12-2013

Developing an Acoustic Method for Reducing North Atlantic Right Whale (Eubalaena glacialis) Ship Strike Mortality Along the United States Eastern Seaboard

Kaitlyn Allen Mullen

Recommended Citation

Mullen, Kaitlyn Allen, "Developing an Acoustic Method for Reducing North Atlantic Right Whale (Eubalaena glacialis) Ship Strike Mortality Along the United States Eastern Seaboard" (2013). *Electronic Theses and Dissertations*. 2060.
http://digitalcommons.library.umaine.edu/etd/2060

DEVELOPING AN ACOUSTIC METHOD FOR REDUCING NORTH ATLANTIC RIGHT WHALE (*EUBALAENA GLACIALIS*) SHIP STRIKE MORTALITY ALONG THE UNITED STATES EASTERN SEABOARD

By

Kaitlyn Allen Mullen

B.B.A. Belmont University, 2002

B.S. University of Maine, 2006

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

(Interdisciplinary in Ocean Engineering)

The Graduate School

The University of Maine

December 2013

Advisory Committee:

Michael L. Peterson, Professor of Mechanical Engineering, Advisor

Sean K. Todd, Professor of Marine Mammal Ecology & Oceanography

Richard Kimball, Professor of Mechanical Engineering

Kate Beard-Tisdale, Professor of Spatial Information Systems

Bruce Segee, Professor of Electrical and Computer Engineering

THESIS ACCEPTANCE STATEMENT

On behalf of the Graduate Committee for Kaitlyn Allen Mullen, I affirm that this manuscript is the final and accepted thesis. Signatures of all committee members are on file with the Graduate School at the University of Maine, 42 Stodder Hall, Orono, Maine.

Michael L. Peterson, Committee Chair November 25, 2013

LIBRARY RIGHTS STATEMENT

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at the University of Maine, I agree that the Library shall make it freely available for inspection. I further agree that permission for “fair use” copying of this thesis for scholarly purposes may be granted by the Librarian. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature:

Date: November 25, 2013

DEVELOPING AN ACOUSTIC METHOD FOR REDUCING NORTH ATLANTIC RIGHT WHALE (*EUBALAENA GLACIALIS*) SHIP STRIKE MORTALITY ALONG THE UNITED STATES EASTERN SEABOARD

By Kaitlyn Allen Mullen

Thesis Advisor: Dr. Michael L. Peterson

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy
(Interdisciplinary in Ocean Engineering)
December 2013

North Atlantic right whales (*Eubalaena glacialis*) are among the world's most endangered cetaceans. Although protected from commercial whaling since 1949, North Atlantic right whales exhibit little to no population growth. Ship strike mortality is the leading known cause of North Atlantic right whale mortality. North Atlantic right whales exhibit developed auditory systems, and vocalize in the frequency range that dominates ship acoustic signatures. With no behavioral audiogram published, current literature assumes these whales should be able to acoustically detect signals in the same frequencies they vocalize. Recorded ship acoustic signatures occur at intensities that are similar or higher to those recorded by vocalizing North Atlantic right whales. If North Atlantic right whales are capable of acoustically detecting oncoming ship, why are they susceptible to ship strike mortality?

This thesis models potential acoustic impediments to North Atlantic right whale detection of oncoming ships, and concludes the presence of modeled and observed bow null effect acoustic shadow zones, located directly ahead of oncoming ships, are likely to impair the ability of North Atlantic right whales to detect and/or localize oncoming shipping traffic. This lack of detection and/or localization likely leads to a lack of ship strike avoidance, and thus contributes to the observed high rates of North Atlantic right whale ship strike mortality. I propose that North Atlantic right whale ship strike mortality reduction is possible via reducing and/or eliminating the presence of bow null effect acoustic shadow zones. This thesis develops and tests one method for bow null effect acoustic shadow zone reduction on five ships. Finally, I review current United States policy towards North Atlantic right whale ship strike mortality in an effort to determine if the bow null effect acoustic shadow zone reduction method developed is a viable method for reducing North Atlantic right whale ship strike mortality within United States waters.

I recommend that future work include additional prototype modifications and testing, application for a marine mammal scientific take authorization permit to test the modified prototype on multiple mysticete species, and continued interfacing of the prototype with evolving United States North Atlantic right whale ship strike reduction policies.

ACKNOWLEDGEMENTS

This work was compiled from a series of previously published peer-review conference proceedings and journal articles. Portions of Chapter 2 were published previously as Todd, S.K., Allen, J.K., Mahaffey, C.M., Damon, J., Hamilton, P., and Kenney, R.D. (2009). An Acoustic Mysticete Shipstrike Mortality Risk Assessment for the Gulf of Maine. *Proceedings of the 5th International Conference on Bio-Acoustics*. Loughborough University, Holywell Park, United Kingdom. 280-287. Portions of Chapter 3 were published previously as Allen, J.K., Peterson, M.L., Sharrard, G.V., Wright, D.L. and Todd, S.K. (2012). Radiated noise from commercial ships in the Gulf of Maine: Implications for whale/vessel collisions. *Journal of the Acoustical Society of America* 132(3) EL229-EL235. Portions of Chapter 4 were submitted as Mullen, K.A.., Peterson, M.L., Mullen, J.P. and Carpenter, R. (in prep.). An acoustic method for reducing baleen whale ship strike mortality. *Marine Technology Society Journal* (13p.). Portions of Chapter 5 were previously published as Mullen, K.A., Peterson, M.L., and Todd, S.K. (2013). Has designating and protecting critical habitat had an impact on endangered North Atlantic right whale ship strike mortality? *Marine Policy* 42: 293-304.

This work greatly benefitted from pioneering work in the field by Edmund R. Gerstein, Joseph E. Blue, and Susan E. Parks. The National Science Foundation IGERT Sensor Science, Engineering, and Informatics Program provided generous financial support for this work. Other sources of financial support included the University of Maine Provost Fellowship, the Maine Space Grant Consortium, and the Bar Harbor Whale Watch Company “Save the Whales, Educate the Children” Scholarship. Undertaking a project of this size requires many community partnerships in the form of

donations of time and supplies. Community contributors to this thesis included Allied Whale, the Bar Harbor Whale Watch Company, New Horizon Cruises, Frenchman Bay Boating Company, RPS Geocet, Inc., Glenn Carpenter Metalworks Studio, Penobscot Bay Pilots Association, College of the Atlantic, and Diver Ed's Dive-In Theater. Special thanks also belong to research assistants George V. Sharrard, Dana L. Wright, Dominique G. Walk, Sabrina Keach, Elija "Lulu" Bates, Julia Stepanuk, and Jonathan Mullen.

This thesis would not have been possible without the innovative and unwavering support of my advisor, Dr. Michael "Mick" L. Peterson. This thesis benefitted greatly from the amount of time my committee members committed to guiding my progress. Thanks to Dr. Sean Todd for introductory field experiences and logistical support, and to Dr. Richard Kimball and Dr. Christopher Clark for sound advice.

This thesis would not have been completed without all the volunteers who contributed time in the field, time on their vessels, and time reviewing the manuscript. Sincere thanks to Capt. Jerry Blandford, Capt. Jeffrey Black, Capt. Gary Fagan, Capt. Matt McFarland, Capt. Larry Nusselein, Robert "Whitey" Carpenter, Sara Jackson, Alec Phippen, Jared Cunningham, Dave Spear, Steve Burns, Colby Moore, Sherri Eldridge, Melinda Neville, Tora Johnson, Neal Currier, Bryce Moody, Kevin Moody, Dennis Pederson, Chad Probst, Darrell White, and Julianne Taylor.

Finally, this thesis would not have been a success without the support and patience of my husband, my family, and my friends. Thanks to all of you for countless hours spent looking beyond the immediate to believe in the possibilities.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADU – Azimuthal drive unit

ATBA – Area to Be Avoided

BNEASZ – Bow null effect acoustic shadow zone

CTD – Conductivity/temperature/depth casts

DMA – Dynamic Management Area

ESA – Endangered Species Act of 1973

GIS – Geographic information system

GOMOOS – Gulf of Maine ocean observation system

GPS – Geographic Positioning System

ICRW - International Convention for the Regulation of Whaling

IMO – International Maritime Organization

MMPA – Marine Mammal Protection Act of 1972

MSRS – Mandatory Ship Reporting System

NEIT – Northeastern Implementation Team

NMFS – National Marine Fisheries Service

NOAA – National Oceanic and Atmospheric Administration

PBR – Potential biological removal

RL – Received intensity level

SEIT – Southeastern Implementation Team

SL – Source intensity level

SMA – Seasonal Management Area

SPUE – Sightings per unit effort

TSS – Traffic Separation Scheme

USGS – United States Geological Survey

CHAPTER 1

INTRODUCTION

1.1 Introduction

North Atlantic right whales are among the most endangered mysticete populations in the world. Protected by an international whaling moratorium in 1949, the population totals an estimated minimum 444 individuals worldwide (International Convention for the Regulation of Whaling [ICRW], 1946; National Oceanic and Atmospheric Administration [NOAA], 2012). The western North Atlantic right whale population likely consisted of 1,000-2,000 individuals in the early to mid-1600s (Reeves et al., 1992), and may have included 10,000-15,000 individuals prior to 1000 A.D. (Gaskin, 1991; National Marine Fisheries Service [NMFS], 1991). No historical population estimate is available for eastern North Atlantic right whales, a population now functionally extinct (Best et al., 2001). Commercial whaling conducted prior to 1850 likely reduced the global North Atlantic right whale population to 100 or less individuals by 1949 (Reeves et al., 2007).

1.2 Distribution and Habitat Use

Commercial whaling records indicate the North Atlantic right whale’s historic geographic range included the coasts of eastern Canada, eastern United States, southern Greenland, Iceland, Ireland, United Kingdom, western Europe and northwest Africa (see Figure 1.1) (Reeves et al., 2007). North Atlantic right whales were likely found close to coastlines in continental shelf waters, although some subarctic oceanic basin travel may have occurred (Reeves et al., 2007; NOAA, 2011). Today North Atlantic right whales primarily inhabit the eastern coasts of Canada and the United States, with identified critical feeding grounds located in the Bay of Fundy, Canada, Roseway Basin, Canada, and Cape Cod Bay, United States (see Figure 1.2) (NOAA, 1994; Brown et al., 2009). The only identified critical North Atlantic right whale calving habitat is located along the coasts of southern Georgia and northeastern Florida, United States (see Figure 1.2) (NOAA, 1994; NMFS, 2012). Recent visual sightings of North Atlantic right whales have also occurred along the coasts of Norway, Greenland, Iceland, the Azores, and inside the Gulf of Mexico (Moore & Clark, 1963; Jacobsen et al., 2004; Hamilton et al. 2007; 2009).

