 km²) and a resolution of 8 days centered at the midpoint of each transect. Surface currents were obtained from the Centre National d’études Spatiales Aviso/Altimetry project (Aviso, Ducet et al. 2000), and had a spatial grid resolution of 0.025 degrees averaged over each day. Wind data was obtained from the National Climatic Data Center at a spatial grid resolution of 0.025 degrees and averaged for each day (NCDC, Zhang et al. 2006). Chlorophyll-A, SST, surface currents, and wind are available at Bloomwatch 180 (NOAA). SSH data were obtained from the Hybrid Coordinate Ocean Model (HYCOM, Chassignet et al. 2007) and Navy Coupled Ocean Data Assimilation (NCODA, Cummings 2006) at a grid scale of 0.083 were averaged over each day, available from the School of Oceanography and Earth Science Technology public database (SOESTb, Halliwell et al. 1998). All satellite and bathymetric data were uploaded into ArcGIS and converted from ASCII to raster format in order for all data sources to be visualized and standardized to each other. Both types of data were extracted for all GPS points from the survey transects. Bathymetric depth data, which did not change over the study period, was extracted for all transects as a single block. Satellite data with an eight-day resolution was extracted per survey for Chlorophyll-A and SST. Daily average data was extracted for the survey transect performed
on that day for surface currents, wind, and sea surface height. To account for errors in the models and in GPS locations, all data except for wind speed was averaged to a grid resolution of 0.15 degrees. Where near shore data were missing, they were interpolated from the nearest neighboring grid square.

Statistics

Data were analyzed using 15-minute blocks in the survey data. Remotely sensed data were formatted to match the average distance travelled within each 15-minute block. This represents a distance at which detections would not be replicated within adjacent blocks. The distributions of environmental variables for detections were compared to the distribution of environmental variables for the total survey effort. These comparisons were made using non-parametric Kruskal-Wallace tests due to unequal variances and sample sizes (Zar 1984). All tests were performed using SPSS Version 22. In order to determine the effect of the time of day and season on detection frequency, differences between observed and expected frequencies were tested using Pearson chi square likelihood ratio tests. Since there was no significant difference in detection frequency based on time of day, this variable was not included in further analyses.

In order to quantify relationships between detection locations and the combination of environmental variables that characterize the habitat, we transformed the detection frequency within the 15-minute blocks into a binary presence/absence variable. A step-wise backwards binary logistic regression (Bolker et al. 2009) was conducted using a block format in order to determine which combination of variables cumulatively were the best predictors of cetacean locations. The binary presence or absence of marine mammals was the dependent variable.
Binary logistic regression modeling is a good method to use when determining the distribution of marine mammals since this method is able to deal with a large proportion of zeros in the dataset (Keiper et al. 2005). Block 1 first accounted for variation attributed to wind, Average isolated RMS SPL, and season, and then Block 2 incorporated the effects of depth, height, current and their interaction terms. The two-block technique was designed in order to first take into account the effect of the abiotic variables, while the second block then examined the effect of the environmental and oceanographic variables. High correlations among predictor variables are particularly problematic for logistic regression (Tabachnick and Fidell 2007). A Pearson’s correlation coefficient matrix was calculated for all variables in pairs within the survey effort. Variable pairs with correlation coefficients ≥0.4 (Taylor et al. In Review) were flagged and the sea surface temperature variable was removed from further analysis based on a priori considerations because another variable, sea surface height, is a better predictor of potentially important oceanographic conditions such as upwelling eddies. In addition, ship speed and average isolated SPL were positively correlated (r = 0.444, P = <0.001) and so ship speed was removed from further analysis due to the fact that ship speed was generally steady throughout interisland transits while average isolated SPL levels are likely to be affected by other environmental variables. Models were evaluated for appropriateness using Hosmer-Lemeshow goodness of fit tests for logistic regression models where a non-significant result indicates a well-fitting model (Hosmer and Lemeshow 1980).
Results

**Summary of acoustic data**

Over 400 hours of data were collected on 22 three-day surveys, covering a total of 9046 km of inter-island transit over a period of 52 weeks (Figure 2.7). On these surveys, 734 separate, non-overlapping, humpback whale calls (also defined by Payne *et al.* (1971) as song units) were recorded during 111 unique sightings (Figures 2.8 and 2.11). Sightings were defined as groups of calls with 1 km or more of silence between recordings of subsequent calls.

![Bar chart](chart.png)

**Figure 2.7:** Number of hours of effort surveyed per week throughout the survey period (52 weeks or one year). Time is shown in weeks since January first since months are non-uniform units of time.
Figure 2.8: Spectrogram of humpback whale calls recorded on February 8, 2012 at 1:19 am. This spectrogram contains four individual calls, each of which is approximately 1 to 1.5 s long.

Of these, 100 occurred in winter (December-Feb), 11 occurred in spring (March-May), and none occurred in summer (June-August) or fall (September-November). The first humpback detection of the season occurred on December 19th, and the last detection occurred on May 9th. The greatest number of detections occurred during the late February transects. For all humpback sightings collected during all transects, sixty-four sightings occurred during nighttime and forty-seven occurred during daytime (Figure 2.9).
Figure 2.9: Percent of total of survey effort vs. time of day (displayed as number of minutes since midnight) and percent of total of survey dolphin detections vs. time of day. There was no significant difference in time of detection between the overall survey effort and the odontocete detections.

The number of calls recorded per sighting ranged from one to 31, with an average of 7 and a median of 4. Because there was a highly seasonal pattern in the presence of Humpback whales, for comparative purposes, the survey dataset was sub-sampled to span a date range that covered 95% of the humpback whale detections. This date range was January 26 – April 3, 2012. Throughout the sub sampled survey effort, bottom depth averaged 1219±61 m with a minimum depth of 9 m and a maximum of 3806 m (Figure 2.10). Humpback whales were found in significantly shallower water with an average depth of 201±24 m (Kruskal-Wallis P <0.001). Animals were detected on the leeward sides of the islands, as well as in the deep-water channels between islands. Of the 111 detections, 77 (69%) occurred in waters less than 183 m (100 fathoms).
Figure 2.10: Distribution of effort by depth for the sub-sampled transects completed between January 26 and April 3, 2012. Depth bin values shown are the end value from each bin (e.g. 500 includes blocks from 1 to 500, etc.).

Figure 2.11: Seafloor depth distribution of location of humpback whale sightings. Most humpbacks occurred in waters under 1000 m in depth, with 69% occurring in waters of less than 183 m (1 fathom). There were high levels of detections in the Maui Channel and over Penguin Bank.
Average SST of the survey subsample was 24.28±0.02°C. Whales were found in slightly warmer waters averaging 24.41±0.04°C. This difference in SST was significant (Kruskal-Wallis P<0.001). Chlorophyll was low across the survey subsample, averaging 0.060±0.008 mg/m³. Humpback whales were found in water with Chlorophyll-A of 0.051±0.003 mg/m³. Current averaged 0.005±0.001 cm/sec over the sub-sampled survey, but whales were found in waters averaging 0.007±0.002 cm/sec. Sea surface height averaged 0.591±0.002 m over survey subsample. Whales were found in waters with sea surface heights averaging 0.594±0.002 m. Wind averaged 8.35±0.11 m/sec⁻¹ over the survey subsample; the average wind speed for whale locations detections and the wind averaged 8.76±0.25 m/sec⁻¹. This corresponds to an average Beaufort wind force scale of five (Figure 2.12). Chlorophyll, current, sea surface height, and wind all showed non-significant differences.

Figure 2.12: Detections per hour of effort in each category of the Beaufort wind scale. No detections occurred in waters under Beaufort 3, and 75 % of survey effort occurred in Beaufort 4 and higher (see Fig. 10). There was no significant difference in wind speed between overall survey effort and humpback detections.
There was no significant difference between detections for time of day ($\chi^2 = 2.604 \ df = 1, \ P = 0.107$), but differences by season were highly significant ($\chi^2 = 71.360 \ df = 1, \ P < 0.001$). Pearson correlation indicated that there was a non-significant negative correlation between wind speed and isolated ambient SPL ($r = -0.143$, Pearson 1901). The final stepwise binary logistic regression model for whale detections indicated that both Average isolated RMS SPL (coefficient = -0.036, $P = 0.139$) and season (coefficient = 0.868, $P = 0.106$) were important in explaining whale locations. This occurred because of a significant effect in the first block. However, in the final model, they were not significant (Table 2.1, Figure 2.13).

**Table 2.1.** Results of the 2 block stepwise binary regression model explaining whale locations

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>S.E.</th>
<th>Wald</th>
<th>df</th>
<th>P</th>
<th>Odds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average isolated</td>
<td>-0.036</td>
<td>0.24</td>
<td>2.189</td>
<td>1</td>
<td>0.139</td>
<td>0.965</td>
</tr>
<tr>
<td>RMS SPL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Season</td>
<td>0.868</td>
<td>0.537</td>
<td>2.612</td>
<td>1</td>
<td>0.106</td>
<td>2.382</td>
</tr>
<tr>
<td>Current</td>
<td>26.907</td>
<td>6.554</td>
<td>16.853</td>
<td>1</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Height</td>
<td>-36.582</td>
<td>5.638</td>
<td>42.102</td>
<td>1</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Depth x Height</td>
<td>-0.005</td>
<td>0.001</td>
<td>22.989</td>
<td>1</td>
<td>&lt;0.001</td>
<td>0.995</td>
</tr>
<tr>
<td>Current x Depth</td>
<td>-0.04</td>
<td>0.012</td>
<td>11.453</td>
<td>1</td>
<td>0.001</td>
<td>0.961</td>
</tr>
</tbody>
</table>

In the final model, whale location was negatively associated with sea surface height (coefficient = -36.582, $P < 0.001$), the interaction term of depth and sea surface height (coefficient = -0.005, $P = <0.001$), the interaction of depth and current (coefficient = -0.04, $P = 0.001$), and positively associated with current (coefficient = 26.907, $P = <0.001$). The interaction
term is defined as the simultaneous influence of two variables on a third. This model was a good fit for these data and explained nearly 35% of observed whale locations (Nagelkerke $R^2 = 0.349$, HL = 0.918, $\text{Chi}^2 = 3.242$, df = 8).

![Figure 2.13: Box-plot comparisons of bathymetry (depth) and satellite (CHL, Current, SST, Sea Surface Height, and Wind Speed) data from humpback locations and sub-sampled survey effort. There were significant differences found for depth, and sea surface temperature using non-parametric tests. The box plot shows the median (center line), the upper and lower quartiles (edges of the box), and the range (edge of the bars or hollow circles). Hollow circles show outliers further than 1.5x the inter-quartile range from either quartile.](image-url)
Discussion

This study found that acoustic monitoring from commercial vessels moving between the Hawaiian Islands was a viable and cost-effective relative to other survey methods. These costs, in comparison to other methods, are further discussed in Chapter 3. Acoustic data was successfully collected about humpback whale occurrences and survey methods were successful under adverse visual detection conditions such as at nighttime and during high wind/sea states.

Comparison with Previous Research

The results from this study are comparable to those achieved by more traditional line transect survey methods for detecting the presence of humpback whales. With this survey method, humpbacks were spatially and temporally located as would be expected given current knowledge of humpback movement and behavior in Hawaii. In this study, the first seasonal detections of humpbacks in December, peak detections of humpbacks during the late-February transects, and the last seasonal detections of humpbacks in May fit with what is known from previous studies (Thompson et al. 1982, Au et al. 2000, Mobley 2001). As in previous studies, the majority of detections (69% in this study) occurred in shallow, warmer waters of less than 100 fathoms (183 m, Herman et al. 1977, Baker and Herman 1981, Mobley et al. 1999), which may confer survival benefits to newborns and their mothers (Lockyer 1981). Some animals were also found in deeper waters, which is consistent with known inter-island movements (Mate et al. 1998a). Slightly greater, although not statistically significant, numbers of detections of humpbacks occurred at night, consistent with the diurnal chorusing behavior reported by Au
et al. (2000). In this study, there was no relationship with humpback whale presence and primary productivity. This is consistent with current knowledge; other than one reported instance of a juvenile lunging through mackerel (Salden 1989), humpback whales are not known to feed in Hawaii. Since they do not feed in this region, there is no expectation that their distribution would be correlated to areas of higher productivity. For the same reason, humpback whale distribution in Hawaii is unlikely to be influenced by sea surface height or current velocity, both of which are indicators of upwelling and therefore primary productivity (Miller and Wheeler 2012, Woodworth et al. 2012). The results of the stepwise binary regression returned somewhat contradictory results, including that the variables that associate with humpback locations were depth x current, current, depth x sea surface height, and sea surface height. While sea surface height and current are not biologically relevant variables when discussing the location of humpbacks in Hawaii, the area encompassing the majority of the humpback whale detections in this study was characterized by moderate currents, slightly negative sea surface height values (which are related to lower levels of upwelling and productivity), and shallow water. These results indicate that the model did accurately describe the variable values associated with humpback whale locations, however, given what is known about humpback distribution and behavior in Hawaii, during the clearly defined humpback season, depth is still the best single predictor of location.