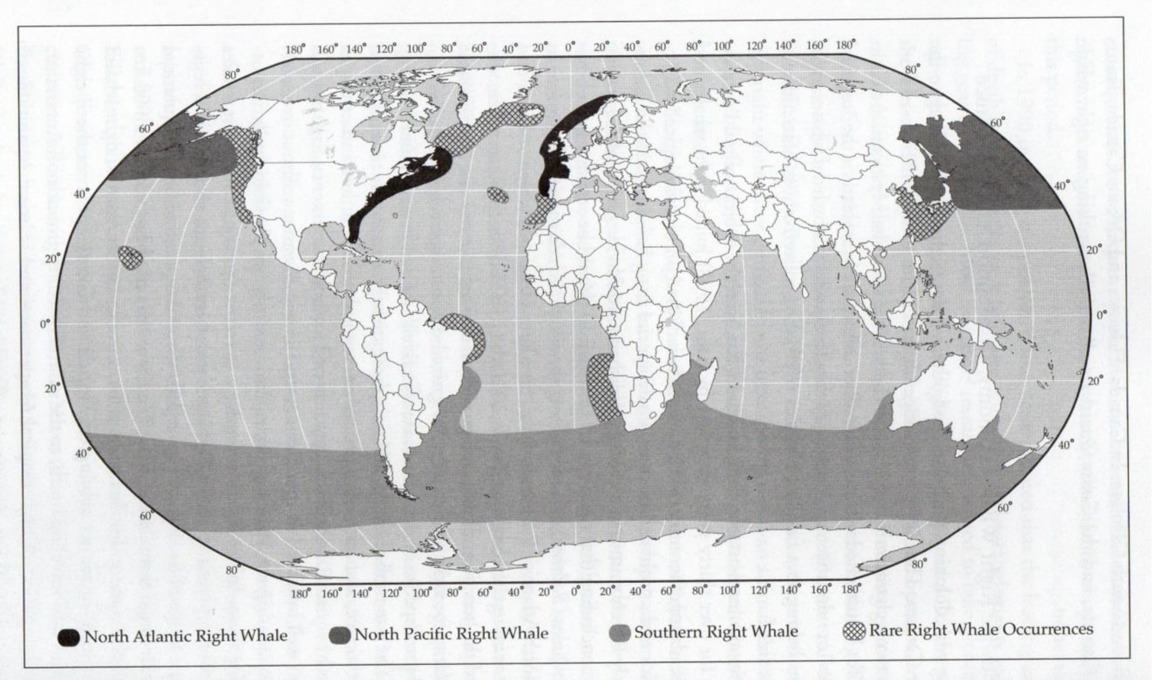


Figure 1.1 A Map of Historic North Atlantic Right Whale Habitat. Reproduced by permission New England Aquarium.

Although identified critical habitat areas are often considered well understood and monitored, only 60% of North Atlantic right whale calves are photographed with their mothers inside the critical calving ground off the coast of Georgia and Florida annually (NOAA, 2011). At least four North Atlantic right whale calves were born off the coast of

North Carolina, United States, well outside the identified critical calving ground (McLellan et al., 2004). In addition, satellite telemetry tagging of individuals indicates North Atlantic right whales can travel great distances in short periods of time (Mate et al., 1997). An individual North Atlantic right whale has also been photo-identified transiting from an identified calving ground to an identified feeding ground twice within three months (Brown & Marx, 2000), suggesting that giving birth and nursing may not be the only reason for North Atlantic right whales to utilize the identified critical calving ground. Genetic research indicates only 45% of North Atlantic right whale fathers currently belong to the genetic catalogue (Frasier et al., 2007), suggesting modern science is unaware of the location of many North Atlantic right whale males from birth to sexual maturity. A North Atlantic right whale breeding ground has recently been discovered inside the Gulf of Maine during November – January (NMFS, 2012), potentially accounting for a portion of the missing genetic population. Photo-identification catalogues also indicate North Atlantic right whales show high inter-annual variability in feeding ground locations, often not visiting a specific feeding ground for years at a time (Hamilton et al., 2007; NMFS, 2012). Given these results, much remains to be learned about North Atlantic right whale habitat use and distribution.

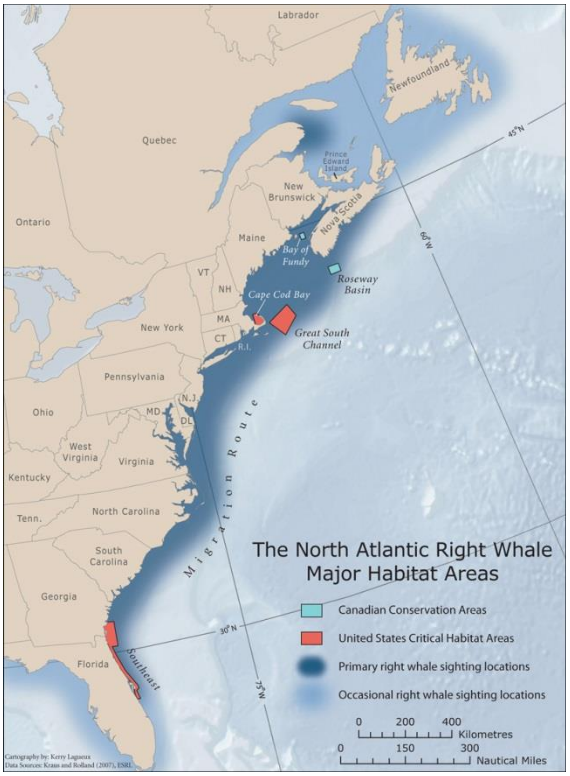


Figure 1.2. A Map of Modern North Atlantic Right Whale Habitat. Map reproduced with permission from New England Aquarium.

1.3 Review of Population Growth Rate

While an international moratorium on commercial whaling of North Atlantic right whales has been in effect since 1949 (ICRW, 1946), the population has been slow to rebound. North Atlantic right whales sustained an average annual population growth rate of 2.4% during 1990-2007, with annual growth rates ranging from 6.1% to -0.8% (NOAA, 2011). In contrast, Southern right whales, a comparative population also significantly reduced by the effects of commercial whaling, exhibit an average annual growth rate of 6.2% (Best et al., 2001). While the North Atlantic right whale population appears to be growing, the inter-annual variability of a comparatively low growth rate (NMFS, 2011), combined with its foray into negative numbers (Caswell et al., 1999), indicates these whales are struggling to survive at a population level.

Generically, a low growth rate is a function of high mortality and low birth rate. Many factors may contribute to observed high mortality rates and low birth rates in North Atlantic right whales (Kraus et al., 2001; 2005; Kenney, 2007; Rolland et al., 2007). Genetic bottleneck effects resulting from commercial whaling may be partially responsible for the long inter-calf intervals observed in female North Atlantic right whales (Waldick et al., 2002). Genetic bottle neck effects may also be partially responsible for high neonate and juvenile right whale mortality levels observed (Waldick et al., 2002; Frasier et al., 2007) as a limited genetic pool may increase the probability of birth defects, premature births, and still births, and decrease the probability of resilience. Absorbed biotoxins as a result of living in polluted coastal areas may further contribute to variable inter-calf intervals observed in female right whales (Reeves et al., 2001; Rolland et al., 2007). Biotoxin presence may also negatively impact neonate and juvenile North Atlantic right whale health (Kraus et al., 2001; Browning et al., 2010), further contributing to observed high mortality rates. Changes in annual copepod locations and life cycle timing that result from an increase in ocean surface temperatures may further contribute to observed long and variable North Atlantic right whale inter-calf intervals as mothers spend more time searching for food and less time accumulating the energy reserves necessary to support successful pregnancy and high neonate survival rates (Kraus et al., 2001; Kenney, 2007). Commercial whaling is currently banned worldwide (ICRW, 1946), and thus has only residual impacts on North Atlantic right whale population recovery. Ocean pollution and rising global sea temperatures may have more direct effects on North Atlantic right whale population recovery (Kraus et al., 2001; Kenney, 2007; Rolland et al., 2007). However, ocean pollution and rising sea temperatures are also global issues that are hard to regulate in a timely and consistent manner (Kenney, 2007). Thus, the ability of wildlife managers to regulate the causes of ocean pollution and rising sea temperatures is limited to manager-specific watershed jurisdictions, and therefore unlikely to produce a positive impact that will be felt throughout known North Atlantic right whale habitat.

Currently, the largest known source of North Atlantic right whale mortality is ship strike (Moore et al., 2005; Henry et al., 2011). Ship strikes result in an average of 1.6 known North Atlantic right whale mortalities per year (1.2 in the U.S., 0.4 in Canada) (NOAA, 2011). While these numbers appear small, the National Oceanic and Atmospheric Administration (NOAA) has set the potential biological removal (PBR) rate for North Atlantic right whales at 0.8 individuals annually (2011). Therefore the average ship strike mortality rate is above the prescribed PBR, and has accounted for up to four known North Atlantic right whale mortalities annually (see Table 1.1) (Jensen & Silber, 2004; Henry et al., 2011). In 1993 and 2006, two of the four North Atlantic right whale ship strike mortalities observed were adult females (Jensen & Silber, 2004; Henry et al., 2011) In 2006 both ship struck adult females were killed while carrying near-term fetuses (Jensen & Silber, 2004; Henry et al., 2012). The deaths of mature females are of concern, as those deaths negatively impact the potential long-term North Atlantic right whale population growth rate (Kraus et al., 2005). As the North Atlantic right whale population appears to be sensitive to any biological removal (NOAA, 2011), it is crucial to eliminate preventable North Atlantic right whale mortalities inside United States waters if the population is to recover.

Year	Ship strike Mortality	Ship Strike Serious Injury
1976	2	0
1977	0	0
1978	0	0
1979	1	0
1980	0	2
1981	0	0
1982	0	0
1983	1	0
1984	0	0
1985	0	0
1986	1	0
1987	0	1
1988	0	0
1989	0	0
1990	0	0
1991	2	1
1992	0	0
1993	4	0
1994	1	0
1995	0	0
1996	3	0
1997	0	0
1998	1	1
1999	1	0
2000	0	0
2001	2	1
2002	1	0
2003	1	0
2004	2	0
2005	2	1
2006	4	1
2007	0	0
2008	0	0
2009	0	0
2010	1	0

Table 1.1 Annual Ship Strike Mortality 1976-2010. Compiled from Jensen & Silber (2003), Nelson et al. (2007), Glass et al. (2010), and Henry et al. (2011; 2012).

1.4 Ship Strike Mortality Reduction in United States Waters

North Atlantic right whales were so named because they were considered the "right" whale to hunt (Frasier et al., 2007). As slow-moving whales found in coastal waters that floated after death, North Atlantic right whales were heavily targeted by commercial whaling fleets from 1000 A.D. – 1949 (Reeves et al., 2007). Whaling was one of the leading economic industries in North America from 1630 – 1924 (Dolin, 2007). As a result many of today's largest North American east coast ports are located in or near historic right whale habitat (see Figure 1.1). Several large North American ports are also located inside or near modern identified NARW critical habitat areas (see Figure 1.2). In 1995, commercial shipping contributed $8 billion in revenue and 9,000 jobs to the port of Boston, Massachusetts (Haar & Cox, 1996). Commercial shipping increased steadily during 2000-2007, contributing $19 billion in economic impact and 66,000 jobs to the port of Jacksonville, Florida in 2009 (Martin Associates, 2009; Dalsoren et al., 2010). Cruise ship passenger landings totaled 380,000 passengers at the port of Boston, Massachusetts, in 2012, breaking records (Massachusetts Port Authority, 2012). This increasing trend is predicted to continue through 2020 (Byington et al., 2011).