Although interfering periodic surface noise did make using autonomous call detection algorithms impractical, Average isolated RMS SPL and wind speed were not correlated during this survey. This indicates that Average isolated RMS SPL, an indicator of periodic surface noise, was not related to wind speed or, by definition, Beaufort wind scale. In this study, wind speed
did not correlate negatively with the number of humpback whales detected, including during
times of high wind when visual surveys would be impractical. Autonomous detectors have been
designed to filter out or disregard narrowband noise, such as noise from ships (Mellinger 2001, Gilespie et al. 2008). Periodic flow noise from surface interactions is generally minimized via
the method of data collection. For example, hydrophone arrays are commonly towed on long,
weighted cables to maximize depth and distance from the vessel (Thode 2004, Barlow et al. 2005). Thus, there has not previously been much impetus to come up with a programming a
solution to the problem of broadband surface noise. In visual surveys, sighting rates generally
decrease with increases in wind speed (Palka 1996, Mobley 2005). In previous aerial visual
surveys for humpback whales in Hawaii, sightings dropped off sharply beyond a Beaufort Sea
State of 3 (Mobley 2001). In the current study, there was no significant relationship between
wind speed and humpback detections. Acoustic surveys have shown demonstrated advantages
over visual surveys with regard to the ability to collect data in adverse sighting conditions (Clark

The standard method for estimating cetacean distribution and abundance is via visual
line-transect surveys (Wade and Gerrodette 1993, Buckland et al. 2001). Acoustic line transect
surveys have been used to estimate cetacean abundance, but their applicability depends on
two key factors. First, the spatial extent of the calls detected must be limited to a defined
sampling area, requiring that a detection function be derived, and, second, to produce an
abundance estimate from the number of calls detected, the ratio of calling to non-calling
animals in a given population must be known, also known as a cue rate (Marques et al. 2009).
This second factor is especially difficult, because one animal may be loquacious, while many
animals may be relatively quiet. An example of this bias from the current survey is that most, if not all, acoustic detections of humpback whales are likely to be singing males, and so females and calves are less likely to be counted. The ability of straight line transects, such as those in this study, to cover a broad area is clearly limited in comparison to gridded line transect surveys. However, multi-year studies using straight line transects aboard platforms of opportunity have yielded information on trends in cetacean abundance (Marini et al. 1996, Arcangeli et al. 2013).

In order to apply the survey methods used in this study across a broader geographic area, it would need to be deployed on a broader array of commercial ship types. For commercial shipping without a barge, and where the equipment would be deployed directly from the ship, further testing of this technique is necessary to determine the level of interference from ship noise. Maximum SPL measurements from most measured commercial ships occur between 30 and 100 Hz, and most also contain a high frequency component (Arveson and Vendittis 2000, Allen et al. 2012, McKenna et al. 2012, Wittekind 2014). In this study, the recorders were separated from the noise of the propeller by the considerable distance (500 m) between the tugboat and the stern of the barge, so noise from the towing vessel was minimized. Most underwater ship noise is caused by propeller cavitation (Wittekind 2014). Three types of underwater noise are caused by propeller cavitation; tonal harmonics from cavitation passing through areas where the velocity of water flow is low, broadband noise in the same frequency range of the tonal harmonics, and high frequency broadband noise caused by cavitation bubble collapse (Wittekind 2014). High frequency noise attenuates relatively quickly, and so the ability to detect cetaceans from commercial vessels of opportunity
could be increased by lengthening the towline. Distancing the hydrophone array from the ship is a method commonly used by dedicated research vessels to minimize ship noise (Barlow et al. 2005). A longer towline increases horizontal and vertical distance between the propeller and the hydrophone to minimize high frequency masking. However, there must be a balance between towline length and the practicality of deploying the towline. One way to deal with this balance is to house all electronics within the underwater unit, rather than having an electronic deck unit with an electrical cable into the water to the hydrophone. This would make it possible to use a non-electrical wire cable (rated to a breaking strength of at least 200 lbs) for towing, which would make it possible to deploy the recorder remotely with a small, commercially available winch. Preliminary design of this deployment method has been started.

If low frequency noise cannot be reduced, effort can still be focused on species with call frequency ranges that do not overlap with low frequency tonal ship noise, as was done in this study. With the interference of low frequency ship noise, this technique has minimal potential for the study of large baleen whales, including blue (typical call range = 18-27 Hz), fin (typical call range = 15-28 Hz), and Sei whales (typical call range = 21-39 Hz, Širović et al. 2004, McDonald et al. 2005, Rankin et al. 2005, Sirovic 2006, Rankin and Barlow 2007, Sirovic et al. 2007). However, there is the potential for detections of cetaceans whose calls are above 1000 Hz, including humpback whales and delphinids. While the frequency range of humpback whales can be as low as 30 Hz, harmonics for some calls also range up to at least 24 kHz (Au et al. 2006, Dunlop et al. 2007, Stimpert et al. 2011). Thus, although the fundamental frequency of many humpback calls might be masked by ship noise, harmonics would still be above the noise. For detection, if not classification, some humpback calls may still be distinguishable even if the
fundamental frequency were masked by ship noise. Dolphin and porpoise calls cover a broad range of frequencies, from the occasionally low frequency calls of Orcinus orca (1-20 kHz) to the high frequency calls of harbor porpoise Phocoena phocoena with a peak frequency of 130 kHz, with many species using frequency ranges between these two extremes (Watkins et al. 1977, Miller et al. 1998, Lammers and Au 2003, Au 2004, Au and Wursig 2004, Johnson et al. 2004b, Madsen et al. 2004, Supin et al. 2004, Villadsgaard et al. 2007, Ibsen et al. 2009, Baumann-Pickering et al. 2010).

Future Work

Localization with a single hydrophone can be accomplished using multipath ray trace propagation modeling of surface and bottom reflections (Aubauer et al. 2000, Laplanche et al. 2005, Nosal and Frazer 2006, Tiemann et al. 2006). With an array that is constantly moving over a changing bathymetry, it is more practical to use a multi-hydrophone array (Barlow et al. 2005). The methods outlined in this study could be improved by changing the single hydrophone to a linear hydrophone array. Detections from a linear array would still have problems of left-right ambiguity (Au and Hastings 2008), but would give additional information about distance from the transect line that would be useful in estimating animal density (Buckland et al. 2001).

Further testing and improvement of equipment would be necessary to apply this method to other shipping modes. However, this technique has potential to increase knowledge of cetacean distribution in poorly surveyed areas worldwide. Reasonable design improvements to the recording system could include housing all recording equipment internally within the
towfish as well as adding a remote switch to deploy and retrieve the gear when coming in and out of port. This would remove the necessity that an acoustic technician physically be present for deployments, as well as allow for deeper deployment of the gear. It also would decrease surface noise interference, thus improve the likelihood that signals of interest could be found autonomously via a detection algorithm, rather through the long process of visual and aural inspection. In addition, removal of broadband noise would make it possible to detect clicks, which would increase the number of species for which this technique is useful.

As managers and scientists attempt to fill gaps in data on protected species, they will need to develop new techniques to complement and improve on existing methods over multiple spatial and temporal scales. Acoustic survey methods are a complement to visual survey methods (Swartz et al. 2003, Barlow et al. 2005, Oleson et al. 2007). Bottom-mounted hydrophones are able to collect acoustic data over a long temporal scale, while towed hydrophone arrays have the advantage of data collection over an extended area (Van Parijs et al. 2009). Acoustic surveys from vessels of opportunity have the potential to combine the advantages of a towed array with those of a bottom-mounted hydrophone by covering great distances over a long time scale. As with the Continuous Plankton Recorder Survey (Reid et al. 2003), a global acoustic survey would require cooperation between scientists and industry and a long-term commitment to coordinate this partnership, but has the potential to provide a similarly important global data set.


*European Research on Cetaceans* 14:14-18.


Gregg, E.J., and A.W. Trites. 2001. "Predictions of critical habitat for five whale species in the
waters of coastal british columbia." Canadian Journal of Fisheries and Aquatic Sciences
58 (7):1265-1285.

Halliwell, G., R. Bleck, and E. Chassignet. 1998. "Atlantic ocean simulations performed using a
new hybrid-coordinate ocean model." EOS, Fall 1998 AGU Meeting.

Herman, L.M., and R.C. Antinoja. 1977. "Humpback whales in the hawaiian breeding waters:
Population and pod characteristics." Scientific Reports of the Whales Research Institute.


sensitivity in the humpback whale." Aquatic Mammals 27 (2):82-91.

echolocating atlantic bottlenose dolphin (tursiops truncatus)." Journal of the Acoustical
Society of America 125 (2):1214-1221.

Elsevier.

echolocate on prey." Proceedings of the Royal Society of London B: Biological Sciences

echolocate on prey." Proceedings of the Royal Society of London Series B-Biological
Sciences 271:S383-S386.


http://coastwatch.pfeg.noaa.gov/coastwatch/ CWBrowserWW180.jsp


Washington, DC.


*Progress in Oceanography* 58 (2):117-173.


Thompson, P.O., and W.A. Friedl. 1982. *A long term study of low frequency sounds from several species of whales off oahu, hawaii*: Biological Systems.


CHAPTER 3. RELATIVE ABUNDANCE AND DISTRIBUTION OF ODONTOCETES IN THE DEEP WATER CHANNELS OF THE MAIN HAWAIIAN ISLANDS

Introduction

The management of protected species requires understanding of their distribution and relative abundance in space and time. While habitat structure in terrestrial and near shore systems is often stationary, allowing for effective spatial management of habitats alone (Levin and Whitfield 1994, Carr et al. 2003), marine ecosystems vary over multiple temporal and spatial scales (Steele 1991). The Marine Mammal Protection Act (16 USC § 1361 et seq.) applies to 25 species in Hawaiian waters (Barlow 2006). This statute prohibits “takes” of marine mammals during activities such as commercial shipping, fisheries, aquaculture, ocean energy development, military training, construction, and tourism, except where permits have been obtained through the National Marine Fisheries Service (NMFS). The specific impacts of these activities to cetaceans include bycatch, entanglement, habitat alteration, changes in prey distribution or abundance, ship strikes and hearing and behavioral disturbance due to anthropogenic noise (Ferguson et al. 2015).

Spatial and temporal data can be particularly important for mitigating anthropogenic impacts to highly mobile marine species that follow dynamic oceanographic features over time during migration, foraging, and breeding (Crowder and Norse 2008, Foley et al. 2010, Block et al. 2011). Spatial and temporal management (time/area closures) are widely used in fisheries to prevent overfishing, habitat destruction, and bycatch (Botsford et al. 1997, Murray et al. 2000, Clapham and Pace 2001, Hobday et al. 2010). Temporal management areas (Merrick 2005,
Merrick and Cole 2007, Wiley et al. 2013) have also been used to mitigate the impacts of ship strikes on northern right whales and to reduce bycatch of harbor porpoises (Murray et al. 2000). The National Oceanic and Atmospheric Administration (NOAA) Cetacean and Density and Distribution Working Group’s CetMap provides species-specific, month-by-month cetacean density and distribution maps with the goal of assisting the National Oceanic and Atmospheric Administration (NOAA), federal agencies, and the public in the analyses and planning required under U.S. law to characterize and minimize the impacts of anthropogenic activities on cetaceans (Ferguson et al. 2015). Unfortunately, adequate information on the temporal distribution of many marine mammal species is not available for the use in marine spatial planning or management decisions (Schipper et al. 2008). Gaining more information on these data-poor species through traditional visual survey methods from large research vessels or aircraft is often prohibitively expensive, particularly for marine species that are rare, inaccessible, or cryptic (Kaschner et al. 2012). Alternative methods of data collection can allow data gaps to be filled for these species and improve management. Alternative methods of data collection include small boat surveys, acoustics, and tagging and often add information not available through traditional surveys (Barlow and Taylor 2005, Williams and Thomas 2009, Mate et al. 2015).

Twenty-five species of cetacean are protected in Hawaii under the MMPA (Barlow 2006). Survey effort to establish the distribution and abundance of odontocetes has been constrained both by weather and available funds. Knowledge of the occurrence and distribution of cetaceans in the main Hawaiian Islands prior to 1982 is summarized by Shallenberger (1981). Mark-recapture photo-id methods were used to estimate the abundance of spinner dolphins
Stenella longirostris (Ostman 1994) and humpback whales Megaptera novaeangliae around the main Hawaiian Islands (Baker 1987, Cerchio 1998). From February to April of 1993, 1995, 1998, and 2000, aerial surveys were used to estimate abundances of 13 species of cetacean within 25 nmi of the main Hawaiian Islands (Mobley 2001). In 2002, the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS), the first systematic survey of all marine mammal species for the Hawaiian Exclusive Economic Zone (EEZ), was conducted by the Southwest (SWFSC) and Pacific Islands Fisheries Science Centers (PIFSC, Barlow 2006). This survey covered 3,550 km of track within the main Hawaiian Islands. Multiple legs of a second HICEAS survey were conducted in 2010 (Barlow et al. 2010, Hill et al. 2010, Oleson et al. 2010, Pitman et al. 2010, Woodworth-Jefcoats 2013), but a final comprehensive survey report has yet to be published. In addition to the HICEAS cruises, a systematic survey of the area around the main Hawaiian Islands occurred in 2009 (Oleson 2009). Visual and acoustic surveys were also conducted on the leeward side of the Big Island of Hawaii in 2011, 2013, and 2014 (Howell 2011, Woodworth-Jefcoats 2013). Two of the PIFSC research cruises occurred during the month of February and August through November, with one occurring during December. PIFSC surveys had low survey effort during the months of January and March through July. Although the NOAA surveys have good spatial coverage, both seasonal coverage and consistency could be improved (Table 3.1). However, non-systematic small boat surveys have been conducted since 2000 throughout the year by R. Baird and colleagues (Baird et al. 2013). These surveys have been generally performed in concentrated areas near the main Hawaiian Islands in sea states of less than Beaufort Sea State 4 (also known as Beaufort Wind Scale). These data have a strong geographical bias toward the leeward sides of islands (Baird et al. 2005), and the Kaieie Waho,
Kaiwi, Kalohi, and Alaenuihaha channels between islands are particularly poorly sampled (Figure 3.1, Table 3.1).