This dichotomy presents a serious challenge for wildlife managers in the United States. North Atlantic right whales are protected under federal law by the Marine Mammal Protection Act of 1972 (MMPA) and the Endangered Species Act of 1973 (ESA) (MMPA, 1972; ESA, 1973). Both of these acts are designed to limit negative anthropogenic impacts on the North Atlantic right whale population (MMPA, 1972; ESA, 1973; Suckling & Taylor, 2006). The MMPA specifically makes it illegal to "take" a marine mammal, where a "take" is defined as "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture or kill" marine mammals without holding marine mammal take authorization permits (MMPA, 1972). Further, the ESA empowers wildlife managers to develop species-specific recovery plans and to identify and protect areas considered to be critical to population level recovery (ESA, 1973). The ESA specifically limits wildlife managers, stating that critical habitat may not comprise all known habitat for an endangered species (ESA, 1973). The ESA further requires wildlife managers to designate critical habitat only if that designation, and thus subsequent protection, does not negatively impact local economies and industries to the point where they cannot function (ESA, 1973; Suckling & Taylor, 2006). While several rules have been passed aimed at reducing North Atlantic right whale ship strike mortality within United States waters (NOAA, 2004; 2008), ship strike remains the leading known cause of North Atlantic right whale mortality (Henry et al., 2012).

United States rules aimed at reducing ship strike mortality involve limiting ship proximity to North Atlantic right whales by re-routing commercial shipping lanes around known North Atlantic right whale seasonal concentrations (NOAA, 2008), requiring individual ships to maintain distances of at least 500 yards from any observed North Atlantic right whale (NOAA, 2004), and reducing the speed of ships entering identified North Atlantic right whale critical habitat areas and/or known seasonal concentrations (NOAA, 2008). The success of these strategies relies on reducing co-occurrence of ships and North Atlantic right whales, and on successful detection and avoidance of North Atlantic right whales by mariners.

While many commercial ships post dedicated lookouts in and around reported North Atlantic right whale concentrations, visual detection of North Atlantic right whales is often difficult. North Atlantic right whales exhibit low, finless profiles when at the surface, making them difficult to detect visually while transiting (see Figure 1.3). In addition, North Atlantic right whales participate in skim feeding, a behavior in which a North Atlantic right whale swims with its mouth open at or just below the surface of the ocean for extended periods of time ingesting zooplankton (Mayo & Marx, 1990). Subsurface skim feeding may make an individual North Atlantic right whale undetectable to a mariner for up to 58 minutes out of each hour at a depth in which the whale is still at high risk for ship strike mortality (Mayo & Marx, 1990; Parks et al., 2012). Commercial ships transiting between ports also commonly transit at night, reducing a mariner's ability to visually detect and/or avoid North Atlantic right whales.

Figure 1.3. Surface Profile of a North Atlantic Right Whale Compared to a Transiting Motor Vessel. Reproduced with permission from New England Aquarium, taken under Permit 15488.

1.5 Are North Atlantic right whales capable of detecting and/or localizing oncoming ships?

There are also few published accounts of North Atlantic right whale behavior prior to or during ship strike encounters. Estimates of North Atlantic right whale ship strike mortality are based almost entirely on floating and beached dead carcasses. Kraus et al. (1988) noted that while feeding North Atlantic right whales often appeared oblivious to ships. Mayo & Marx (1990) observed that on 64 of 137 occasions, North Atlantic right whales turned into the path of ships transiting parallel to them. Richardson et al. (1995) reported that North Atlantic right whales tend to move away from rapidly approaching ships. Terhune & Verboom (1999) observed an individual North Atlantic right whale swimming directly into the path of a transiting ship. Nowacek et al. (2004) noted that five of six tested North Atlantic right whales rose to the surface to investigate a near-stationary ship playing back a series of "alert" signals. Although these accounts are limited, and likely do not comprise the full range of individual North Atlantic right whale reactions to close ship encounters, they indicate that in general, North Atlantic right whales do not accurately detect and/or accurately localize moving ships. However, research indicates that North Atlantic right whales may be capable of detecting and localizing stationary ships playing back signals of at least 173 dB re 1μPa @ 1m (Nowacek et al., 2004).

Current literature assumes that as a first approximation, North Atlantic right whales should be able to acoustically detect and localize signals in the same frequency and intensity ranges that comprise recorded vocalizations. This is supported by paired acoustic and visual observations of individual North Atlantic right whales orienting towards the location of vocalizing surface active groups (Parks, 2003). Therefore, North Atlantic right whales should be able to acoustically detect and localize audio signals 50-2500 Hz at signal to noise ratio intensities of 43.8 – 51.8 dB re 1 μPa (Parks, 2003). Published assessments of commercial shipping noise reveal that most ship acoustic signatures are dominated by frequencies <1000 Hz, and are louder than 150 dB re 1 μPa @ 1m when transiting at speeds greater than five knots (Arveson & Vendettis, 2000;

Hatch et al., 2008; McKenna et al., 2012). Current literature also suggests oceanic background noise in these frequencies appears to be increasing as shipping traffic increases (Hatch et al., 2008; Hildebrand, 2009). Recent broadband ambient noise levels published for a variety of oceanic environments ranged from 92 - 140 dB re 1 μPa (Hatch et al., 2008; Hildebrand, 2009; Parks et al., 2011), likely rendering individual ship acoustic signatures detectable to North Atlantic right whales at close ranges. Why then, do North Atlantic right whales appear able to accurately detect and localize a near-stationary research vessel playing back an "alert" signal, but appear unable to detect, localize, and/or react to oncoming ships?

This thesis chronicles an effort to characterize the acoustics of close whale/ship encounters in an effort to determine if there are acoustic barriers to North Atlantic right whales detecting a vessel's signature, thereby facilitating such behaviors as turning into the paths of oncoming ships. Specifically, this thesis asks: Are there acoustic impediments that may prevent North Atlantic right whales from detecting and/or localizing an oncoming vessel in time to successfully react to and avoid that vessel? If so, can a North Atlantic right whale's ability to detect and/or localize an oncoming vessel be enhanced by a technological solution, potentially extending the North Atlantic right whale's ability to react in time to avoid ship strike mortality? Finally, is the technological solution proposed and developed compatible with United States North Atlantic right whale ship strike reduction policy?

1.6 Chapter Descriptions

Thus, Chapter 2 describes the effort undertaken to characterize the acoustic environment during close North Atlantic right whale/ship encounters within an identified critical feeding ground. Acoustic signatures were obtained from peer-reviewed literature and input into a ray-tracing program. The ray-tracing program also included seasonal sea temperatures and salinities measured at a variety of depths, obtained from the Gulf of Maine Ocean Observation System (GOMOOS), for seven locations within the Gulf of Maine (GOMOOS, 2008). Bottom rugosity for those same seven locations was obtained from the United States Geological Survey (2004). All Gulf of Maine locations modeled in the ray-tracing program were identified as having a high risk of North Atlantic right whale ship strike mortality based on the co-occurrence of North Atlantic right whales and shipping traffic. Results from the ray-tracing program models revealed the presence of bow-null effect acoustic shadow zones in five of the seven modeled locations during the summer and fall seasons for all ship acoustic signatures modeled. Bow-null effect acoustic shadow zones appeared in the model 189 of 196 scenarios, and varied in length, depth, and aspect ratio based on season, ship type, and location modeled.

Chapter 3 verifies the presence of the modeled bow-null effect acoustic shadow zones by recording three-dimensional orbital sound spectra from passing vessels located in the Bar Harbor, Maine shipping channel June – September 2009. Ship source levels recorded ranged from 178 ± 3.1 to 219 ± 3.8 dB re 1μPa@1m. Ship noise radiated asymmetrically, and was observed to be loudest at the stern aspect and quietest at the bow aspect regardless of ship type. Bow null effect acoustic shadow zones were also observed in all four ship types recorded. The intensity of bow-null effect acoustic shadow zones was found to vary with ship speed and vessel type, and to correlate with ship length to draft ratios.

Chapter 4 describes the development, design and initial field-testing of a technological solution to reduce and/or eliminate bow-null effect acoustic shadow zones. Pre-recorded vessel noise was played back through a pair of underwater speakers at specified depths and angles to change the orbital vessel sound spectra; thus providing baleen whales with an increased opportunity to acoustically detect and/or localize an oncoming ship. Field-testing was conducted on five different motor vessels within the Bar Harbor, Maine shipping channel. Bow null effect acoustic shadow zones were eliminated for all five ships tested at speeds of less than 5.5 knots.

Chapter 5 reviews the effect identifying critical North Atlantic right whale habitat has had on ship strike mortality within United States waters. Chapter 5 identifies current North Atlantic right whale ship strike reduction policy based on protecting North Atlantic right whales within critical habitat areas, and then assesses if the technological solution developed in Chapter 4 may become a viable ship strike reduction strategy within the context of the Endangered Species Act.

Finally, Chapter 6 reviews the findings of Chapters 2-5, and provides suggestions for future work.

CHAPTER 2

MODELING THE ACOUSTICS OF ENDANGERED MYSTICETE/SHIP STRIKE INTERACTIONS IN THE GULF OF MAINE

2.1 Chapter Abstract

Shipstrike is one of the leading causes of mysticete mortality in the world, particularly in the Gulf of Maine, a mysticete feeding ground. To determine if there is acoustic basis for shipstrike mortality, we analyzed multiple factors contributing to mysticete shipstrike events. These factors include: physical properties influencing the speed, propagation and shadowing of sound both spatially and seasonally, vessel acoustic signatures and shielding properties, and substrate-based reflection based on sediment type and rugosity. In all sound velocity profiles, sound velocity reaches a maximum at the surface, and declines rapidly during the first 10-50 meters below the surface, increasing localization difficulty for mysticetes present in all identified risk areas. Sound velocity profiles at all locations change due to seasonal variation in thermocline and halocline depths, varying by as much as 30 m/s among locations during any single given season. Furthermore, the reflectivity of ocean floor sediment type has a large impact on how quickly a vessel’s signal attenuates, with mud reflecting the lowest signal intensity and granite reflecting the highest signal intensity for each vessel signature analyzed; distinct acoustic shadow zones develop in five of the seven areas modeled during the summer and fall seasons. Regardless of the depth of the modeled area, at least one shadow zone is present at the surface 100 meters – 2000 meters directly in front of the oncoming boat, presenting a significant handicap to mysticetes attempting to detect and localize an oncoming vessel.

2.2 Introduction

Whale-vessel collisions—or ship strikes—are one of the most common anthropogenic causes of cetacean mortality. Data suggest that the U.S. eastern seaboard has the greatest frequency of ship strikes world-wide (Jensen & Silber, 2003). More specifically, the Gulf of Maine is of particular interest because of its established value as a feeding area for several species. The geographic location of a strike often goes unreported, making area-based protective measures difficult. Therefore, it is useful to model areas of high-predicted ship strike risk.

Studies have demonstrated that the frequency of ship strikes is associated with both vessel-specific factors and the species involved (Laist et al., 2001; Jensen & Silber, 2003). A vessel's acoustic signature and the physical properties of the water column surrounding the ship may be two of these factors (Blue & Gerstein, 2005). A vessel's acoustic signature varies with engine type and placement, propeller type and placement, hull material, and speed (Arveson & Vendittis, 2000). In addition, the temperature, salinity, depth, ocean floor sediment type, and rugosity all affect underwater transmission of a vessel's acoustic signature (Urick, 1983). Accordingly, a vessel's acoustic signature may change significantly over time, as speed and environmental factors change. Furthermore, commercial vessels locate their main service engines and propellers at the rear of the vessel, causing a portion of the engine-based acoustic signature to be reflected by the hull before being transmitted into the water column, creating an acoustic shadow directly in front of the vessel, known as the bow null effect (Arveson & Vendittis, 2000;

Blue & Gerstein, 2005). Thus, source environmentally-based variation in vessel acoustic signatures may hinder a baleen whale's ability to detect, localize and avoid potential harmful encounters with shipping traffic.

Here, we develop a model that accounts for environmental variability in ship acoustic signature propagation in seven areas previously identified to have high ship strike mortality risk for North Atlantic right whales based on the co-occurrence of ships and whales (Mahaffey, 2006). In developing this model, we used site-specific oceanographic properties to simulate a two-dimensional sound field directly in front of a vessel, thus characterizing the acoustic landscape a whale might experience. This model will enable us to determine if and when acoustic shadow zones occur in these areas, increasing the difficulty of detecting, localizing and avoiding an oncoming vessel.

2.3 Methods

2.3.1 Modelling Relative Geographic Shipstrike Risk

Seven locations within the Gulf of Maine, the primary feeding ground for North Atlantic right whales, were identified to have qualitative "high" ship strike mortality risk based on predictive GIS modeling of the co-occurrence of North Atlantic right whales and shipping traffic (Mahaffey, 2006). These seven regions are the Isle of Shoals, Great South Channel, Lower Boston Traffic Separation Scheme (TSS), Massachusetts Bay, the Inner Schoodic Ridges, Jordan Basin, and the Northeast Channel (Figure 2.1). Acoustic models were developed for each of these seven identified locations in order to characterize the acoustics of close North Atlantic right whale/ship encounters where the risk of ship strike mortality was likely to be highest.

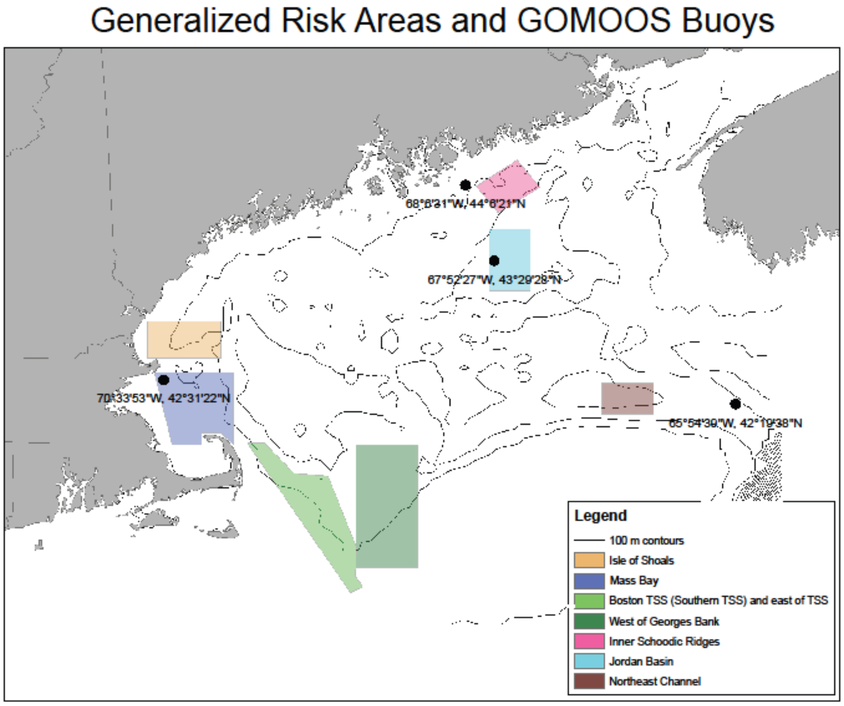


Figure 2.1. Buoy Locations Relative to Seven Previously Identified Ship Strike Risk Areas within the Gulf of Maine. The location of the GOMOOS buoys utilized for hydrography data are shown as black circles. High ship strike risk areas were previously identified by Mahaffey (2006).

2.3.2 Modeling Acoustic Shipstrike Risk

The Gulf of Maine Ocean Observation System (GOMOOS) provided basic hydrography data for Massachusetts Bay (Buoy A01), Isle of Shoals (Buoy B01), the Inner Schoodic Ridges (Buoy I01), Jordan Basin (Buoy M01) and the Northeast Channel (Buoy N01) from January 1, 2002 – December 31, 2007 (GOMOOS, 2008). Data obtained included sea surface temperature and salinity, as well as temperatures and salinities at multiple depths specific to each buoy. We separated all data by season (Jan-Mar, Apr-Jun, Jul-Sep and Oct-Dec) and calculated pooled averages, standard deviations and standard errors. We obtained equivalent oceanographic variables for the Boston TSS and George's Bank by using data from conductivity/temperature/depth (CTD) casts taken on transects with similar coordinates (Flagg, 1987). The seasonal averages of water temperatures and salinities used the same three-month season segregation as the GOMOOS-derived data. We then converted seasonally averaged hydrography data to sound velocity profiles for each of the seven identified collision risk areas using Medwin's equation for sound velocity

$$c = 1449.2 + 4.5T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \tag{2.1}$$

where c = sound velocity in meters per second, T = temperature in degrees Celsius, S = salinity in practical salinity units, and z = depth in meters (1975).

Using Gulf of Maine 15 arc-second bathymetry data (Roworth & Signell, 2002) and sediment data from the US Geological Survey East Coast Sediment Texture Database (USGS, 2004) we identified the approximate depth and the average composition of the sediment at each of the seven identified collision risk areas. We calculated an approximate reflection coefficient for each risk area by multiplying the percentage of each sediment type found in a given area by a standard reflection coefficient for that sediment type. For example, in Jordan Basin, the mean sediment composition was 0.27% gravel, 7.81% sand, 61.00% silt and 30.93% clay. Thus, the calculation for the sediment reflection coefficient in Jordan Basin is seen below

$$R_{JB} = R_G * 0.0027 + R_{SA} * 0.0781 + R_{SI} * 0.61 + R_C * 0.3093 \tag{2.2}$$

where R_{JB}= reflection coefficient for Jordan's Basin, R_G = reflection coefficient of gravel, R_{SA} = reflection coefficient of sand, R_{SI} = reflection coefficient of silt, and R_C = reflection coefficient of clay

In addition, we constructed mock rugosity profiles of the ocean floor in each of the seven identified risk areas after determining "typical" patterns existing in those areas from Gulf of Maine 15 arc second bathymetry data (Roworth & Signell, 2002) (Table 2.1).

Region	*Minimum Depth (m)*	*Maximum Depth (m)*	*Mean Depth (m)*	*Mean Sediment Size (phi units)*	*Combined Reflection Coefficient (% reflectance)*
Great South Channel	-209	-35	-123	2.07	76.652
Inner Schoodic Ridges	-254	-64	-140	6.36	59.706
Lower Boston TSS	-211	-31	-111	1.91	77.188
Northeast Channel	-351	-259	-311	4.54	69.834
Jordan Basin	-305	-185	-242	6.92	56.550
Isle of Shoals	-197	3	-91	3.95	70.398
Massachusetts Bay	-214	-12	-73	2.24	75.723

Table 2.1. Characteristics of Potential Risk Areas.

We then input the above-derived data into Ray v.1.47, a MATLAB two-dimensional acoustic ray-tracing program to determine underwater sound propagation in the seven identified shipstrike risk areas (Bowlin et al., 1992). An acoustic profile of the M/V *Overseas Harriette*, a Japanese cargo ship (length 173 meters, displacement 25,515 tons, propeller depth 7.5 meters, average speed 15.5 knots) was used as a representative ship design for all acoustic rays traced in this model (Arveson & Vendittis, 2000). For any given model run, we traced 200 individual acoustic rays from the vessel to a distance five kilometers ahead of the vessel, highlighting areas where acoustic shadow zones and acoustic channels likely form under different seasonal and environmental factors in each of the seven identified risk areas.

We qualitatively categorized the resulting sound fields derived by the model into four grades of propagation impact (low, mild, moderate, severe), based on the influence of environmental variables on signal transmission. We propose that environments that minimally affect propagation constitute low ship strike risk areas, as signal degradation is minimized and thus vessel detection is maximized. For example, low propagation impact may be characterized by highly reflective sediments, little variation in ocean floor depth, a homogenous sound velocity profile, and few shadow zones. Severe propagation impact may be the result of highly absorptive sediments, significant variation in ocean floor depth, a heterogeneous sound velocity profile, and the presence of three or more acoustic shadow zones within the first kilometer ahead of the boat.

2.4 Results and Discussion

Environmentally-induced impacts on signal propagation are summarized in Table 2.2. During the months of October – March, environmental impact on signal transmission was significantly reduced in all areas except the Northeast Channel. For all seasons, the most severe impact on acoustic propagation, and therefore the conditions most conducive to hinder vessel detection appeared to occur at the Isle of Shoals, Massachusetts Bay, and the Northeast Channel areas. We therefore identify these areas as higher risk for baleen whale ship strike, based on their more cryptic propagation characteristics. The Northeast Channel is an area with less dedicated survey effort compared to the other identified geographic shipstrike risk areas. Given the results of our analysis, additional survey effort in this area is encouraged.

Location	***Ocean Floor Sediment Reflectivity***	***Ocean Floor Rugosity***	***Variation in Sound Velocity vs. Depth***	***Presence of Acoustic Shadow Zones (Oct-Mar)***	***Presence of Acoustic Shadow Zones (Apr-Sep)***
Isle of Shoals	Moderate	Moderate	Moderate	Low	Severe
Great South Channel	Mild	Severe	Moderate	Mild	Moderate
Lower Boston TSS	Mild	Severe	Severe	Mild	Moderate
Massachusetts Bay	Mild	Moderate	Moderate	Mild	Severe
Inner Schoodic Ridges	Low	Severe	Low	Mild	Moderate
Jordan Basin	Severe	Low	Severe	Mild	Moderate
Northeast Channel	Moderate	Mild	Severe	Moderate	Severe

Table 2.2. Relative Acoustic Propagation Impact in the Identified High Ship Strike Risk Areas.

All seven risk areas exhibit the greatest change in sound velocity over depth during July-September (Figures 2.2 – 2.8). Variation in sound velocity with depth is directly related to acoustic channeling, and thus the formation of acoustic shadow zones. As a result, a higher number of acoustic shadow zones are likely present in all seven risk areas during April-September.

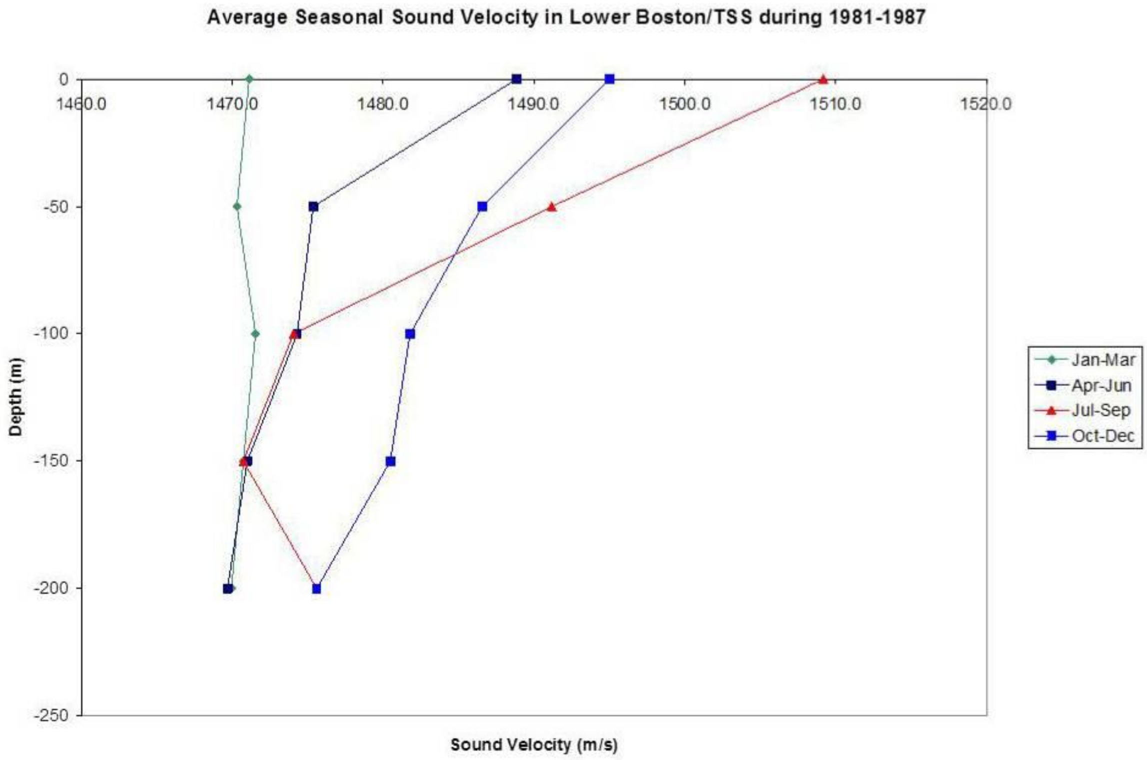


Figure 2.2. Calculated Seasonal Sound Velocity Profiles for the Lower Boston TSS.