A lack of information on seasonality and distribution of Hawaiian odontocetes has the potential to influence the effectiveness of management decisions in Hawaii. These gaps in knowledge are especially relevant to the mitigation of fisheries bycatch (Forney et al. 2011), and anthropogenic noise from naval sonar (Dolman 2007). In addition to a lack in consistency and seasonality, there are inherent problems with visual line transect surveys, especially in high wind areas. Most surveys of marine mammals are conducted using standardized visual survey methods. In general, two observers scan a quadrant from 90 degrees off center to the front of the vessel using 50x “Big eye” binoculars, while a third observer records data and scans 180° with naked eye and 7x binoculars (Kinzey et al. 2000). The probability of detecting an animal depends on many factors, including animal behavior, sea state, and observer competence (Barlow 1999, Forney 2000, Barlow and Forney 2007). While visual line-transect surveys are generally limited to a strip width of 3-7 km, animals can be detected acoustically from up to tens or hundreds of km away (Stafford et al. 1998, Barlow and Taylor 2005). Acoustic surveys for marine mammals provide an alternative to visual methods, especially when visual methods are impossible or ineffective, such as at night or in rough seas. For some species, especially those that are cryptic or with long dive times, acoustic detection rates are higher than or comparable to visual detection rates (Clark 1997, Akamatsu et al. 2001, Swartz et al. 2003). Barlow and Taylor (2005) were able to detect seven times more sperm whales with acoustic than visual methods. Acoustic methods have been used many times to estimate cetacean distribution across space and time. Distribution and relative abundance of striped
dolphins (Gordon 2000) and both a seasonal difference in acoustic encounter rate and a clustering of the whales around geographic features were found using acoustic methods (Oleson et al. 2007). Seasonal trends in humpback whale chorusing sounds agreed with known breeding periods (Au et al. 2000). Stationary hydrophones in the northwest Hawaiian Islands have revealed previously unknown distributions of humpback whales (Lammers et al. 2011) and show inshore movements of spinner dolphins corresponding to known diurnal behavior (Lammers et al. 2008).

One problem with acoustic sampling is that species identification can be difficult without directly observing the animal. Advances in signal classification programs have allowed a greater ability for species prediction from acoustic recordings. Delphinids produce three types of signals: broadband echolocation clicks, burst pulses, and whistles. Whistles are narrow band, frequency modulated signals, and sometimes are harmonic. Whistles are usually used for classification algorithms, although there is some evidence that clicks also may be useful (Roch 2007). Classification programs compare the parameters of unidentified whistles to those of known species to statistically predict the species producing the unknown whistle.

In Hawaii, weather constraints result in a preponderance of usable survey coverage on the leeward sides of islands, and an especially low coverage in the deep water Alenuihaha and Kaieie Waho Channels (Figure 3.1). Spatially biased sampling effort can lead to biased distribution and habitat modeling (Stolar and Nielsen 2015). As a result of the constraints of weather and cost, there are information gaps on the distribution and relative abundance of cetaceans in the main Hawaiian Islands for the windward sides of the islands (Ferguson et al. 2015) and the deep-water channels between islands.
Table 3.1: Summary of times, number of cetacean species encountered, coverage, and of four sources of potential information on marine mammal distributions in Hawaii.

<table>
<thead>
<tr>
<th>Start Date</th>
<th>End Date</th>
<th># Species</th>
<th>Region</th>
<th>Method, Platform</th>
<th>Track Length/Area Covered</th>
<th>Acoustics</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-Feb-93</td>
<td>8-Apr-98</td>
<td>13</td>
<td>Main Hawaiian Islands</td>
<td>Line transect, Airplane</td>
<td>71,954 km²</td>
<td>No</td>
<td>Mobley et al. (2001)</td>
</tr>
<tr>
<td>Feb-00</td>
<td>6-Dec</td>
<td>-</td>
<td>Main Hawaiian Islands</td>
<td>Non-systematic, Small Boat Line transect, Ship</td>
<td>-</td>
<td>No</td>
<td>Baird et al. (2013)</td>
</tr>
<tr>
<td>6-Aug-02</td>
<td>27-Nov-02</td>
<td>21</td>
<td>Hawaii EEZ (HICEAS)</td>
<td>Line transect, Ship</td>
<td>3550 km</td>
<td>Yes</td>
<td>Barlow (2006)</td>
</tr>
<tr>
<td>4-Feb-09</td>
<td>27-Feb-09</td>
<td>12</td>
<td>Main Hawaiian Islands</td>
<td>Line transect, Ship</td>
<td>1257.2 km</td>
<td>Yes</td>
<td>Oleson (2009)</td>
</tr>
</tbody>
</table>

The goal of this study is to fill in gaps in current data on odontocete distribution in Hawaii, especially in the deep water channels between islands where data are spatially and temporally biased; during all four seasons, including the under-sampled months, during the night (which is not possible with visual surveys) and in high Beaufort conditions. In addition, this study will examine the distribution of the detected cetaceans in relation to remotely sensed depth and satellite data for possible future use in odontocete habitat modeling.

Methods

Data Collection

In order to test the objectives of this study, acoustic surveys were conducted using barges of Young Brothers, the largest inter-island shipping company in Hawaii. This was conducted concurrently with another study, the methods of which are in Chapter 2 of this thesis. The shipping barges have a length of approximately 35 ft., and are towed on approximately 500 m of metal cable by a tugboat. The barges leave Honolulu approximately...
twice per week to three locations: Kawaihae on the Big Island of Hawaii, Nawilili on Kauai, and Hilo on the Big Island (Figure 3.1).

![Map of Young Brothers routes](image)

**Figure 3.1:** Map of Young Brothers routes (shown in black) used to collect data for this survey. Channels of interest are labeled. Annual average offshore wind speed was modeled by the National Renewable Energy Laboratory at a height of 90 m and out to 50 nmi from shore (Schwartz et al. 2010). Average wind speed ranges from Beaufort Wind Scale (BF) 2 to 6. White areas indicate no data. Much of the marine mammal research in Hawaii has taken place in low wind areas to the west of the islands, indicated in blue above. A funnel effect between the islands results in especially high wind speeds in the Alenuihaha, Kalohi, and Pailolo channels (Chavanne et al. 2002).

The trip to Nawiliwili takes approximately 14 hours, and the trips to the Kawaihae take approximately 20 hours. In an average week, there are four trips for each route, two at night and two during the day. This survey used two of these routes: from Honolulu to Nawiliwili and
Honolulu to Kawaihae, in order to cover all the deep water channels between the Hawaiian Islands as well as well as for the practical reason of limiting equipment to the deeper harbors, where it was less likely to be damaged (Figure 3.3). Transects were conducted approximately every two weeks as ship availability allowed. The recording equipment for this project included a modified EAR (Lammers et al. 2008). The EAR is normally used as a stationary recorder, with the batteries, electronics, and hydrophones contained within one cylindrical unit (Figure 3.2).

![Figure 3.2: A stationary EAR resting on the ocean floor near coral.](image)

For these surveys, the electronics, batteries, and recording gear of the EAR were housed in a waterproof Pelican™ case on the deck of the barge, with an extended cable leading to the hydrophone at the end of the cable, which extended behind the barge into the water. The towline for the hydrophone could not be longer than 9 m, to avoid damage to the acoustic equipment. Harbor depth is 6 m and all towed equipment had to be lowered into the water within the harbor, because no crew was allowed on the barge during the channel crossings for safety reasons. The two-towfish system maximized the depth of the hydrophone while keeping the equipment light enough to be deployed by a single person and significantly reduced
periodic broadband surface noise compared to a single towfish system or a weighted hydrophone (Figure 3.3).

**Figure 3.3:** Schematic of towfish depth at zero and underway (above 4 mph). The shallow towfish (A) has wings set at a steeper angle than the deep towfish (B), resulting in a deeper angle of dive.

The short (9 m) length of the cable necessitated the addition of a pre-amplifier. A custom-designed pre-amplifier was used between May 9, 2011 until March 20, 2012 for cost savings, and then was replaced with a MTI TBS-101B Differential Voltage Preamplifier to save time spent building custom preamplifiers during equipment repairs when the saltwater intruded on the equipment after damage to the cable by floating debris (on July 26, 2012) and during docking (on April 26, 2012). The pelican case was strapped through a metal eye on the deck of the barge.
(Figure 3.4), with the cable and towline (the strong rope which was used to minimize strain on the electronics cable) trailing into the water.

Figure 3.4: Recording Equipment Setup. The Pelican Case with recording equipment is strapped to the stern of the barge (A), while the cable and hydrophone trail into the water (B). One of two aluminum towfish stabilizes the towline (teal rope) and keeps the hydrophone at depth (C).

Two towfish were attached to the towline, at 6 m and 7.6 m from the connection to the barge. The towfish were constructed out of aluminum pipe and internal lead weight to stabilize the hydrophone cable and keep it as deep under the surface as possible. Wings angled downward at 30° caused the towfish to dive, while it was stabilized by a dorsal fin and internal lead weights. The hydrophone cable was secured to the towing line and connected to the electronics module on the barge. The system had a total (built in and system) gain of 30 dB. The EAR uses a Sensor Technology SQ26-01 hydrophone with a sensitivity of 193.5 dB re 1 V_{rms}/\mu Pa and a flat response frequency (± 1.5 dB) from 1 Hz 28 kHz. Sample rate was set at 50 kHz with a 67% recording duty cycle (recording for 120 s out of every 180 s) from May 9, 2011 to July 4, 2011, and a sample rate of 80 kHz and a recording duty cycle of 57% (recording for 120 s out of every 210 s) between July 5, 2011 and May 4, 2012. Sample rate was increased in the hopes of

Surveys alternated between the Nawilwili and the Kawaihae routes and were conducted approximately every two weeks, as scheduling and berthing allowed. At the start of each survey, the recorder and GPS unit was turned on in Honolulu harbor by the acoustic technician. The time for the EAR recorder was synced to the satellite time for the GPS recorder. The GPS unit recorded the satellite time and the barge position every 30 seconds. On reaching the destination, the recorder was turned off, data were downloaded, and batteries were recharged or replaced while the barge was offloaded. The process was repeated on the survey back to Honolulu.

**Acoustic Analysis and Whistle Classification**

Due to the limitations on the length of the towline, some recordings contained short (~2 s) periodic surface flow noise (Figure 3.5). Since cetaceans occur at a lower density in the low-nutrient waters of Hawaii in comparison to higher productivity coastal areas (Barlow et al.)
2007, Allen and Angliss 2015, Waring et al. 2015, Bradford et al. in review), minimizing the number of missed calls (also defined by Mellinger et al. (2007) as false negative detections), was a priority. Most autonomous detectors, such as PAMGUARD and ISHMAEL, are able to filter out narrowband noise, but do not function well with broadband noise (Mellinger 2001, Gillespie et al. 2008). To avoid false negatives, an acoustic technician visually and aurally searched through all data to detect dolphin whistles. Dolphin clicks were detected, but were not included in further analysis because of a lack of classification algorithms for Hawaiian cetacean species (Houser et al. 1999, Soldevilla et al. 2008, Roch et al. 2011). Dolphin whistles were saved as individual .wav files along with the date and time that they were recorded and the GPS location of the detection was determined by matching up the synced time.

![Figure 3.5](image.png)

**Figure 3.5:** Example spectrogram of broadband periodic flow noise caused by surface interference.

Whistle contours were classified using the Real-time Odontocete Call Classification Algorithm (ROCCA) beta version, which is part of the Passive Acoustic Monitoring Guardianship (PAMGUARD) open source software package. ROCCA measured 10 variables from 9 delphinid species (Figure 3.6). The ROCCA program has the capability of measuring up to 38 additional
parameters for increased future precision. ROCCA correctly classifies all but one of the twelve species within its database at greater than chance, with the best performance for bottlenose dolphins *Tursiops truncatus*, false killer whales *Pseudorca crassidens*, and rough-toothed dolphins *Steno bredanensis* (Oswald and Oswald 2013). NOAA’s Southwest Fisheries Science Center and Pacific Islands Fisheries Science Center are currently using ROCCA for whistle classification during cetacean line transect surveys. Whistle ROCCA data for each sighting was run through a two-stage random forest classifier. In the first stage, whistles were classified to one of three categories: large delphinids (*Globicephala melas*, *Pseudorca crassidens*, and *Steno bredanensis*), medium delphinids (*Tursiops truncatus* and *Stenella attenuata*) or small delphinids (*Stenella longirostris* and *coeruleoalba*). In the second stage, whistles within each category were classified to species, except for small delphinids, which were not classified in any more detail. Small delphinids were combined because they are acoustically similar, and two visual sightings of spinner dolphins were incorrectly classified as striped dolphins (Table 3.2). Acoustic sightings on the same day were defined as groupings of whistles with more than 30 minutes of complete silence between them.
Figure 3.6: Spectrogram of a bottlenose dolphin whistle (512-point FFT, Hanning window), showing the ten variables that were measured from each whistle. These variables are: 1) beginning frequency, 2) end frequency, 3) minimum frequency, 4) maximum frequency, 5) duration, 6) number of inflection points (changes from negative to positive or vice versa), 7) number of changes 10% increases or decreases in frequency, 8) slope at the beginning sweep, 9) slope of the end sweep, and 10) presence of harmonics (From Oswald et al. 2007).

Following analysis by the technician, all acoustic data were high-pass (HP) filtered at 1000 Hz to remove low frequency ship noise and isolate periodic surface flow noise, and then the average root mean square (RMS) sound pressure level (SPL) across all frequencies was calculated for each 120 second file using the same methods as Lammers et al. (2008). This
metric, which is a measure of the amount of flow noise in each file, shall hereafter be referred to as Isolated Average RMS SPL.

**Satellite Data**

The five remotely sensed products used for this study were surface Chlorophyll-A, sea surface temperature (SST), surface currents, wind, and sea surface height (SSH). Bathymetric values were obtained from the Main Hawaiian Islands Multibeam Bathymetry and Backscatter Synthesis 50 m Bathymetry grid (SOESTa). Chlorophyll-A, which is used as a proxy for phytoplankton biomass, and SST were obtained from the NASA Aqua MODIS sensor with a spatial grid resolution of 0.025 degrees (equivalent to approximately 2.8 km²) and a resolution of 8 days centered at the midpoint of each transect. Surface currents were obtained from the Centre National d’études Spatiales Aviso/Altimetry project (Aviso, Ducet et al. 2000), and had a spatial grid resolution of 0.025 degrees averaged over each day. Wind data was obtained from the National Climatic Data Center at a spatial grid resolution of 0.025 degrees and averaged for each day (NCDC, Zhang et al. 2006). Chlorophyll-A, SST, surface currents, and wind are available at Bloomwatch 180 (NOAA). SSH data were obtained from the Hybrid Coordinate Ocean Model (HYCOM, Chassignet et al. 2007) and Navy Coupled Ocean Data Assimilation (NCODA, Cummings 2006) at a grid scale of 0.083 were averaged over each day, available from the School of Oceanography and Earth Science Technology public database (SOESTb, Halliwell et al. 1998). All satellite and bathymetric data were uploaded into ArcGIS and converted from ASCII to raster format in order for all data sources to be visualized and standardized to each other. Both types of data were extracted for all GPS points from the survey transects. Bathymetric
depth data, which did not change over the study period, was extracted for all transects as a single block. Satellite data with an eight-day resolution was extracted per survey for Chloryphyll-A and SST. Daily average data was extracted for the survey transect performed on that day for surface currents, wind, and sea surface height. To account for errors in the models and in GPS locations, all data except for wind speed was averaged to a grid resolution of 0.15 degrees. Where near shore data were missing, they were interpolated from the nearest neighboring grid square.

**Statistics**

Data were analyzed using 15-minute blocks in the survey data. Remotely sensed data were formatted to match the average distance travelled within each 15-minute block. This represents a distance (averaging 3.3 km) and reduces the likelihood of pseudo-replication of sightings between adjacent blocks. The distributions of environmental variables for sightings were compared to the distribution of environmental variables for the total survey effort. These comparisons were made using non-parametric Kruskal-Wallace tests due to unequal variances and sample sizes (Zar 1984). All tests were performed using SPSS Version 22. In order to determine the effect of time of day and season on sighting frequency, differences between observed and expected frequencies were tested using Pearson chi square likelihood ratio tests. Since there was no significant difference in sighting frequency based on time of day, this variable was not included in further analyses.

Because of the small sample sizes for each species, all odontocete species were analyzed as a single group. In order to quantify relationships between detection locations and
the combination of environmental variables that characterize the habitat, we transformed the detection frequency within the 15-minute blocks into a binary presence/absence variable. A step-wise backwards binary logistic regression (Bolker et al. 2009) was conducted using a block format which analyzes the variables in predetermined groups in order to determine which combination of variables cumulatively were the best predictors of cetacean locations. The binary presence or absence of marine mammals was the dependent variable. Binary logistic regression modeling is a good method to use when determining the distribution of marine mammals since this method is able to deal with a large proportion of zeros in the dataset (Keiper et al. 2005). Block 1 first accounted for variation attributed to wind, Isolated Average RMS SPL, and season, and then Block 2 incorporated the effects of depth, SSH, current and their interaction terms. The two block technique was designed in order to first take into account the effect of the abiotic variables, while the second block then examined the effect of the environmental and oceanographic variables. High correlations among predictor variables are particularly problematic for logistic regression (Tabachnick and Fidell 2007). A Pearson’s correlation coefficient matrix was calculated for all variables in pairs within the survey effort. Variable pairs with correlation coefficients ≥0.4 were flagged and evaluated. Sea surface temperature and sea surface height were positively correlated (r = 0.495, P = <0.001) and the sea surface temperature variable was removed from further analysis based on a priori considerations because sea surface height is a better predictor of potentially important oceanographic conditions such as upwelling eddies. In addition, ship speed and Isolated Average RMS SPL were positively correlated (r = 0.444, P = <0.001) and so ship speed was removed from further analysis due to the fact that ship speed was generally steady throughout
interisland transits while Isolated Average RMS SPL levels are likely to be affected by other environmental variables. Models were evaluated for appropriateness using Hosmer-Lemeshow goodness of fit tests for logistic regression models where a non-significant result indicates a well-fitting model (Hosmer and Lemeshow 1980).

**Results**

Over 400 hours of data were collected on 22 three-day surveys, covering a total of 9046 km over a period of 52 weeks (Figure 3.7). On these surveys, 496 dolphin whistles were recorded during 57 unique sightings (Figure 3.8 and Figure 3.11). Sightings were defined as groups of whistles with 30 min or more of silence between recordings of subsequent whistles.

![Figure 3.7: Number of hours of effort surveyed per week throughout the survey period (52 weeks or one year). Time is shown in weeks since January 1 since months are non-uniform units of time.](image)
Figure 3.8: Spectrogram of odontocete whistles recorded on June 29, 2011 at 21:33 HST. These whistles were classified as *Stenella longirostris/coeruleoalba* with ROCCA.

This gives an average of 0.63 odontocete sightings per 100 km surveyed. If humpback whale sightings are included, this equates to 1.8 sightings per 100 km. Of the odontocete sightings, 17 occurred in winter (December-Feb), 16 occurred in spring (March-May), 22 occurred in summer (June-August) and 13 occurred in fall (September-November). Thirty-eight odontocete sightings occurred at night and thirty occurred during the day (Figure 3.9).

Figure 3.9: Percent of total of survey effort vs. time of day (displayed as number of minutes since midnight) and percent of total of survey dolphin detections vs. time of day. There was no significant difference in time of detection between the overall survey effort and the odontocete detections.
The number of whistles recorded per sighting ranged from one to 71, with an average of 8.7 and a median of 4. Of these sightings, 4 were identified visually, while the remaining 53 were classified with the ROCCA classification algorithm. Three of four visual identifications agreed with the acoustic identification. Throughout the entire survey effort, water bottom depth averaged $1183\pm26$ m with a minimum depth of 9 m and a maximum of 3806 m (Figure 3.10).

The majority of odontocetes were found in water shallower than 1000 m, but they were also found in water with a maximum depth of 3631 m (mean depth was $855\pm121$ m). Odontocetes were found in significantly shallower water than the overall survey effort (Kruskal-Wallis $P=0.041$). Animals were detected in waters to the leeward sides of the islands, as well as in the deep-water channels between islands. The species identified are summarized in Table 3.2,
along with the average bottom depth for each species. Sightings classified as *Stenella longirostris/coeruleoalba* occurred near the four-island region of Maui, Lanai, Molokai, and Kahoolawe, as well as on Penguin Bank and on the lee of the Big Island of Hawaii. Sightings also occurred in the channel between Oahu and Kauai. Detections of *Pseudorca crassidens* occurred off Oahu, off Penguin Bank, in the four islands area, and on the Kona Coast of Hawaii. Detections classified as *Globicephala macrorhynchus* occurred off the Penguin Bank, in the channel between Kauai and Oahu, and off the Kona coast of Hawaii. Detections classified as *Steno bredanensis* were located off of Kauai, Oahu, and between Molokai and Kauai. Detections classified as *Tursiops truncatus* occurred on Penguin Bank and near Kauai. The single detection classified as *Stenella attenuata* occurred near Oahu.

**Table 3.2:** Species detected, with breakdown of visual IDs and total detections.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common Name</th>
<th>Visual IDs</th>
<th>Detections</th>
<th>Mean water Depth (Standard Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Globicephala macrorhynchus</em></td>
<td>Short Finned Pilot Whale</td>
<td>0</td>
<td>6</td>
<td>1682 ±554</td>
</tr>
<tr>
<td><em>Pseudorca crassidens</em></td>
<td>False Killer Whale</td>
<td>0</td>
<td>8</td>
<td>527 ±156</td>
</tr>
<tr>
<td><em>Stenella longirostris/coeruleoalba</em></td>
<td>Spinner Dolphin/Striped Dolphin</td>
<td>2</td>
<td>35</td>
<td>850 ±183</td>
</tr>
<tr>
<td><em>Stenella attenuata</em></td>
<td>Pantropical Spotted Dolphin</td>
<td>0</td>
<td>1</td>
<td>492</td>
</tr>
<tr>
<td><em>Steno bredanensis</em></td>
<td>Rough-toothed dolphin</td>
<td>0</td>
<td>4</td>
<td>861 ±335</td>
</tr>
<tr>
<td><em>Tursiops truncatus</em></td>
<td>Bottlenose Dolphin</td>
<td>2</td>
<td>4</td>
<td>34 ±10</td>
</tr>
</tbody>
</table>
Chlorophyll was low across the entire survey, averaging $0.119\pm0.009$ mg/m$^3$. Odontocetes were found in water with significantly lower Chlorophyll-A levels of $0.049\pm0.003$ mg/m$^3$ (Kruskal-Wallis $P=0.001$). Current averaged $-0.004\pm0.001$ cm/sec$^{-1}$ over the entire survey, but odontocetes were found in waters averaging $-0.003\pm0.004$ cm/sec. Average sea surface temperature of the entire survey was $25.38\pm0.02^\circ$C. Odontocetes were found in waters averaging $25.46\pm0.10^\circ$C. Sea surface height averaged $0.635\pm0.001$ m over the entire survey. Odontocetes were found in waters with sea surface heights averaging $0.647\pm0.008$ m. Wind
averaged 8.86±0.05 meters/sec\(^{-1}\) over the entire survey; the average wind speed for odontocete sightings was 8.79±0.31 meters/sec\(^{-1}\). Current, sea surface temperature, sea surface height, and wind all showed non-significant differences. A wind speed of between 8 and 10.8 m/s corresponds to a Beaufort wind scale of 5 (Figure 3.12).

![Figure 3.12: Detections per hour of effort in each category of the Beaufort wind scale. No detections occurred in waters under Beaufort 3, and 75% of survey effort occurred in Beaufort 4 and higher (see Figure 3.14). There was no significant difference in wind speed between survey effort and odontocete detections.]

The mean Isolated Average RMS SPL for the survey was 28.62 ± 0.14 dB, while the mean Isolated Average RMS SPL for the sightings was 26.70 ± 0.88 dB. There was a significant correlation between speed of the vessel and Isolated Average RMS SPL (r=0.444, P=<0.001, Figure 3.13). However, there was a non-significant negative correlation between wind speed and Isolated Average RMS SPL (r = -0.143, Pearson 1901).
Figure 3.13: Isolated Average RMS SPL vs Wind Speed and vessel speed (labeled as “speed”) for the entire survey and for just the odontocete sightings. The correlation for the speed of the vessel with the Isolated Average RMS SPL was significant (r=0.444, P=<0.001), while the correlation between the wind speed and the Isolated Average RMS SPL was not.
There was no significant difference between sightings for either time of day ($\chi^2 = 0.941$, df = 1, $P = 0.332$) or by season ($\chi^2 = 2.471$, df = 3, $P = 0.481$). The final stepwise binary logistic regression model of dolphin sightings on both biotic and abiotic variables indicated that odontocete location was slightly negatively associated with Isolated Average RMS SPL (coefficient = -0.04, $P = 0.033$), depth (coefficient = -0.002, $P = 0.031$), and the interaction of depth and sea surface height (coefficient = -0.003, $P = 0.053$) (Table 3.3). Although this model only has weak associations with the variables included, the model is a good fit for the data ($HL = 0.459$, $\chi^2 = 7.744$, df = 8).

**Table 3.3** Results of the 2 block stepwise binary regression model explaining dolphin locations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>S.E.</th>
<th>Wald</th>
<th>df</th>
<th>P</th>
<th>Odds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS SPL</td>
<td>-0.04</td>
<td>0.019</td>
<td>4.566</td>
<td>1</td>
<td>0.033</td>
<td>0.961</td>
</tr>
<tr>
<td>Depth</td>
<td>-0.002</td>
<td>0.001</td>
<td>4.632</td>
<td>1</td>
<td>0.031</td>
<td>0.998</td>
</tr>
<tr>
<td>Depth x Height</td>
<td>-0.003</td>
<td>0.002</td>
<td>3.753</td>
<td>1</td>
<td>0.053</td>
<td>1.003</td>
</tr>
</tbody>
</table>
Figure 3.14: Box-plot comparisons of bathymetry (depth) and satellite (CHL, Current, SST, Sea Surface Height, and Wind Speed) data from odontocete locations and survey effort. There were significant differences found for both depth and chlorophyll using non-parametric tests. The box plot shows the median (centerline), the upper and lower quartiles (edges of the box), and the range (edge of the bars or hollow circles). Hollow circles show outliers further than 1.5x the inter-quartile range from either quartile.

Figure 3.15: Box-plot comparisons of Isolated Average RMS SPL data from odontocete locations and survey effort. There was not a significant difference found using non-parametric tests.
Discussion

Addressing Biases in Survey Effort

The ultimate goal of this study was to fill in gaps in current data on odontocete distribution in Hawaii, especially in the deep-water channels between islands where data are spatially and temporally biased. This survey successfully detected odontocetes during all four seasons, including the under-sampled months of January and March through July. There was no significant difference in the number of sightings between seasons, indicating a lack of seasonality for odontocetes around and between the Hawaiian Islands. Survey transects were also successfully conducted at night, which has not been possible with visual surveys (Mobley et al. 2000, Barlow 2006, Baird et al. 2013, Bradford et al. in review). There was no significant difference in the number of detections between night and day, indicating that nighttime surveying should also be included in future research on odontocete distribution and habitat modeling. Odontocetes are still acoustically active at night. The current limitation of cetacean surveys to daylight hours may lead to overlooked distribution and diurnal behavior. For example, daylight-only surveys of Hawaiian spinner dolphins might not detect their diurnal offshore foraging behavior (Benoit-Bird and Au 2003). Of the 57 acoustic detections, only four were visually confirmed. The lack of visual sightings is unsurprising, considering that more than 75% of survey effort in this study was conducted in Beaufort Sea State 5 and above (Figure 3.15). This is in stark contrast to previous surveys done in Hawaii, where sighting rates dropped off rapidly beyond Beaufort 3 (Mobley 2001, Baird et al. 2005). For small boat surveys, the mean Beaufort scale for all species was less than 2 (Baird et al. 2013). In the 2002 and 2010
NOAA surveys, visual sighting effort was limited to Beaufort 0-6 (Barlow 2006, Bradford et al. in review). There has been no comparison between visual and acoustic detections for the 2010 NOAA survey, although it is planned (Bradford et al. in review). In visual surveys, the relative probability of detection for animals directly on the survey line drops with increasing Beaufort Sea state for many cetacean species, and the rate of decrease is higher for odontocetes than for mysticetes (Figure 3.16, Barlow 2015). The current study does not calculate $g(0)$, because calculating $g(0)$ would be inappropriate without information on survey strip width.

**Figure 3.16:** Decreases in detection probability $g(0)$ on the survey line for visual line transect surveys for seven of the six species detected in this study. *Pseudorca crassidens* is omitted.

Adapted from Barlow (2015).