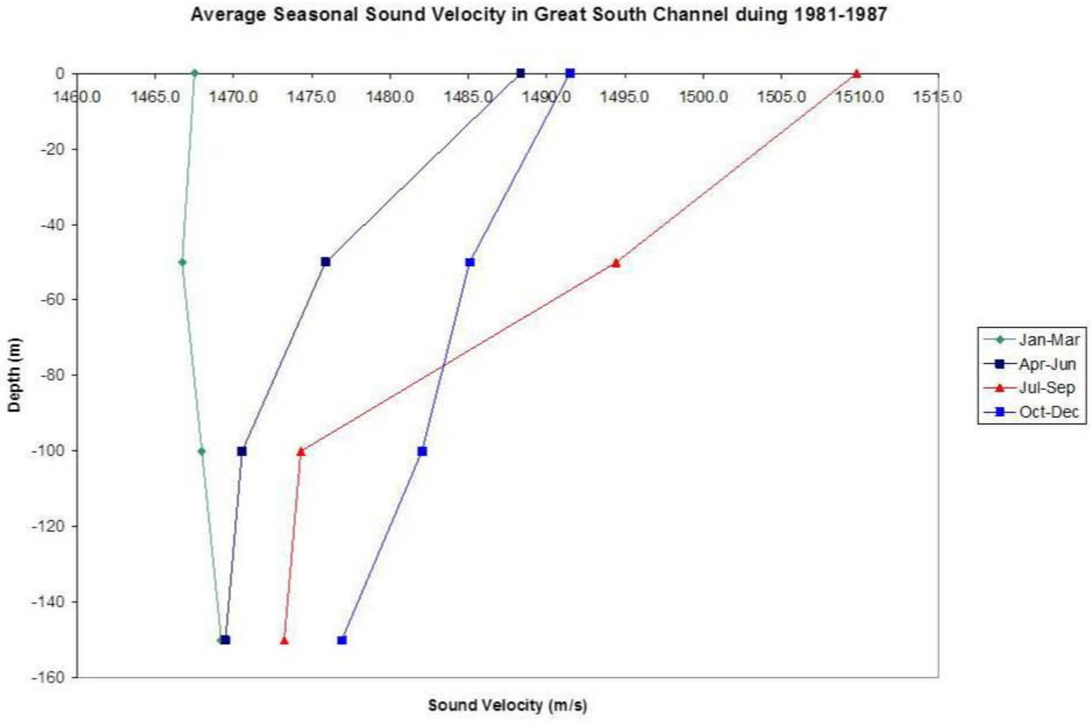


Figure 2.3. Calculated Sound Velocity Profiles for the Great South Channel.

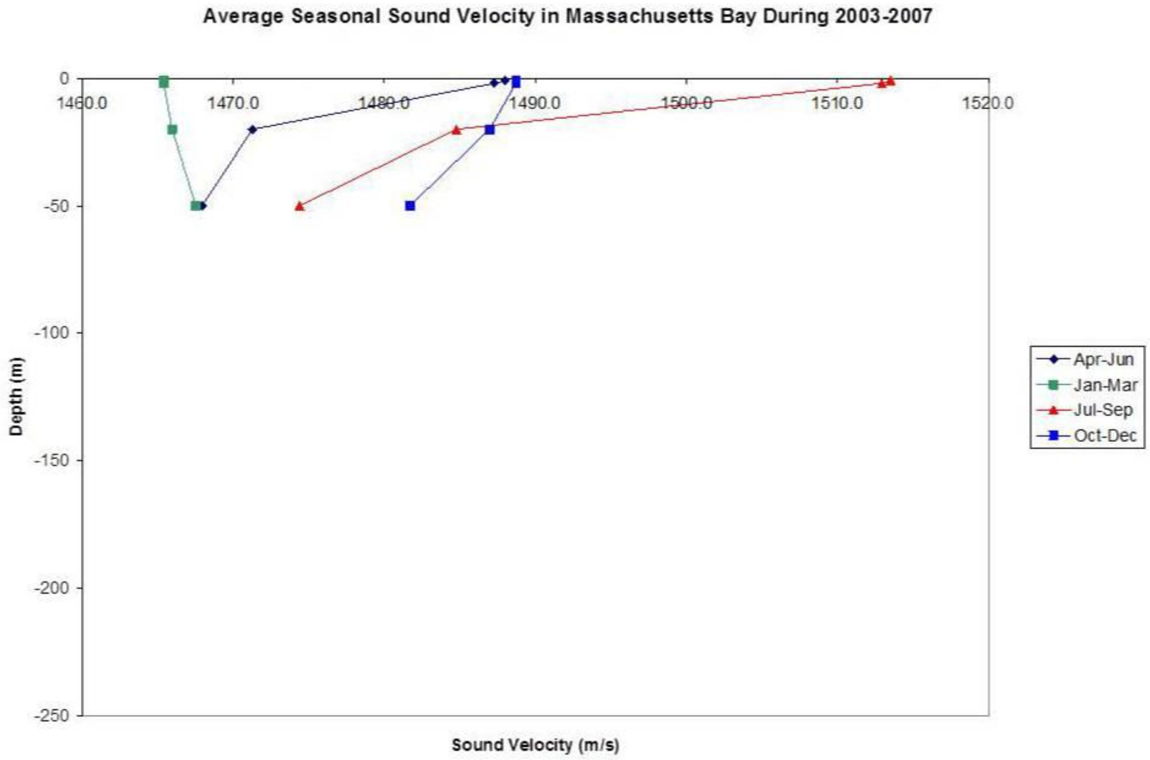


Figure 2.4. Calculated Seasonal Sound Velocity Profiles for Massachusetts Bay.

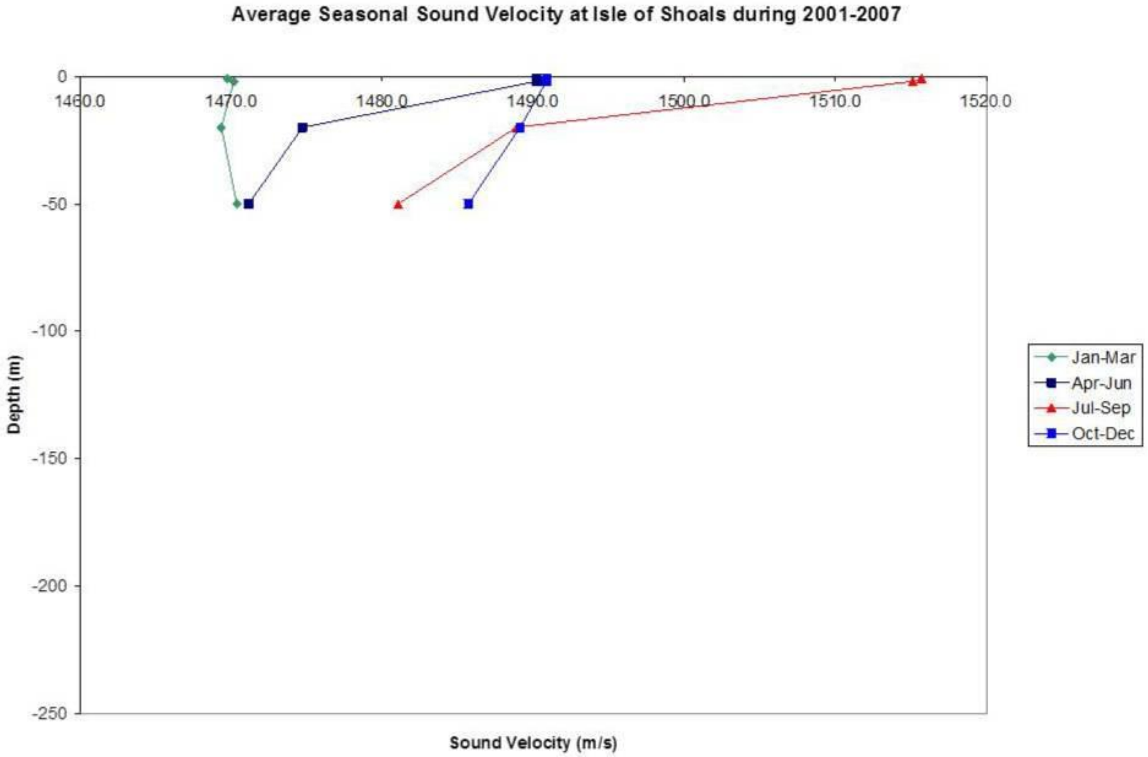


Figure 2.5. Calculated Seasonal Sound Velocity Profiles for the Isle of Shoals.

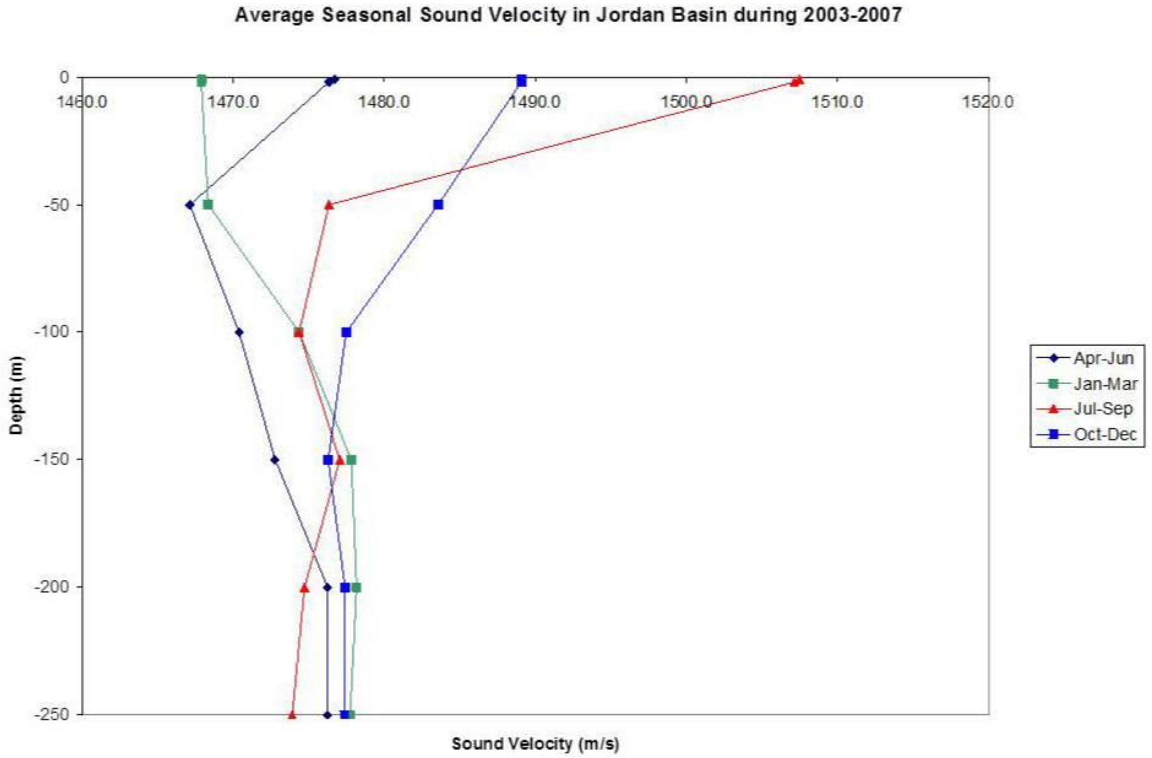


Figure 2.6. Calculated Seasonal Sound Velocity Profiles for Jordan Basin.