Much of the ocean surrounding the main Hawaiian Islands has an average yearly Beaufort wind scale of 4 or greater (Schwartz et al. 2010). With the steep drop in visual detection probability for these species, acoustic survey methods may be an important complement to visual surveys.
Figure 3.17: Generalized ambient noise spectra attributable to various sources, including Beaufort Sea State, compiled by Wenz (1962) and replotted in Richardson (1995) using modern units.
Beaufort wind state also has an effect on underwater ambient sound. Wenz (1962) stated a “rule of fives,” which said that between 500 Hz and 5 kHz, spectrum levels decrease 5 dB per octave as frequency increases, and increase 5 dB with each doubling of wind speed (Figure 3.17). In shallow water (less than 183 m) at 1 kHz, the frequency with the highest SPL for wind noise, the SPL would be 56 dB re 1 µPa for a wind speed of 5 knots (BF 2, Richardson 1995). Using these rules, a rough estimate for SPL at BF 6 would be 66 dB re 1 µPa. In another rough estimate using the sonar equation:

\[ RL = SL - 20 \times \log(R) \]

where RL is the received level, SL is the source level, and R is the distance sound travels, the range where the RL of a 130 dB signal, 1 kHz sound would be above wind noise is estimated to be approximately 15 km for BF 6 and 56 km for BF 2. Again, these are only rough estimates and a more complete analysis would need to be done to determine the detection ranges of cetaceans that incorporate sound speed profiles, frequency, and other important information. However, even this rough estimate is interesting to compare to the sighting ranges of visual surveys, which are often limited to less than 10 km or the visual distance to the horizon from the ship’s flying bridge (Barlow and Lee 1994). Visual surveys for both sea turtles and cetaceans have shown a negative linear relationship between Beaufort and sighting distance, with perpendicular distance, and the resulting sighting rate, reduced by a constant proportional amount ((Beavers and Ramsey 1998, Barlow et al. 2001) Figure 3.18).
Figure 3.18 Covariates of Beaufort sea-state plotted against unadjusted, ungrouped perpendicular sighting distances (m) for sea turtles the eastern tropical Pacific, 1989-90. From Beavers (1998). Barlow (2001) found similar results for decreases in perpendicular sighting distance of cetaceans during the same study but did not report them in a similar figure.

The data collection for this study was conducted predominantly in the difficult visual survey conditions that characterize the rough, deep-water channels between the Hawaiian Islands. Data was also collected at night, when visual surveys are not possible. The acoustic survey effort used in this study is less biased in regards to wind speed than previous surveys using visual methods, in particular those which focus on areas with low wind speed/Beaufort (Baird et al. 2005). Isolated Average RMS SPL did not correlate with odontocete detections. This was observed by finding no difference in Isolated Average RMS SPL between odontocete sightings and overall survey effort, and odontocete sightings showed a slight increase with lower Isolated Average RMS SPL through the logistic regression modeling. While the mean Isolated Average RMS SPL for the odontocete sightings (26.70 ± 0.88 dB) was lower than for the overall survey
effort (28.62 ± 0.14 dB), the variance in SPL values for the survey was very low, indicating that the noise level in the environment being sampled was generally constantly high. The spatial distribution of the odontocete sightings and the range of Isolated Average RMS SPL values indicate that this survey method was able to detect odontocetes in all but the highest noise environments. The positive correlation between speed and Isolated Average RMS SPL shows a skewed distribution which indicates that while there is an increase in Isolated Average RMS SPL with increasing speed, there is a large range in Isolated Average RMS SPL at low speed. Additionally, the skewed distribution of ship speed indicates that low speeds (generally <6mph) were only obtained while leaving and entering ports. In other words, the ship traveled slowly when it is heading into and out of port, but travels at a steady speed (averaging 8.32 ± 0.05 mph) at other times. The relationship of speed and depth reinforces the result that there was no difference in Isolated Average RMS SPL between odontocete sightings and overall survey effort by showing that at low speed, the ship was generally located in shallow water, while at cruising speeds, the ship was located across the entire range of depths encountered during the survey. The average number of sightings per 100 km was comparable to that of other studies in the Hawaii region; directed, small boat surveys have found 2.3 odontocete sightings per 100 km (Baird et al. 2013), ship-based surveys have found 1.8 (Bradford et al. in review) and 1.3 sightings per 100 km (Barlow 2006). Aerial surveys had 5.41 sightings per 100 km of effort for all cetaceans, and 0.6 sightings per 100 km for odontocetes (Mobley et al. 2000). By comparison, this survey found an average of 1.8 cetacean sightings per 100 km of effort, in line with other ship based survey methods. This leads us to believe that our survey method is capable of
collecting comparable data on the presence of odontocetes given the challenging survey
conditions faced.

\textit{Distribution of Odontocete Species}

Detections of all odontocetes species as a group were found in shallower water relative
to the survey effort (855±121m), but this is likely to be highly influenced by the most numerous
species, \textit{Stenella longirostris/coeruleoalba} which is generally found in shallow near shore water
and in this survey was found at an average depth of 850 ±183 m. Greater sample sizes would be
needed to make statistically robust conclusions about other individual species. Results of the
stepwise binary regression showed that the variables that associate with odontocete locations
were shallow water and lower SPL. High sea surface height is generally associated with
upwelling (Miller and Wheeler 2012), and many of the odontocetes detected in this survey
were found on the shelf areas on either side of the deep water channels.

The greatest numbers of sightings (N = 35) in this study were classified as \textit{Stenella
longirostris/coeruleoalba}. \textit{Stenella longirostris} is one of the most well-studied odontocetes in
the Hawaiian islands, likely because of its near shore distribution and characteristic spinning
behavior (Norris \textit{et al.} 1994). Previous aerial surveys in Hawaiian waters have found them as the
second (Mobley 2004), fourth (Barlow 2006) and fifth most abundant odontocete species (Baird
\textit{et al.} 2013). Population levels of \textit{Stenella longirostris} dolphins around the main Hawaiian
Islands are currently estimated to be 3,351 individuals (CV = 0.45, Barlow 2006) based on ship
surveys done in 2002. These numbers were not updated for the 2010 surveys because the
species was not sighted (Bradford \textit{et al.} in review). Since 2002, changes in detection probability
along the survey line \( g(0) \) estimation have been updated, and so population may be significantly different than previous estimates (Barlow 2015). The sightings of the Stenella longirostris/coeruleoalba group by depth is similar to that found for spinner dolphins (Baird et al. 2013), but is very different than that of striped dolphins, which were predominantly found in deeper water (4000 m and deeper). Andrews et al. (2006) found indications of genetic flow between spinner dolphin stocks in Kauai, Oahu, and Maui, but that Kona spinner dolphins were genetically distinct. In light of the lack of genetic flow, we would expect to detect fewer spinner dolphins traveling in Alenuihaha channel between Maui and the big Island of Hawaii than in the Kaieie Waho channel between Oahu and Kauai.

The second largest number of detections was classified as Pseudorca crassidens \( (N = 8) \). In previous studies in the main Hawaiian Islands, this species has been the 8\(^{th}\) (Baird et al. 2013) and 10\(^{th}\) (Barlow 2006) most abundant species in the main Hawaiian Islands. However, this species was seen in very low numbers during aerial surveys in 1995, 2000, and 2003 (Mobley et al. 2000). The Hawaii Insular Stock, which is differentiated from the larger pelagic stock via genetics, photo id, and movement data (Chivers et al. 2007, Baird, Gorgone, et al. 2008, Baird, Webster, et al. 2008), was estimated to number 151 (\( CV = 0.20 \)) individuals from 2006-2009. The most current stock assessment estimates that the pelagic population is 1552 (\( CV = 0.66; 95\% \text{ CI} = 479–5030 \)) and the Hawaii Insular Stock population as 552 (\( CV = 97-3123 \), Bradford et al. 2014). Previous studies of this species have found them predominantly in water of 4000 m or deeper, although they have also been found in shallow waters (Baird et al. 2013). The locations of Pseudorca detections from the current study are different than those found in
small boat surveys around the main Hawaiian Islands, which had concentrations in the Kalohi channel between Maui and Lanai, as well as off the leeward Coast of the Big Island.

The third largest number of detections was classified as *Globicephala macrorhynchus* (N = 6). These have been the most frequently encountered species in small boat surveys (Baird *et al.* 2013) and is estimated to have the fifth largest abundance in the Hawaiian EEZ (19503, VV = 0.49, CI = 7,889-48,214, Bradford *et al.* in review). It was the third most abundant species found in aerial surveys (Mobley *et al.* 2000). Detection probability in visual surveys of this species is less impacted by increases in wind or sea state, as evidenced by the slow rate of decrease of its g(0) value (Figure 3.16).

The fourth largest number of detections was classified as *Steno bredanensis* (N = 4). Baird (2008) found most *Steno bredanensis* in the waters off Kauai and the Kona coast of the big island, with one sighting near Oahu. Population levels of rough toothed dolphins around the main Hawaiian Islands are currently estimated to be 72,528 individuals (CV = 0.39, CI = 34,786-151,219, Bradford *et al.* 2014) based on ship surveys. The previous estimate of abundance for this species, before g(0) correction, was 8,709 (CV = 0.45, Barlow 2006). This species was also not detected in very low numbers during aerial surveys (Mobley *et al.* 2000). Photographic ID studies have indicated a small population with high site fidelity for this species off of the island of Hawaii, and a larger population size off of Kauai with a lower site fidelity (Baird, Gorgone, *et al.* 2008). Only two individuals were photographed moving between these two populations. New estimates of g(0) for *Steno* indicate that visual detectability for this species decreases steeply above a Beaufort of 1 (Figure 3.16, Barlow 2015). The mean Beaufort scale where they were sighted in small boat surveys was 1.7 (Baird *et al.* 2013). With such a small sample size for
the current study, it is impossible to come to any concrete conclusions about distribution. However, it is interesting to note that all detections of this species were in locations where they have previously been rarely reported (Baird et al. 2013), possibly because surveys have not been conducted in these areas. Equal numbers of detections were classified as *Tursiops truncatus* as *Steno bredanensis* (N = 4). Population levels of *Tursiops* around the main Hawaiian Islands are currently estimated to be 21,185 individuals (CV = 0.57, CI = 7,673-62,203, Bradford et al. in review) based on ship surveys. The previous estimate, based on outdated g(0) values, was 3,215 for the entire EEZ (CV = 0.59, Barlow 2006). This species was the most common odontocete identified during aerial surveys (Mobley et al. 2000).

Although detections from a straight-line transect cannot be used for abundance estimates due to the absence of data concerning the distance from the trackline to the animal, the results of this study highlight the need to examine alternative methods for collecting density data, especially for cryptic species and in areas with high wind speeds. Abundance estimates from acoustic data have been calculated for several species, including beaked whales (*Berardius* spp., *Hyperoodon* spp., *Indopacetus pacificus*, *Ziphius cavirostris*, *Mesoplodon* spp. and *Tasmacetus shepherdi*, Barlow and Taylor 2005, Marques et al. 2009), and sperm whales (*Physeter macrocephalus*, Barlow and Taylor 2005, Lewis et al. 2007). These acoustic abundance estimates have focused on species which are difficult to detect visually and/or rare. Abundance estimates from distance sampling take into account many variables, but two of the most important are sample size (N) and estimated strip width (ESW). New analysis shows that visual detectability decreases as Beaufort Sea State increases, for all species but especially for inconspicuous species (Barlow 2015). The 95% confidence interval for abundance estimates is in
the range of the tens of thousands for several species (Bradford et al. in review). The coefficient of variation is equal to the standard deviation divided by the mean, while the confidence interval is equal to:

\[ \bar{x} \pm z \frac{s}{\sqrt{n}} \]  

(1)

where \( \bar{x} \) is the mean, \( z \) is equal to 1.96, \( s \) is the standard deviation, and \( n \) is the sample size.

Expanding the use of acoustic line transect methods to other species that are difficult to detect in high wind conditions, including delphinids such as *Stenella longirostris*, *Steno bredanensis*, *Stenella attenuata*, and *Tursiops truncatus*, has the potential to increase ESW and, in turn, decrease the error surrounding population estimates. For example, concurrent acoustic and visual surveys of sperm whales did not show significantly different abundance estimates, and the use of acoustic surveys both increased the detection range and the number of detections (Barlow and Taylor 2005). In order for acoustic methods to be used for distance estimation, more information is needed on species specific call features in multiple contexts, animal depth, and range of detection (Cholewiak et al. 2013). Even accepting the assumption used in previous studies that \( g(0) = 1 \) for acoustic surveys (Barlow and Taylor 2005), group size currently must still be estimated visually.

**Future work**

Future improvements to the equipment used in this study and implications for data quality were discussed at length in Chapter 2. In addition, this study relies heavily on the ROCCA acoustic classification algorithm to predict species for each detection (Oswald et al. 2003,
Oswald et al. 2013). This algorithm is currently based on dolphin whistles collected on the same species in the eastern tropical Pacific, and so there may be some variation in the whistle types from the different regions. Efforts are ongoing to improve the classification algorithm by adding more data collected from more areas, including from Hawaiian waters. This might reduce the amount of unclassified whistles, and further improvements might be made to the algorithm to strengthen its ability to classify faint or incomplete whistles.

Many surveys have collected concurrent visual and acoustic data (see Table 3.1, and (Swartz et al. 2003, Oleson et al. 2007, Moore et al. 2010), but few studies have compared visual and acoustic sightings (Akamatsu et al. 2001, Mellinger and Barlow 2003, Barlow and Taylor 2005, Oleson et al. 2007). Comparison of concurrent visual and acoustic sightings may give insight into calling rate and the relationship between calling rate and group size. Use of acoustics complements visual methods for large, easily visible species (Oleson et al. 2007) and acoustic detections can be higher than visual detections for small or cryptic species (Barlow, Ferguson, et al. 2005, Barlow and Taylor 2005). Further comparisons of these visual and acoustic survey types may improve uncertainty abundance estimates and increase our ability to effectively manage these species.


Barlow, J. 2015. "Inferring trackline detection probabilities, g (0), for cetaceans from apparent densities in different survey conditions." *Marine Mammal Science*.


  echolocating atlantic bottlenose dolphin (tursiops truncatus)." Journal of the 

  echolocate on prey." Proceedings of the Royal Society of London B: Biological Sciences 

  echolocate on prey." Proceedings of the Royal Society of London Series B-Biological 
  Sciences 271:S383-S386.

Kaschner, K., N.J. Quick, R. Jewell, R. Williams, and C.M. Harris. 2012. "Global coverage of 
  cetacean line-transect surveys: Status quo, data gaps and future challenges." PloS one 7 
  (9):e44075.

  climate off central california, 1986 to 1994 and 1997 to 1999." Marine Ecology Progress 

  research ship line-transect surveys by the southwest fisheries science center." NOAA, 
  SWFSC Administrative Report LJ-00-08.


http://coastwatch.pfeg.noaa.gov/coastwatch/ CWBrowserWW180.jsp


Ostman, J.S.O. 1994. "The social organization and social behavior of the hawaiian spinner dolphins (stenella longirostris)." Ph.D., University of California.

Oswald, J., and M. Oswald. 2013. "Rocca (real-time odontocete call classification algorithm) user's manual."


"Gaussian mixture model classification of odontocetes in the southern california bight and the gulf of california." *Journal of the Acoustical Society of America* 121 (1737-1748).


SOESTb. "School of oceanography and earth science technology (soest) public database "  


CHAPTER 4. UNDERWATER SOUND MEASUREMENTS OF A HIGH SPEED JET-PROPELLED MARINE CRAFT: IMPLICATIONS FOR LARGE WHALES

NB: This Chapter has been published in Pacific Science as


Abstract: Radiated noise from a high speed jet propelled watercraft (the M/V Alakai, 1,646 tons, length 117 m) was measured at hydrophone depths of 3, 6, and 10 m while the ship passed by at speeds of 6.17 m/sec (12 knots), 12.35 m/sec (24 knots), and 19.03 m/sec (37 knots). Noise spectra were similar for all speeds and hydrophone depths. Spectra peaked below 100 Hz and dropped off continuously at higher frequencies. Calculated source level noise was 10 to 20 dB lower than noise from propeller driven ships and much lower than for ships of similar speed. Although exposure to noise radiating from the M/V Alakai over short time periods is unlikely to cause hearing damage to whales, the combination of low radiated noise levels and high transit speeds leads to a shorter closing time (defined as time between when source level of the ship at a stationary receiver is greater than ambient noise and time that a ship traveling directly toward the receiver arrives at its location) between ship and whale. Compared with other types of ships traveling at similar speeds, closing time for the Alakai ranges from 20 sec shorter (at 6.17333 m/sec (12 knots)) to 22 min shorter (at 19.0344 m/sec
(37 knots)). Shortest closing time for the Alakai is 89.1 sec at a speed of 6.17 m/sec (12 knots). Shortened closing time might reduce successful detection and avoidance of high speed jet propelled ships by whales, and increased speed shortens the time during which whales have the opportunity to respond to this detection.

Introduction

Two main issues of concern for the impacts of high-speed jet-propelled craft (HSC) to cetaceans are the impact of anthropogenic noise and the possibility of ship strikes. Jet-propelled craft (which use water jets) are fundamentally different from conventional craft in that they have no external propellers. Instead, an intake at the bottom of the hull allows water to pass underneath the vessel and into a pump. The water pressure inside the inlet is increased by the pump and forced backwards through a nozzle to propel the craft. As a result of this increased water pressure, jet-propelled craft have a higher cavitation inception speed than conventional craft with external propellers. Cavitation is the primary source of underwater noise from marine craft (Badino et al. 2012). In 2009, measurements were taken of the radiated noise of a jet-propelled high-speed craft (the M/V Alakai, International Maritime Organization no. 9328912) at different speeds to estimate its acoustic impact and to determine its detectability and possible impact on whales.

In addition to its influence on ship detectability and strikes, ship noise could also have other adverse effects on whales. Hearing is an important sensory system for cetacean foraging and communication because sight, touch, and chemoreception have limited ranges and signal
speeds underwater. Anthropogenic noises, such as those produced by ships, can have deleterious physiological, acoustical, and behavioral effects on cetaceans. Physiological impacts include hearing damage (Southall 2007, Clark et al. 2009, Mooney et al. 2009) and increased stress hormone levels (Rolland et al. 2012). Sounds can result in acoustic masking of communication signals (Clark et al. 2009, Jensen et al. 2009, Hatch et al. 2012). Behavioral changes related to anthropogenic sound include avoidance (Moore and Clarke 2002, Dunlop et al. 2013), changes in call characteristics (Parks et al. 2007, Holt et al. 2009, Parks et al. 2011), changes in song length (Fristrup et al. 2003, Risch et al. 2012), and changes in dive behavior (Nowacek et al. 2007, Pirotta et al. 2012). Humpback whales produce two types of signal: songs and social sounds. Songs are between 5 and 20 min long and consist of repeating themes (Payne and McVay 1971). Although the exact function of these songs is not fully understood, there is consensus that the songs play an important role in behavior and social interactions (Tyack and Whitehead 1983, Frankel et al. 1995, Au et al. 2000). In this study, we present measurements of underwater sound for a high-speed craft and discuss the potential ability of cetaceans to acoustically detect this ship type from various distances in comparison with detection of conventional ships with external propellers.

**Materials and Methods**

Radiated noise was measured from the Alakai, an aluminum-hull catamaran ferry designed by Austal USA. It is 117 m long and 24 m wide, with a displacement of 1,646 tons. The ferry is powered by four engines (MTU 20V 8000 M70) with two propulsion jets (KaMeWa 125
The ferry’s maximum speed is 20.5778 m/sec (40 knots). Measurements of both speed and sound were made in three locations that were comparable in depth and bottom type in the vicinity of Honolulu Harbor (O’ahu, Hawai‘i) to minimize alterations to the ferry’s usual route and operational procedures (Figure 4.1). Underwater sound recordings were made with the Alakai making passes by the recording ship at 6.17 m/sec (12 knots), 12.35 m/sec (24 knots), and 19.03 m/sec (37 knots).

Figure 4.1. Map showing the locations where the radiated noise from the Alakai was measured at speeds of 12 knots (54 m depth), 24 knots (215 m depth), and 37 knots (250 m depth). Inset map shows the island of Oahu. Specific geomorphology of the bottom is unavailable at these locations, but is probably sand or pavement (defined
as lowrelief, carbonate rock with coverage of algae, hard coral, gorgonians, zooanthids or other sessile vertebrates dense enough to partially obscure the underlying surface).

The Alyce C, a 10 m sport fishing boat, was used as the recording platform. The water depth was 54 m for the 6.17333 m/sec (12knot) measurement, 215 m for the 12.3467 m/sec (24 knot), and 250 m for the 19.0344 m/sec (37knot) measurement. The Alakai’s route was chosen so that the noise radiating from the bow, broadside, and stern aspects could be measured. A similar trajectory was used for all three runs at different speeds. Recordings were made continuously during each pass, and a subset of each pass was used for analysis. GPS positions (accurate to 15 m) from both the Alakai and the Alyce C were used to calculate the distance for closest approach of the ship and to calculate the sound pressure levels (dB re 1 µPa at 1 m) for the three different aspects (bow, broadside, and stern of the Alakai).

Three hydrophones located at different depths (3 m, 6.5 m, and 10 m) recorded simultaneously on two synced digital recorders. Two calibrated spherical hydrophones were used, an International Transducer Corporation model 1032 (s = −192 dB re V/µPa up to 45 kHz) and an Edo Western model (s = −194 dB re 1 V/µPa over a 40 kHz range). The transducer at 10 m was custom built with a spherical piezoelectric ceramic element housed in a cylindrical package including preamplifiers (s = −185 dB re 1V/µPa and a flat response up to 200 kHz). Two different digital recorders (Microtrack) operated at a sample rate of 44.1 kHz with 16 bits. The recorders were turned on simultaneously, and a calibration noise was made to provide a more precise sync signal to each hydrophone.
The root mean square (RMS) sound pressure level at the receiving boat was calculated using the following equation:

\[
p_{\text{rms}} = \sqrt[2]{\frac{1}{T} \int_0^T p(t)^2 \, dt}
\]  

where \( p(t) \) is the acoustic pressure as a function of time. An integration time of 1 sec was used to determine the sound pressure level as a function of time for each second of recording for all three hydrophones. The radiated noise from the Alakai at different aspects (bow, broadside, and stern aspects) was calculated in the laboratory, using timesynced video and the timestamped GPS tracks from the Alakai to determine the time at which the ferry would have its bow directed (within 10°) toward the hydrophone array, when it would be broadside, and when it would have its stern directed within 45°. Aspect was determined from both the video footage and the angle from the Alyce C’s location to the Alakai’s route. Once the appropriate times were found, the distance between the two vessels was calculated and the received sound pressure level was referenced to 1 m re 1 μPa using the following equation:

\[
SPL_{\text{1m}} = SPL_{\text{rec}} + 20 \log(R)
\]  

where \( SPL_{\text{1m}} \) is the sound pressure level at 1 m, \( SPL_{\text{rec}} \) is the recorded sound pressure level, and \( R \) is the distance between the hydrophone and the sound source. This equation assumes spherical spreading of the acoustic energy, which is an approximation of the sound propagation. Modeling based on simple propagation is sufficient due to the short ranges, and detailed modeling of the propagation is beyond the scope of this project. The range at which
the Alakai noise from the bow aspect would be louder than ambient noise was found by calculating the spherical spreading (equation 2) and determining at what distance $R$ the SPL of ship noise was greater than the SPL of ambient humpback whale chorusing during peak season (at this time, ambient noise levels are determined by the level of whale chorusing (Au et al. 2000)). Closing time, defined here as the difference between the time when the sound of the ship is louder than the ambient noise during peak chorusing and the time when the ship would arrive at that location, was determined using the following equation, which divides the range (or distance between the animal and the ship) by the speed of the ship:

\[
Time = \frac{Range}{Speed}
\] (3)

Results

Examples of the timeline of sound pressure levels before, during, and after passage of the ferry are shown in Figure 4.2. At the closest approach, the ferry was nearly broadside to the hydrophone array and there is a peak in the recorded sound levels at 10 m depth, as can be seen in Figure 4.2. The sound pressure level at 1 m, as a function of speed, is shown in Figure 4.3 for the three different aspects of the Alakai with respect to the three hydrophones at depths of 3, 6.5, and 10 m. The hydrophone at the 10 m depth always measured the loudest sounds for three speeds of the Alakai. This is probably a result of the fact that, at shallower depths, sound waves can be reflected off the surface, resulting in faster attenuation. Intensity of the ship sounds generally increased with speed except for two situations for the stern aspects involving the hydrophones at 3 and 6.5 m depth. The radiated sound measured
broadside to the Alakai had the highest intensity at 37 knots, 12 to 15 dB higher than at the bow and stern aspects. The radiated sounds from the bow and stern had very similar intensity values. The loudest sound SPL (197.1 dB re 1 μPa) occurred at the broadside aspect with the Alakai traveling at a speed of 19.03 m/sec (37 knots).

**Figure 4.2.** Examples of received sound pressure levels as a function of time for the hydrophone at the 10 m depth. Recordings for depths of 3 m and 6.5 m were similar. The range between the Alakai and the Alyce C varied as a function of time according to the specific trajectory of the ferry.
Figure 4.3. The broadband (0–22 kHz) sound pressure levels of the ship noise as a function of speed and aspect of the Alakai. SPLs were calculated using Equation 2. GPS accuracy resulted in an uncertainty of ±23.5 dB. This type of uncertainty is inherent in any study that uses GPS locations to determine distance for SPL calculation.

The frequency spectra of the radiated sounds with the ferry traveling at 19.03 (37 knots) are shown in Figure 4.4 for the 10 m hydrophone, the 6.5 m hydrophone, and the 3 m hydrophone. All of the spectra were similar and consisted of broadband noise between 0 and 22 kHz (the upper limit being determined by the Nyquist frequency). The levels were highest at lower frequencies (100 Hz and lower) and decayed continuously at higher frequencies. There were no tonal signals recorded during ship passes. Although most ships typically have
distinguishing acoustic characteristics between 0 to 5 kHz, only broadband noise was evident in these lower frequencies.

![Figure 4.4](image-url)

**Figure 4.4.** The frequency spectra of the radiated noise from the Alakai traveling at 37 knots, integrated over 1 s, as measured by the hydrophone at a depth of 10 m for the bow aspect (front of the ship), the beam aspect (perpendicular to the ship), and the stern (back of the ship). Frequency is on the horizontal axis and the relative amplitude is on the vertical axis. Low frequency noise was also broadband with no distinguishing acoustic features. The spectra were computed with a Fast Fourier transform (FFT) algorithm within Matlab, using a rectangular window and 44,100 points. Hydrophone sensitivity was not included when creating these spectra.

**Discussion**

The effects of ship traffic on cetacean populations are of increasing concern. Total numbers of ships on the ocean have increased over the last 50 yr, as has the speed at which these ships can travel. Reports of large whale ship strikes have increased in parallel with an
increase in ship tonnage and speed (Laist et al. 2001, Vanderlaan et al. 2009). Coincident to these changes has been a 10–12 dB increase in low frequency ambient noise (Andrew et al. 2002, Jensen et al. 2004, McDonald et al. 2006). As was shown in the study reported here, the radiation of sound from ships is dependent on both the angle from the beam (defined as perpendicular to the ship) and the depth (Allen et al. 2012). Mitigation of ship strikes for ships of the type in this study must be based on research on the effect of noise and approaching ships on whale behavior.