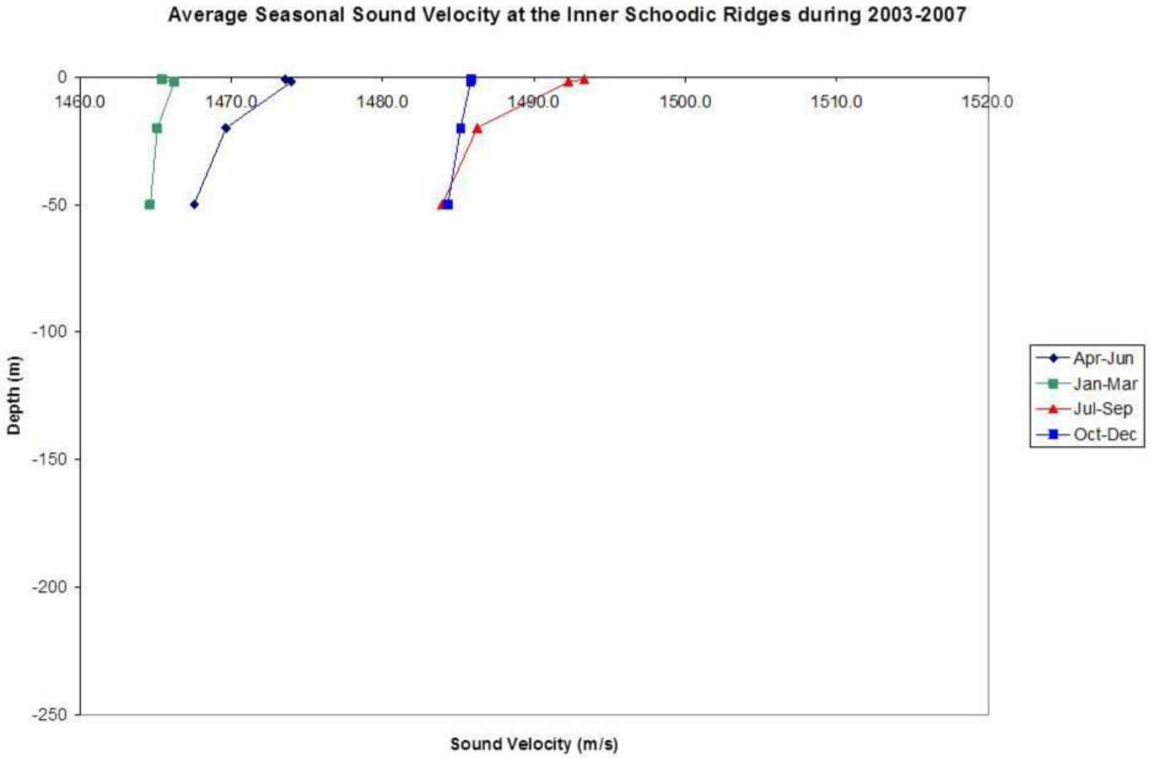


Figure 2.7. Calculated Sound Velocity Profiles for the Inner Schoodic Ridges.

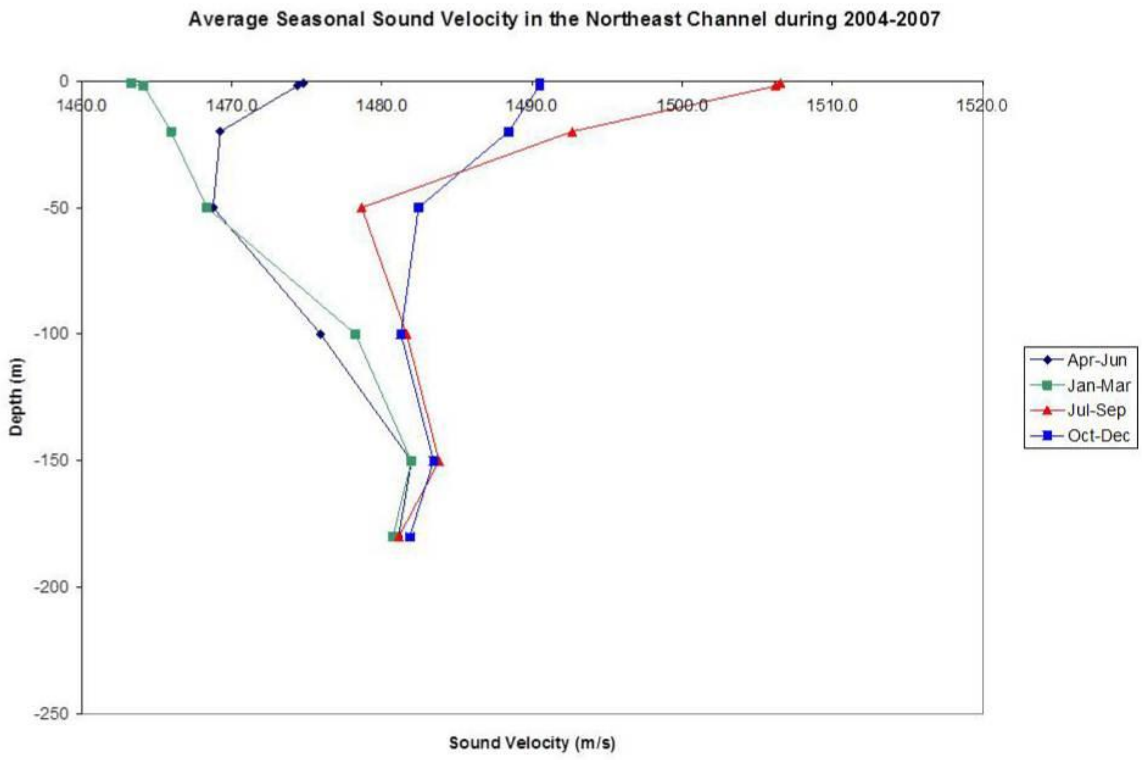


Figure 2.8. Calculated Seasonal Sound Velocity Profiles for the Northeast Channel.

Rugosity, or the amount of variation in ocean depth over any given area, appears to have little to no effect on acoustic ray transmission except when combined with highly reflective ocean floor sediment types and shallow seas. In our study, the effects of rugosity on acoustic ray transmission were only seen at the Inner Schoodic Ridges, where large variations in ocean depth over small areas led to an increase in the number of acoustic shadow zones present near the surface (within the first 30 meters). In all other cases, rugosity had little to no effect on acoustic ray transmission, and thus is likely not a significant consideration when modeling ship strike risk based on acoustic detection.

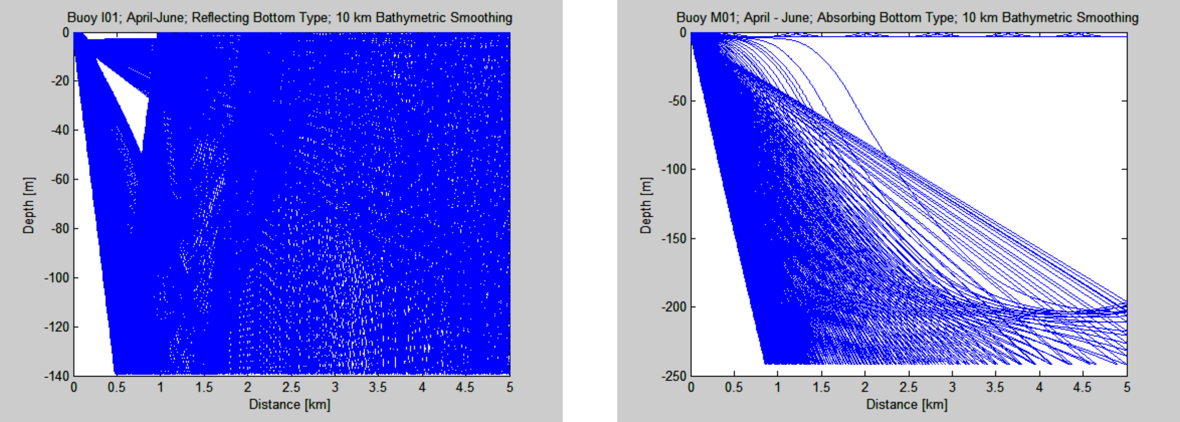


Figure 2.9. Two Hundred Acoustic Rays Traced for the Inner Schoodic Ridges and Jordan Basin Risk Areas for April-June. The Inner Schoodic Ridges (left) is primarily composed of granite, a highly reflective sediment type, while Jordan Basin (right) is primarily composed of mud, a highly absorptive bottom type.

Both variation in porosity and sediment type influenced seafloor reflectivity, impacting transmission loss at the point of reflection. These effects were analyzed as a single reflectivity value in this study; future work should perhaps focus on the role of porosity, which will be more variable spatially and seasonally. Highly reflective sediment types, such as granite, produced acoustic rays that propagated over the entire five kilometer model range, and had a tendency to create more acoustic shadows than lower reflective sediment types, such as mud. Lower reflective sediment types did not enable acoustic rays to travel as far, with all ray transmission ending 0.5-3.5 kilometers in front of the ship (Figure 2.9).

2.5 Conclusions

Using a previously published GIS-based spatiotemporal analysis, the Isle of Shoals, Great South Channel, Lower Boston TSS, Massachusetts Bay, Inner Schoodic Ridges, Jordan Basin and Northeast Channel were identified as areas of highest risk in the Gulf of Maine for North Atlantic right whale ship strike (Mahaffey, 2006). Acoustic modeling suggested that within these areas propagation of a vessel's acoustic signature would be most compromised, and therefore acoustic-based detection of a vessel would be most hindered, in the Isle of Shoals, Massachusetts Bay, and the Northeast Channel during April-September. Acoustic propagation of vessel signature was modeled as moderately impacted in the Great South Channel, Lower Boston TSS, Inner Schoodic Ridges and Jordan Basin. During October – March impacts on propagation characteristic were significantly reduced in all areas except the Northeast Channel.