The northern Pacific population of humpback whales is a specific example of one species that could be impacted by this ship type. In Hawai‘i, the number of ship strikes has been increasing since 1975 (Lammers et al. 2013). Humpback whales (Megaptera novaeangliae), which migrate seasonally to Hawai‘i during their breeding and calving season, are of particular interest because of their growing population around the Hawaiian Islands (Barlow et al. 2011). Historical records of whale strikes in Hawai‘i occur most frequently from January through March (Thompson and Friedl 1982, Mobley 2001), when whales are at their highest densities. Ship strikes are primarily reported off the island of Maui. Of known age classes, 60% of the reported collisions were with juveniles or calves. The majority of reported ship speeds in collisions were over 5.14 m/sec (10 knots), which is consistent with other research demonstrating a relationship between increased speed and higher ship strike frequency (Vanderlaan and Taggart 2007, Gende et al. 2011). At the maximum legal approach distance, the radiated sound of the Alakai is not expected to cause threshold shifts in humpback whale hearing. Although there have been no hearing measurements to date for any of the large whales, modeling suggests that they can hear sounds between 100 Hz and 10 kHz (Houser et al. 2012).
With the Alakai traveling at 19.03 m/sec (37 knots) at a range of 91 m (the closest legal distance that a ship can approach), the highest received level was calculated as 160 dB. At a speed of 19.03 m/sec (37 knots), the Alakai would expose a whale to this level of sound for 10 sec or less. However, singing humpback whales emit units in their songs that have intensities up to approximately 170 dB (Au et al. 2006), and humpback whales have been observed swimming within one body’s length of the singer (Darling and Berube 2001). Thus at least for short time periods, it is likely that such sound levels will not cause either temporary or permanent hearing damage (also known as threshold shifts) to humpbacks. However, the frequencies of the noise from the Alakai do correspond to those of humpback song and could interfere with communication. The fundamental frequencies of humpback song can be as low as 200 Hz, although harmonics can range up to 24 kHz (Au et al. 2006).
Figure 4.5. Comparison of noise measurements from the Alakai and other ships of similar speeds and SPLs. All measurements are taken from the broadside of the ships. The Alakai is consistently quieter than other ships, especially at high speeds. Data from McKenna et al. (2012) is indicated by * and data from Allen et al. (2012) is indicated by **.
Figure 4.6. Estimated range in km at which the received sound of the Alakai would be louder than ambient noise of humpback whale song during whale chorusing in peak humpback season for whales located at a depth of 3 m and 10 m. This is the distance at which a ship could be potentially detected. SPL measurements from the bow aspect of the ship are used because this is the orientation in which a ship would be approaching the whale.

The noise from the bow at a speed of 19.03 m/sec (37 knots) had a maximum intensity of 184.5 dB. The Alakai is quieter than ships traveling at similar speeds (Figure 4.5, Allen et al. 2012, McKenna et al. 2012). Most ship noise comes from propeller cavitation (Badino et al. 2012), and the fact that water jet propulsion involves no external propellers may be reducing the amount of cavitation. Ship size and speed are correlated with higher noise levels (McKenna et al. 2013), but other metrics such as hull shape, propeller type, and ship loading probably play a part and warrant study. Figure 4.6 shows the detection range, which we define here as the distance at which the radiated sound of the ship is quieter than 120 dB, the ambient noise level
during peak whale season (RMS sound pressure level from Au et al. 2000) for receivers at depths of 3 m and 10 m. Detection range was calculated by inserting the SPL$_{1m}$ values determined from the recordings into equation 2 and increasing the value of R until the SPL$_{rec}$ value was smaller than 120 dB. We chose this simple definition of detection range because there are currently no available studies of large whale hearing ability. The detection range assumes higher discrimination ability than is probably realistic for humpback whales, and thus is an overestimation of detection ranges. In addition, humpback whale abundance has been increasing since 2000 (Barlow et al. 2011), and so ambient noise levels during chorusing have probably also increased, which would result in a smaller detection range and shorter closing time. The detection range calculated here is shortest at 6.17 m/sec (12 knots) and increases with increasing speed. Detection ranges are shorter for receivers at 3 m than at 10 m. Thus, a whale at 10 m depth would detect the ship from farther than a whale at 3 m. A whale at 3 m is more likely to be struck by the ship, because of its closer proximity to the surface. We define closing time as the time between when the source level of the Alakai at a stationary receiver is greater than ambient noise and the time that a ship traveling directly toward the receiver arrives at its location. In comparison with other ship types traveling at similar speeds, closing time for the Alakai at all speeds is between 20 sec (at 6.17 m/sec (12 knots)) and 22 min (at 19.0344 m/sec (37 knots)) shorter. At the slowest speed of 6.17 m/sec (12 knots), the shortest closing time for the Alakai ranged from 89.1 sec at 10 m to just 13 sec at 3 m (Table 4.1, Figure 4.7).
Table 4.1: Comparison between Alakai Speed, SPL, Distance (m) at which the ship is audible above ambient noise, and Closure time (s, defined as the time between when the source level of the ship at a stationary receiver is greater than ambient noise and the time that a ship traveling directly toward the receiver arrives at its location) with ships traveling at similar speeds. Speed and SPL data for other vessel types from Allen et al. 2012, McKenna et al. 2012 and distance and closure were calculated as part of this study.

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Speed (m/s)</th>
<th>SPL at 1 m re 1 µPa</th>
<th>Distance (m)</th>
<th>Closure (s)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fishing Vessel</td>
<td>5.4</td>
<td>179.0</td>
<td>890.0</td>
<td>164.8</td>
<td>Allen</td>
</tr>
<tr>
<td>Fishing Vessel</td>
<td>5.8</td>
<td>192.0</td>
<td>3980.0</td>
<td>690.8</td>
<td>Allen</td>
</tr>
<tr>
<td>Fishing Vessel</td>
<td>6.0</td>
<td>180.0</td>
<td>1000.0</td>
<td>167.6</td>
<td>Allen</td>
</tr>
<tr>
<td>Alakai</td>
<td>6.2</td>
<td>174.9</td>
<td>550.0</td>
<td>89.1</td>
<td>This Study</td>
</tr>
<tr>
<td>Tanker (Chemical)</td>
<td>6.2</td>
<td>176.6</td>
<td>670.0</td>
<td>108.1</td>
<td>McKenna</td>
</tr>
<tr>
<td>Fishing Vessel</td>
<td>6.4</td>
<td>187.0</td>
<td>2230.0</td>
<td>349.6</td>
<td>Allen</td>
</tr>
<tr>
<td>Container</td>
<td>11.0</td>
<td>184.2</td>
<td>1620.0</td>
<td>147.3</td>
<td>McKenna</td>
</tr>
<tr>
<td>Container</td>
<td>11.2</td>
<td>188.1</td>
<td>2540.0</td>
<td>226.8</td>
<td>McKenna</td>
</tr>
<tr>
<td>Cruise Ship</td>
<td>11.3</td>
<td>219.0</td>
<td>89120.0</td>
<td>7910.3</td>
<td>Allen</td>
</tr>
<tr>
<td>Alakai</td>
<td>12.3</td>
<td>179.9</td>
<td>980.0</td>
<td>79.4</td>
<td>This Study</td>
</tr>
<tr>
<td>Catamaran</td>
<td>13.9</td>
<td>201.0</td>
<td>11220</td>
<td>804.8</td>
<td>Allen</td>
</tr>
<tr>
<td>High Speed Craft</td>
<td>18.4</td>
<td>210.0</td>
<td>31620</td>
<td>1716.9</td>
<td>Allen</td>
</tr>
<tr>
<td>Alakai</td>
<td>19.0</td>
<td>197.1</td>
<td>7160.0</td>
<td>376.2</td>
<td>This Study</td>
</tr>
</tbody>
</table>
Reactions of marine mammals to the noise of approaching ships are poorly understood and variable by species (Nowacek et al. 2004b, MiksisOlds et al. 2007, Southall 2007). Manatees show avoidance reactions to louder ships, reducing the risk of ship strikes (Miksis Olds et al. 2007), but North Atlantic right whales react to alert stimuli by surfacing or even approaching the ship, putting them at greater risk of ship strike (Nowacek et al. 2004a). Whale behavior on hearing the sound of an approaching ship could fall into one of three categories: no reaction, approaching the ship, and avoiding the ship. Considering the dearth of information on cetacean response to ship noise, we do not feel that we can make a prediction about how humpback
whales will react to the sound of an incoming ship. More research is needed on this subject, or more species. If a whale did show an avoidance response, it is uncertain whether the closing times at most speeds and depths are long enough for the whale to hear the ship, recognize it as a threat, and move out of the way (Figure 4.7). The recognition and response time of human observers to whales in the path of a ship is beyond the scope of this paper, but merits further study. Slowing ship speed may give human operators more time to respond to whales in the path of the ship. Slower ships are involved in fewer ship strikes, and mitigation efforts in some parts of United States waters include speed restrictions to protect vulnerable whale populations, such as the North Atlantic Right Whale (Kraus et al. 2005), showing that decreased speed reduces ship strikes even with a possible concurrent decrease in maneuverability.

**ACKNOWLEDGEMENTS**

The authors would like to thank Joe Reich, Joseph Mobley, Jerry Blaine, Valerie Alys, and Andrew McDougal, as well as the Hawaii Superferry Company for their cooperation.
Works Cited


CHAPTER 5. A PORTABLE METHOD FOR THE USE OF DIFAR TECHNOLOGY TO STUDY BEHAVIOR AND RELATIVE MOVEMENT OF MARINE MAMMALS

Introduction

Locating and tracking whales underwater has been essential in understanding many aspects of their biology, including dive behavior (Johnson et al. 2004), migration patterns (Blackwell et al. 2007), and reactions to anthropogenic noise (Tyack et al. 2011). Cetaceans rely on sound for underwater communication (Tyack 1986) and foraging (BarrettLennard et al. 1996). Consequently, some species of cetacean are detected more frequently via acoustics than with standard visual methods (Barlow and Taylor 2005). There are many methods for underwater localization and tracking, including directly tagging the whales, using large hydrophone arrays, and using towed line arrays of hydrophones. Placing tags directly on whales is highly time-intensive, and is not always practical for tracking multiple animals concurrently, for difficult to tag species, or over large areas.

Two main tools used to detect and localize cetaceans are pressure and vector sensors. Although acoustic vector sensors have been used by the US Navy since the late 1940s (R. A. Holler), they have been used infrequently for scientific studies. Only recently have acoustic studies of large whales begun to use DIFAR (Directional Frequency Analysis and Recording) for large whale research (Thode et al. 2000, Greene et al. 2004). DIFAR and other acoustic vector sensors record information on both the magnitude and direction of an acoustic sound, such as a whale call. In contrast, the pressure sensor hydrophones more commonly used for localization
do not give directional information, although direction can be calculated with an array of two or more hydrophones. These hydrophones can be bottom-mounted or free-floating, but during moving vessel surveys they are generally towed in a line. To locate mid- to high frequency sources, the time delay between the arrivals of the sound (also known as Time-Distance of Arrival, or TDOA) at each pair of hydrophones in a line array is used to estimate the position of the sound source to within a point along a hyperbola. When the source is close to the array (relative to hydrophone spacing), intersecting hyperbolae localize the source of a sound (Figures 5.1 and 5.2). For a distant source, hyperbolae for each receiver pair are nearly identical (i.e. they don’t intersect at steep angles) so only bearing can be estimated.

![Diagram](image)

**Figure 5.1:** Geometry of a two-hydrophone array with a sound-producing animal at position s(x, y). From Au and Hastings, 2008. With two hydrophones, location of a sound source can only be determined along a hyperbola. For this figure, t = time delay between hydrophones, d = distance between hydrophone and sound source, c = speed of sound.
Figure 5.2: Localization with a linear array of three hydrophones. From Au and Hastings 2008. $s_x$ and $s_y$ indicate the $x$ and $y$ locations of the sound source, $t$ symbolizes time, with the time for the sound to reach a specific hydrophone indicated in the subscript (for example, $t_1$ is the time it took for the sound to travel from the source to hydrophone 1) time delay between hydrophones, with the hydrophone number that the delay is measured between (for example, $t_{21}$ is the time delay between hydrophone $h_2$ and $h_1$) indicated by the subscript, $d =$ distance between hydrophones, and $c =$ sound speed. Red dots indicate two locations found with this method, illustrating the left-right ambiguity.

The limitations of towed linear hydrophone line arrays include left-right ambiguity in the localization and reduced ability of the research vessel to stop or turn due to the need to maintain the array in a straight line (D'Spain et al. 2006). Resolving the left-right ambiguity requires the vessel to change course and often requires concurrent non-acoustic surveys to go off effort. These arrays also need to be fairly large and can be unwieldy, requiring the installation of a bulky and expensive towing winch on the ship’s deck.

While pressure sensor arrays require multiple well-spaced elements to provide a bearing toward a sound, vector sensors, such as those in DIFARs, can be quite compact. In contrast with pressure arrays, vector sensors provide information on both the particle motion
and pressure changes created by a sound wave at a single location; hence, the name vector sensor, which implies that there is both information on the size and direction of the signal. A DIFAR sensor is composed of one omni-directional pressure sensor (similar to the hydrophones in TDOA arrays), plus two orthogonal (perpendicular, like a plus sign or a cross) vector sensors. The types of vector sensor vary depending on the model of DIFAR sonobuoy in use, but are functionally analogous to geophones.

Vector sensors within DIFAR work on the principle of inertia: a mass in motion tends to stay in motion, and a mass at rest tends to stay at rest. A typical DIFAR sensor may contain a large mass at the center with four orthogonal arms extending outward in an x shape (Figure 5.3). In accordance with Newton’s first law of motion, mass tends to stay still, and is balanced on a small pivot point. When a force (such as a sound wave) acts on the DIFAR sensor, it moves the container but not the inertial mass. As the container tilts in relation to the inertial mass, the ends of the four “arms” put pressure on piezoelectric crystals, translating the pressure from the arms into electrical signals. The first change in pressure from an arriving wave can be either negative or positive, meaning that each pair of orthogonal vector sensors can only resolve that a sound is arriving along their axis, but cannot resolve which direction the sound is coming from. The omni-directional pressure hydrophone solves this problem by recording the magnitude and sign (whether positive or negative) of the first pressure change. An internal compass is used to orient the array and the end result is a vector that points in the direction of the sound source (D'Spain et al. 1991 Personal Communication).
Figure 5.3: Inside of a DIFAR sensor, adapted from Armstrong (1990).