Particularly, the presence of modeled bow null effect acoustic shadow zones is likely to have a negative impact on the ability of baleen whales to accurately detect and/or localize oncoming ships. Most animals respond to sensory gradients by moving away from gradients likely to cause danger. In the case of bow null effect acoustic shadow zones, North Atlantic right whales detecting oncoming ships in the presence of this sensory gradient are therefore likely to avoid oncoming ships by following a reduction in the overall sensory gradient; i.e. avoiding oncoming ships by moving closer to the bow null effect acoustic shadow zone region. As bow null effect acoustic shadow zones were present at all modeled locations and during every modeled season, it is suggested that future studies focus on better identifying physical factors which contribute to the formation of these shadow zones, the spatial area of these shadow zones, and potential methods for reducing the presence of these shadow zones.

CHAPTER 3

IN SITU OBSERVATION OF SHIP ACOUSTIC PROPAGATION

3.1 Chapter Abstract

To understand mysticete acoustic-based detection of ships, radiated noise from high-speed craft, cruise ships, catamarans and fishing vessels was recorded June-September 2009. Calibrated acoustic data (<2500 Hz) from a vertical hydrophone array was combined with ship passage information. A cruise ship had the highest broadband source level, while a fishing vessel had the lowest. Ship noise radiated asymmetrically and varied with depth. Bow null-effect acoustic shadow zones were observed for all ship classes and were correlated with ship-length-to-draft-ratios. These shadow zones may reduce ship detection by near-surface mysticetes.

3.2 Introduction

Shipping traffic has increased worldwide (International Maritime Organization [IMO], 2007; 2009), coinciding with an increase in reported whale/ship collisions (Laist et al., 2001; Panigada et al., 2006; Douglas et al., 2008; Carillo & Ritter, 2010) . Ship collision has been identified as a significant anthropogenic cause of mysticete mortality (IMO,2008; 2009), and as the leading known cause of mortality for highly endangered North Atlantic right whales (Kraus et al., 2005; Moore et al., 2005).

The majority of reported whale/ship collisions indicate the ship hitting a whale, but a number have noted mysticetes hitting slow moving ships (British Broadcasting Company, 2010; Gabriele et al., 2011). Of the reported whale/ship collisions that have been observed, in some documented cases an individual whale transiting parallel to a vessel turned directly into the path of the ship (Mayo & Marx, 1990; Terhune & Verboom, 1999). This action may imply the whale did not correctly detect and/or localize the ship.

Long-range ship detection, or its failure, might be based in the acoustics of the ship and the sensory perception of the whale. Current literature assumes that mysticete hearing should encompass the same frequencies at which they vocalize (Richardson et al., 1995). If this is accurate, the mysticete auditory range overlaps substantially with peak intensities recorded from transiting ships (Arveson & Vendittis, 2000; Gerstein & Blue, 2005; Trevorrow et al., 2008; McKenna et al., 2012). Thus, mysticetes should have the capacity to acoustically detect an oncoming ship (Richardson et al., 2005). Why, then, do whale/ship collisions occur?

Several recent studies have analyzed concurrent distribution of ships and mysticetes (DeStephanis & Urquiola, 2006; Todd et al., 2009; Ritter, 2010; William & O'Hara, 2010). Additional work has considered probability of lethal impact based on ship speed (Laist et al., 2001; Ward-Geiger et al., 2005; Vanderlaan & Taggert, 2007). Few studies have examined three-dimensional propagation of ship acoustic signatures transiting mysticete habitat. Combining ship spectral information and propagation with whale behavior is critical to understanding the causes of mysticete shipstrike.

In this work, a vertical hydrophone array was used to record 24 ships of four ship classes transiting the Bar Harbor, Maine, USA, shipping channel during June – September 2009. Just offshore of this location is an important feeding habitat for endangered North Atlantic right whales, and an established feeding ground for endangered finback and humpback whales (Waring et al., 2011). Source levels were calculated at hydrophone depths of 5, 15 and 25 meters to characterize the three-dimensional acoustic environment a mysticete would encounter during a whale/ship approach.

3.3 Methods

Received levels (RLs) were measured by obtaining calibrated vertical hydrophone array recordings of ship acoustic signatures. The array was comprised of three omnidirectional C54XRS hydrophones with flat frequency response range of 6 Hz - 203 kHz and calibrated sensitivity of -20 dB re: 1 V/μPa. RL data were associated with transiting ship track data determined by onboard GPS recorders accurate to +/- 1 meter. Ship orientation relative to the hydrophone array was calculated using directional compass observations. After each passage, vertical sound speed profiles were calculated using data from conductivity/temperature/depth (CTD) casts. Additional bathymetric topography and sediment characterization data were obtained from the Gulf of Maine 15 arc-second bathymetry database (Roworth & Signell, 2002) and the U.S. Geological Survey East Coast Sediment Texture Database (US Geological Survey, 2004) respectively. The hydrophone array was suspended near the Bar Harbor shipping lane, with water depth of 38.7-46.0 meters and a rocky sea floor (for sample ship tracks, see Appendix A).

Ship GPS tracks were used to calculate ship speed and distance from the hydrophone array. All ships recorded passed the array on their starboard side. Trials were not used in data analysis if ships significantly changed their orientation or if multiple ships were in close proximity to the hydrophone array.

Source levels (SLs) for each ship were calculated as follows:

$$SL = RL(r) + Nlog(r) + \alpha r \text{ at location } P(d,\theta) \tag{3.1}$$

$$\alpha = \frac{\frac{8.68\pi}{c} f_r f^2}{f_r^2 + f^2} \tag{3.2}$$

$$f_r = \frac{1}{2\pi\tau_r} \tag{3.3}$$

where RL = pressure level recorded by the hydrophone (dB re 1μPa^2/Hz), SL = source pressure level (dB re 1μPa^2 @ 1m), r = ship range from the hydrophone array (m), N = coefficient for geometric transmission loss (dB/m), α = coefficient for absorption transmission loss (dB/m), d = hydrophone depth (m), θ = ship orientation relative to the hydrophone array (directional compass degrees, f_r = molecular relaxation frequency (kHz), f = frequency (kHz), c= sound velocity (m/s), τ_r = molecular relaxation time of salt water (s) (Urick, 1983; Arveson & Vendettis, 2000; Medwin, 2005)

Geometric transmission loss was further defined as follows:

$$\lambda = fc \tag{3.4}$$

$$\text{If } \lambda \geq d, \text{ then } N = 10\log(r) \tag{3.5}$$

$$\text{If } \lambda < d, \text{ then } N = 20\log(r) \text{ until } x\lambda = d; \tag{3.6}$$

$$\text{If } x\lambda \geq d, \text{ then } N = 10\log(r) \tag{3.7}$$

where λ = wavelength (m), d= depth of the water column (m), and x = a constant specific to each wavelength relative to the source depth (Urick, 1983).

Equation 3.5 applies to long wavelengths in comparison to water column depth, accounting only for cylindrical spreading loss at low frequency components. For shorter wavelengths, Equation 3.6 and Equation 3.7 are combined to calculate geometric spreading loss in two portions: 1) from the source to the first wave bottom reflection and 2) from the first wave bottom reflection to the hydrophone location.

CTD casts and depth estimates were combined to calculate sound speed profiles in a manner consistent with Mackenzie (1981). Sound speed profiles were used to calculate the wavelength (m) at each frequency component of recorded ship acoustic signatures, as well as to calculate the coefficient of absorption transmission loss (α) (see Equation 3.2 and Equation 3.4).

SL calculations were made in 1 Hz bins from 1-2500 Hz for each ship recorded at hydrophone depths of 5, 15 and 25 m. Source intensities in 1 Hz bins were integrated over frequency to compute broadband pressure level at each depth. All SL calculations reflect ship pressure variation above the ambient noise level; not a ship's absolute source level. As ship signal pressure is related to ship speed, all calculated SLs are for a specific ship speed.

An estimate of the root mean square error in the SL calculation can be obtained using the attenuation from a range of empirical values collected by Francois and Garrison (1982) and the ΔSL = root mean square error (dB) relationship:

$$\Delta SL = \pm\sqrt{\Delta RL^2 + (\frac{N\Delta r}{r})^2 + (\Delta\alpha r)^2 + (\alpha\Delta r)^2)} \tag{3.8}$$

Ship information (Lloyd's Registry of ships)								Maine DMR	Acoustic Measurements								
Ship Type	MMSI number/ official number*	Ship length (m)	Ship draft (m)	Year built	Gross tonnage (10^3)	Horse power (10^3)	Propulsion Type	Registration number	Vessel speed (kts)	Range at CPA[b] (km)	Received level at CPA[c]	Source level at 1 m[c]	Peak frequency (Hz)	Water depth at CPA (m)	Maximum range data was collected bow-aspect (km)	Maximum range data was collected stern-aspect (km)	Average Ambient Noise[c]
High Speed Craft																	
	311364000[*]	97.2	3.4	2002	6.6	38.5	jet	n/a	35.8	2.3	119	210	44	58.8	3.6	3.7	56
Cruise Ships																	
	247117400[a]	203.2	6.2	2003	42.3	37.5	propeller	n/a	21.9	1.7	129	219	44	56.1	2.1	2.1	56
	311307000	294.1	8.2	2002	92.3	79.9	ADU	n/a	19.3	2.5	96	203	48	59.7	3.1	3.2	64
	244958000	219.2	7.7	1993	55.6	47.0	propeller	n/a	17.4	2.8	91	196	40	62.4	3.5	3.4	59
	311583000	293.2	8.5	2004	90.1	68.0	ADU	n/a	20.5	1.9	116	210	43	57.2	2.6	2.5	52
Catamarans																	
	1144667[*]	37.8	1.8	2003	0.5	7.2	jet	n/a	29.9	0.6	97	189	45	57.2	2.7	2.9	67
	1040508[*,a]	34.1	1.5	1996	0.2	2.7	jet	n/a	27.4	1.5	117	197	44	25.9	3.4	3.4	43
	1101923[*]	28.0	1.4	1999	0.1	3.1	jet	n/a	27.1	3.2	84	201	46	35.8	4.1	4.3	54
Fishing Vessels																	
	n/a[*]	12.1	1.2	1997	<0.1	0.5	propeller	221984	12.4	1.5	103	187	44	30.5	2.1	2.2	52
	n/a	10.4	1.1	1994	<0.1	0.3	propeller	411937	18.6	0.7	133	193	50	36.6	1.3	1.4	58
	n/a	11.6	1.2	1998	<0.1	0.6	propeller	313451	8.4	0.2	131	174	48	34.6	1.1	1.1	53
	n/a	11.0	1.1	1985	<0.1	0.3	propeller	230474	13.5	1.1	112	181	43	37.2	1.9	1.9	54
	n/a	11.3	1.1	1989	<0.1	0.4	propeller	468112	14.8	0.9	119	184	47	47.8	1.3	1.3	62
	n/a	11.5	1.1	2003	<0.1	0.4	propeller	213975	11.2	1.8	113	192	45	61.5	2.2	2.1	59
	n/a	10.8	1.1	1999	<0.1	0.3	propeller	233856	16.9	2.0	101	188	44	54.9	2.4	2.4	55
	n/a	12.2	1.2	1991	<0.1	0.6	propeller	329644	18.4	1.6	118	195	46	52.7	2.1	2.0	56
	n/a	11.6	1.2	2000	<0.1	0.6	propeller	213765	15.9	1.3	115	187	46	34.8	1.8	1.7	74
	n/a	11.6	1.2	2001	<0.1	0.5	propeller	319017	15.2	2.1	95	184	44	39.7	2.4	2.5	69
	n/a	12.2	1.2	2006	<0.1	0.6	propeller	412556	13.7	0.6	126	182	48	55.1	1.1	1.1	51
	n/a	10.7	1.1	2003	<0.1	0.3	propeller	312884	11.6	0.5	129	180	51	56.3	1.2	1.1	55
	n/a	12.2	1.2	2009	<0.1	0.5	propeller	114801	14.1	1.3	112	184	43	46.4	1.7	1.8	54
	n/a	10.4	1.1	1998	<0.1	0.3	propeller	501873	12.9	1.5	107	182	44	37.2	1.9	2.0	65
	n/a	11.0	1.1	1983	<0.1	0.3	propeller	591313	10.5	1.6	102	179	47	34.6	2.1	2.1	68
	n/a	10.4	1.1	1992	<0.1	0.3	propeller	266474	9.9	1.9	98	178	49	35.9	2.3	2.4	49

[*] No MMSI Number available; official number as listed in Lloyd's Registry of ships

[a] Ships shown in Figs. 3.1 and 3.2.