Most recent use of vector sensors for marine mammal research has used two methodologies: single DIFAR sonobuoys dropped to give a bearing toward a species of interest (Sirovic 2006), or multiple bottom-mounted instruments (McDonald et al. 2001). An array of two or more free-floating GPS enabled DIFAR sonobuoys has the ability to transmit localization data from an easily deployed platform via radio signal directly to a ship, plane, or land-based station. Sonobuoys can be deployed from moving vessels or aircraft, allowing the survey to continue collect other priority data, such as photo-id, biopsy samples, visual observations, or
line transect acoustic surveys. While survey effort continues, the most likely location of a calling animal can be determined from the intersection point between the vectors of the two DIFAR sensors, combined with the intersection point of the hyperbola determined by time difference of arrival (explained in Figure 5.10, and included to increase the precision of localization).

This chapter describes modification and field testing of inexpensive DIFAR sonobuoys that were modified to automatically detect, classify, record, and report humpback whale phonations, and outlines a method for using DIFAR data to localize the whales. The goal of this work was to establish a method to use DIFAR to localize whales. DIFAR is easily deployed from a moving vessel or plane, and can send data via radio or satellite signals. This technology could be used in any situation in which no moored acoustic recorder was available or where a platform, such as a research vessel on a survey trackline, needed to continue moving and is unable to stop effort to observe whale behavior over time.

Materials and Methods

Equipment

For the demonstration test, two commercially available AN/SSQ-53F sonobuoys (made by Sonobuoy Tech Systems) were removed from their launch container and modified with additional battery packs to increase recording time during testing, a digital signal processor, and a 64 GB digital archiving system that saved all recorded data onboard the sonobuoy. This sonobuoy has a calibrated hydrophone with a sensitivity of -122 +/- 3dB re 1 µPa at 100 Hz and a frequency range of 5 to 2400 Hz in DIFAR mode. The digital archiving system allowed access
to the data prior to the standard sonobuoy multiplexing process, a method by which multiple analog signals are combined into one complex signal, and then broadcast to a land receiver via radio signal. A custom Matlab classification algorithm in the onboard signal processor classified humpback whale calls and transmitted them via multiplexed radio signal to a shore listening station. However, the calls detected and classified transmitted via this method were not used for further analysis. The pre-multiplexed recordings were done to allow future comparison between the multiplexed, radio-transmitted data against the original analog data from the buoy. An anchoring system was added to the sonobuoys to keep them stationary during the demonstration test, and an additional float and flag were also added to ensure the test sonobuoys would be recoverable and visible to passing vessel traffic. Modifications to the buoys were done by Guidestar Engineering and Skysight Technologies (Figure 5.4).

Figure 5.4: Modified DIFAR Sonobuoy, showing (clockwise from top right) the hydrophone, the battery pack, and the float and radio antenna.
Preliminary Deployments

On March 2-5, 2009, two modified DIFAR sonobuoys were deployed from the R/V Miriam, a 43-foot research vessel, in Yokahama Bay, Oahu (Figure 5.5). The sonobuoys were anchored to the bottom throughout the day and retrieved each evening to download the onboard data and recharge the batteries. Data were also multiplexed and sent via radio-signal to a listening station at the Satellite Tracking Station on the cliffs above Yokahama Bay. Two teams of three visual observers, including one experienced and trained observer, were stationed on the cliffs above Yokahama Bay to perform visual and behavioral tracking of all whales. The two groups of observers sat in specific locations and recorded the bearing, azimuth, behavior, and time for each whale sighted using binoculars. Unfortunately, the majority of these observers did not have formal training in marine mammal observation, and as a result their observations were unreliable and are not included in this study.

Figure 5.5: Location of test DIFAR sonobuoy deployments (red triangles) in Yokahama Bay
Data Analysis for Localization

Pre-multiplexed data were analyzed using a multi-step process. First, an acoustic technician used a custom MatLab program to open each DIFAR data file, step through each file in ten second blocks, select non-overlapping calls out of the file, save each call as an individual .wav file and save the time and bearing for each call to an Excel data sheet. Only non-overlapping calls were selected to prevent bearings to two different whales from being used for localization. This process took between six minutes and an hour per file, depending on the number of humpback whale calls per file. In the next step, a second custom program cross-correlated each individual call for Sonobuoy 1 against each call for Sonobuoy 2 to give a list of cross-correlation values for each pair of calls (Figure 5.6). With accurate time measurements, this cross-correlation process would allow for precise measurement of time of arrival differences for calls and for cross-DIFAR location information to be included in the final location estimate. Since we worked with a smaller data set, we cross-correlated all calls, but during normal survey efforts it would only be necessary to cross-correlate calls within a specific window of time.
Figure 5.6: Cross-correlations between two matching calls. Red indicates the sound pressure of the first signal, blue is the second signal, and pink is the strength of the cross-correlation coefficient value.

Next, a third MatLab program listed the maximum cross correlation coefficient for each call (Figure 5.7), and a fourth listed the mean, max, and the values within one standard deviation of the mean.

From this point, discussion will be of methods developed and tested with hypothetical data, because a GPS clock malfunction in one of the buoys made matching calls in time impossible. In the next step of the analysis, GPS locations should be calculated for calls with cross-correlation coefficients of greater than 0.5 from both sonobuoys using the GPS locations for each sonobuoy and the DIFAR Azimuth (Figure 5.8).
Figure 5.7: Example of the cross correlation values between one call from Sonobuoy 1 and all the calls from Sonobuoy 2. The high cross-correlation value is the same call recorded on Sonobuoy 2.

Figure 5.8: Example of how the locations of whales are determined using only the calculated bearing toward the whale sound from the DIFAR Sonobuoy. S1 indicates the position of Sonobuoy 1, with bearing shown in pink and S2 indicates the position of Sonobuoy 2, with bearing in red. This method of localization assumes no errors in the DIFAR azimuths, and also does not include hyperbola and ambiguity surfaces.
With correct time and GPS data available, the final step of analysis would be to use the methods of Nosal and Frazer (2006) to create ambiguity surfaces using the DIFAR azimuths and the time-difference of arrival hyperbola. To create an ambiguity surface, a grid is plotted around the area of interest; in this case, the GPS locations of the TASS sonobuoys. The size of this grid will depend on the size of the array, but for this model we used a grid range of 20 km by 20 km, with step sizes of 10 m, centered at the median location between the deployment locations of the two sonobuoys. The ambiguity value incorporates the angular error of the DIFAR, which is listed by the manufacturer as ±10 degrees. This error value was also verified in the field for similar AN/SQ53 DIFAR sonobuoys by McDonald et al (2004). In addition, the time difference of arrival (TDOA) between the two DIFAR can be used to calculate a TDOA ambiguity surface. This TDOA should be used to calculate a parabola with a Gaussian weighing function with a standard deviation of 500 m (Nosal 2013). Finally, the ambiguity surfaces from the DIFAR azimuths and the TDOA estimate are multiplied together to give a total ambiguity surface. Incorporating the TDOA surface adds additional information on source location data to increase localization accuracy (Figure 5.9) and using ambiguity surfaces removes the assumption that there is no error in the DIFAR azimuth and/or TDOA estimate.
Figure 5.9: Theoretical example of an ambiguity surface for DIFAR data. This ambiguity surface was generated using the deployment locations of the two sonobuoys and an estimated TDOA for an animal calling at this location. For better visualization of the process used, the bearing and TDOA only ambiguity surfaces are added in this example. However, for analysis it is preferable to multiply the bearing and TDOA surfaces.

Results

Both TASS sonobuoys functioned as designed, and humpback whale calls were successfully recorded (Figures 5.10 and 5.11), classified and transmitted from the sonobuoy to the land-based radio station. Five hours of data were recorded on both sonobuoys on March 2, 2010.
Figure 5.10: Spectrogram of humpback whale calls from on-board recordings on Sonobuoy 1.

Figure 5.11: Recordings of humpback whale calls, showing the difference in signals recorded on the Omnidirectional, North/South, and East/West components of the DIFAR array. For the North/South and East/West signals, the perpendicular signal is shown in light blue to illustrate the difference (for example the E/W signal is perpendicular to the N/S signal).
Unfortunately, the GPS on Sonobuoy 2 malfunctioned, with the result that there was no accurate location or, equally importantly, time stamp, for this sonobuoy. Without time and GPS data for one of the two sonobuoys, neither TDOA nor DIFAR localization was possible without an unacceptable number of assumptions. For example, in order to do further analysis we would have had to assume either that 1) Sonobuoy 2 remained stationary in its drop location or 2) Sonobuoy 2 followed the same pattern of movement from its drop location as Sonobuoy 1 (Figure 5.12). Since Sonobuoy 1 moved on the order of several hundred meters throughout the day, we deemed Assumption 1 to be unlikely. Given the variable current conditions in Yokahama Bay, Assumption 2 was also unacceptable. Finally, matching of calls between the two sonobuoys without time information from Sonobuoy 2 was not within the scope of this project.

Figure 5.12: Relative GPS movements of Sonobuoy #1 during the five hour testing period.
Discussion

Preliminary deployments indicated the floating DIFAR array method of localization would work well on whale calls within the frequency range of the sonobuoys if the problems with the onboard GPS were corrected. Compared to many other acoustic localization systems, this equipment is inexpensive and relatively easy to deploy, and further development of the system could make considerable improvements. Regardless of the fact that we were unable to do the final analysis of the recorded humpback signals because of the GPS malfunction, we believe that this method of recording and analysis has the potential to greatly assist the use of acoustics to study the underwater movement of cetaceans. The use of DIFAR in conjunction with TDOA likelihood surfaces would improve precision for all DIFAR localization systems, not only the system discussed in this chapter. Analysis of whale phonations and their movements relative to each other may have implications for the function of communication in behavior. For humpback whale song specifically, this could shed light on the function of song, which is still incompletely understood (Helweg et al. 1992, Frankel et al. 1995, Frankel and Clark 2000, Darling and Berube 2001, Darling et al. 2006, Cholewiak 2008, Abbot et al. 2010).


Cholewiak, D. 2008. Evaluating the role of song in the humpback whale (megaptera novaeangliae) breeding system with respect to intra-sexual interactions: ProQuest.


CHAPTER 6. CONCLUSIONS

Filling Gaps in Information on Distribution, Behavior, and Abundance

The work described in this dissertation was directed toward the goal of finding new methods to fill critical gaps in our current knowledge of the distribution and abundance of cetaceans, both in Hawaii and beyond. To achieve this goal, two new methods were tested in the preceding chapters. The first of these methods used vessels of opportunity to gather acoustic data on a species with a well-known temporal and spatial distribution as well as on species for which these distributions are less well studied. In Chapter 2, the temporal and spatial distribution of humpback whales was investigated using acoustic surveys from vessels of opportunity, and these results were compared with known distributions from previous studies. In Chapter 3, the same method was used to investigate the spatial and temporal distribution of odontocetes in the waters of the main Hawaiian Islands. Chapter 3 discusses the previous efforts at assessing the distribution of odontocetes, which have been both spatially and temporally biased. The implications of using commercial vessels of opportunity were further investigated using a case study in Chapter 4. In the second method, discussed in Chapter 5, a methodology was developed using DIFAR to solve some of the problems of using line and bottom mounted arrays to localize cetaceans.
Summary of Conclusions and Results

1. Vessel of opportunity data corroborated with known data on humpback whale spatial and temporal distribution and oceanographic variables.

2. Long-term vessel of opportunity datasets may be a useful tool to fill gaps in distributional data for data-poor species in areas that are rarely surveyed with improvements in noise levels and information about effective survey strip width, and this data could be combined with remotely sensed oceanographic data for habitat modeling.

3. Acoustic survey methods may be an important method to account for low probabilities of detection in high-wind areas where visual surveys are difficult, such as the windward sides and channels between the main Hawaiian Islands, as long as improvements can be made in surface related noise levels and distance to animals can be incorporated to calculate effective survey strip width.

4. Both ship speed and noise are important to consider for anthropogenic impacts to cetaceans.

5. A viable method for tracking movements of humpback whales is possible using DIFAR.
Future Work

The importance of thoughtful, careful design and testing in the use of new technology to collect biological data cannot be overstated. Most innovative equipment used for marine mammal research has gone through multiple iterations. These have included fixed passive acoustic recorders such as the Ecological Acoustic Recorder (EAR) and the High Frequency Acoustic Recording Package (HARP), as well as acoustic and video recording tags such as the Digital Acoustic Recording Tag (DTag), Bioacoustic Probe (B-Probe) and the National Geographic crittercam (Marshall et al. 2007, Meyer et al. 2007, Wiggins and Hildebrand 2007, Johnson et al. 2009, Bocconcelli et al. 2012, Sousa-Lima et al. 2013). The Continuous Plankton Recorder, discussed in Chapter 2, has undergone at least eleven technical redesigns (Reid et al. 2003). The research outlined in this dissertation uses the very first version of a new type of research equipment, and, as with most new techniques, has ample room for improvement. During the first tests of new equipment, needed improvements became apparent. For example, earlier versions of the crittercam were extremely bulky, included a Hi-8 video camera, and could only be used on very large whales (Calambokidis et al. 2007). Throughout the last 20 years, improvements in this technology have made it possible to tag animals as small as 80 cm (Knight 2015). In much the same way, lessons were learned during the research for this dissertation that would greatly improve future efforts. It is rare that a new technique works perfectly the first time, and it is often only through real-world testing that these improvements can be made. One specific example of these lessons learned is that prioritizing equipment design to collect clean, quiet data will streamline later analysis and improve the ability to use autonomous
detection and classification algorithms. For the methods used in Chapters 2 and 3, it would have been optimal to implement an equipment design at the beginning of the project to lower the recording equipment deep enough to prevent noise from surface interference. In addition, the use of an array, rather than a single hydrophone, would allow for distance estimation to the animals and calculation of strip width and $g(0)$, and to determine the relationship between these two factors and ambient and flow noise. This is discussed in greater detail in Chapter 3. Another example of a lesson learned applies to the method outlined in Chapter 5. Here, it would have been preferable to conduct tests throughout data collection to ensure that all components of the equipment were functioning properly. However, if the opportunity to collect this type of data is available in the future, the appropriate methodology is now established and data could be analyzed promptly. Additional specific details on future directions are outlined in the respective chapters of this thesis. These lessons learned will allow better preparation while planning to fill the critical gaps in knowledge of cetacean distribution and its relationship to the ocean habitat.
Works Cited


*Progress in Oceanography* 58 (2):117-173.