[b] CPA is the closest point of approach

[c] dB re 1 μPa^2 (1-2500 Hz).

Table 3.1. Summary of Ship Characteristics.

3.4 General Spectral Patterns

A total of 24 ships in four ship classes were recorded (see Table 3.1). All four cruise ships were placed in the same ship class for comparison purposes, although two are azimuthal drive unit (ADU) –driven and two are propeller-driven. A single ship class was used because when these ships are transiting an area at a constant bearing ADUs function like regular propellers and the placement of working ADUs is similar to comparable propeller placement.

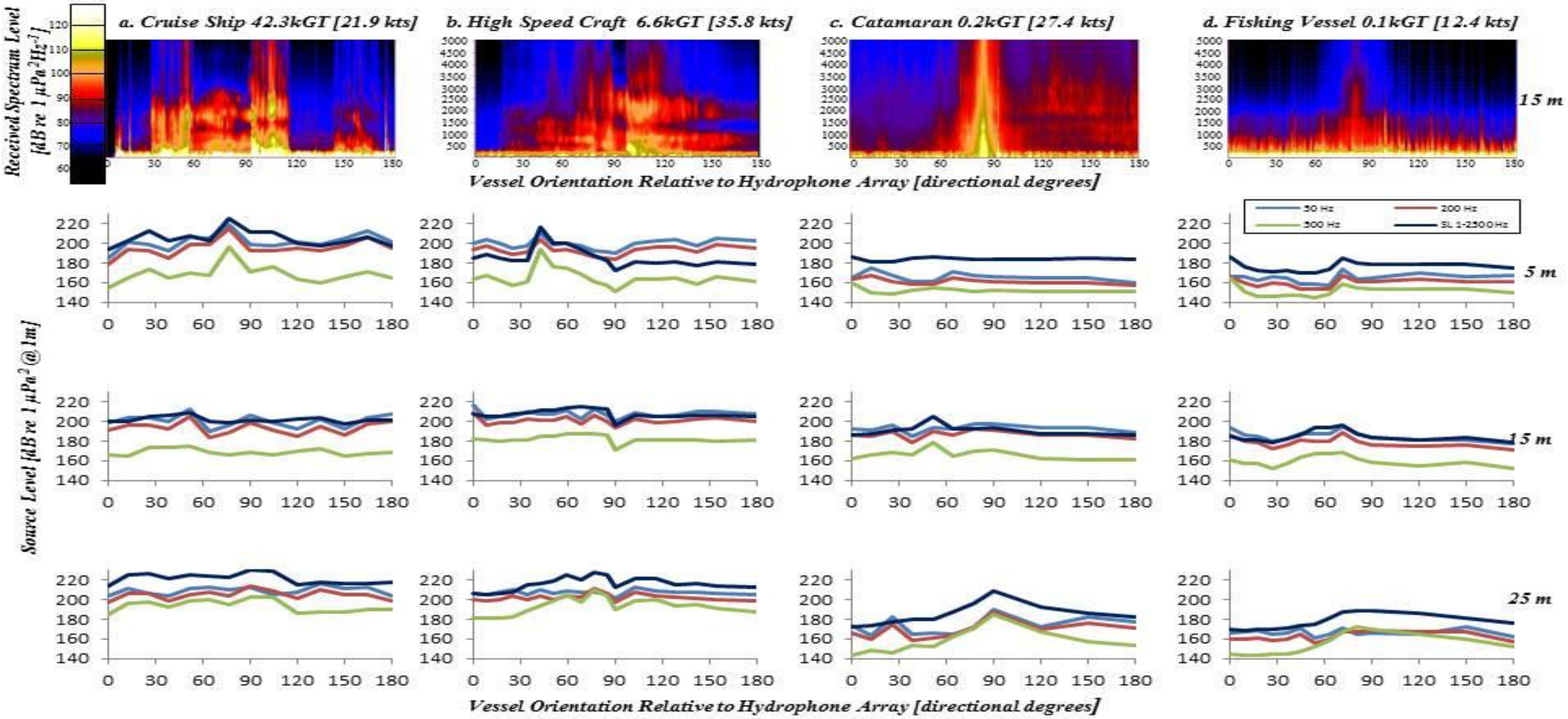
The highest broadband source level was for a cruise ship and calculated to be 219 ± 3.8 dB re 1µPa@1m, while a fishing vessel had the lowest at 178 ± 3.1 dB re 1µPa@1m. Difference in source level, in part, is likely a function of variation in ship speed and size (gross tonnage). Comparison of all 24 ships showed a moderate effect on SLs with increasing speed ($R^2 = 0.5017$; $n = 24$) and increasing size ($R^2 = 0.3738$; $n = 24$). However, this did not hold true when comparing ships within each ship class. Increasing catamaran ship length resulted in a negative relationship with increasing SLs ($R^2 = 0.9454$; $n = 3$), while increasing cruise ship size had no relationship to increasing SLs ($R^2 = 0.0757$; $n = 4$).

The calculated SLs presented here are higher and qualitatively different than those reported for modern commercial ships (McKenna et al., 2012), and may be attributed to a difference in ship classes studied. In contrast to McKenna et al. (2012), commercial ships in this study were smaller, transited at higher speeds and utilized multiple propulsion methods, all of which could affect resulting SLs. In general, smaller vessels require less power to propel them forward, and thus tend to exhibit lower broadband SLs than larger vessels. In addition, increasing ship speed is often related to increasing broadband SLs.

Finally, modern commercial ship SLs recorded in McKenna's study (2012) were from propeller-driven ships, while SLs recorded by this study included propeller-, ADU-, and jet-driven ships.

3.4.1 Radial Spectral Patterns

Three-dimensional acoustic data is shown for a subset of representative vessels in Figure 3.1. Comparisons can be made between ship classes, however significant variability also exists within ship classes. For additional three-dimensional ship passage data, see Appendix B. Surface (5 m) and deep water (25 m) broadband SLs were 10-15 ± 2.8 dB less than mid-water (15 m) broadband SLs for the catamaran (Figure 3.1.c.) and fishing vessel (Figure 3.1.d.). The catamaran and fishing vessel were observed transiting the shipping lane at shallower water depths than the cruise ship (Figure 3.1.a.) and high-speed craft (Figure 3.1.b. and Table 3.1). Lower RLs observed at 5m and 25m in the smaller boats may be a result of variations in depth-dependent transmission loss at frequencies higher than 100 Hz (Urick, 1983; Gerstein & Blue, 2005).



*Hydrophone depth listed at the right.

Figure 3.1. Spectrum Levels During Close-Range Ship Passages at 15 m Depth for Four Ship Classes. Ship classes include (a) cruise ship (MMSI 247117400). (b) high speed craft (MMSI 311364000). (c) catamaran (Official 1144667). (d) fishing vessel (Official 221984). Figures are centered relative to angular ship passage. Top figure series shows received level as color (dB re 1 μPa^2/Hz) at hydrophone depth 15 m using sequential 1 s spectral averages to form the long-term spectrogram (Hanning window, DFT length of 256 samples and 50% overlap). Bottom figure series show calculated source levels (SLs) for hydrophone depths 5, 15, and 25 m.

All four ship classes exhibited peak (3 dB bandwidth) broadband SLs aft at orientations >90˚ and minimum broadband SLs off the bow at orientations <60˚ at 25 m, supporting previous data that deep water modern commercial ship acoustic signatures are louder from the side-aspect and stern-aspect than from the bow-aspect (McKenna et al, 2012). This result was observed for all four ship classes despite differences in hull design, propulsion-type and speed. Factors such as a poorly maintained propeller can increase overall ship noise from cavitation bubbles (Arveson & Vendittis, 2000). Jet-propelled ships may be quieter near the stern as jet-created bubbles absorb acoustic energy from internal engines and generators (Medwin, 2005). Finally, variations in ship speed can impact the directionality of a ship's signal as different ship components (propellers, engines, generators, etc.) dominate the acoustic signature at different ship speeds (Arveson & Vendittis, 2000; Gerstein & Blue, 2005; Medwin, 2005).

All ship classes exhibited an increase of 1-15 ± 2.8 dB in 15˚ broadband SLs relative to bow broadband SLs at 5 m, while no real pattern of increase emerged from bow to 15˚ at other depths. This is indicative of bow-null effect acoustic shadow zones (Gerstein & Blue, 2005; Trevorrow et al, 2008). This is a key result since mysticetes located near the surface of the water column may thus have increased difficulty detecting, and therefore avoiding oncoming ships.

3.4.2 Bow-null effect acoustic shadow zones

Bow null effect acoustic shadow zones (BNEASZs) were observed for all ship classes (Figure 3.1). At 5 m depth, the cruise ship exhibited the greatest variation in broadband source level from the bow to 15˚ (+15 ± 2.8 dB), while the fishing vessel had the least (+6 ± 3.4 dB) (Figure 3.3). Although the high-speed craft and catamaran were transiting at greater speeds than the cruise ship, they exhibited less change in broadband source level from 0-15˚ (+11 ± 2.2 dB and +9 ± 2.4 dB respectively). This difference suggests that hull construction and/or propulsion-type may play a larger role in the development and size of observed BNEASZs than increased ship speed. Increasing length to draft (L:D) ratios showed a positive relationship with increasing SLs observed from the bow to 15˚ for all ship classes (R^2=0.6252; n=4) (Figure 3.2). Thus, L:D ratios may be useful when predicting radiated ship noise.

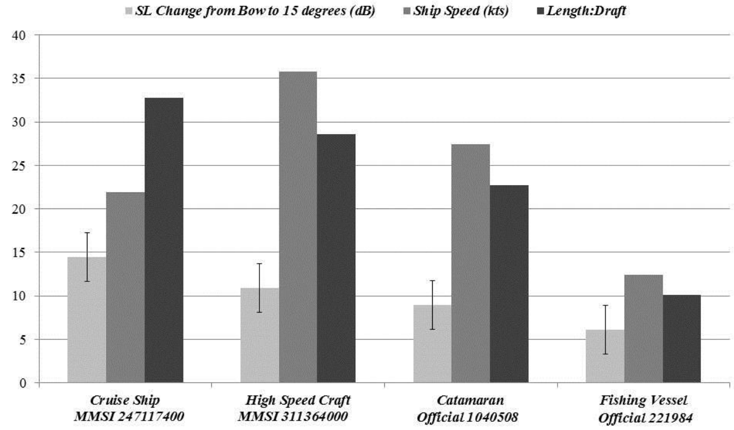


Figure 3.2. Broadband Source Level (SL) Change with Ship Orientation Change for Four Ship Classes. Ship classes include catamaran (Official 1144667), high speed craft (MMSI 311364000), cruise ship (MMSI 247117400), fishing vessel (Official 221984) relative to ship speed (kts) and ship length to draft ratio. Increase in length to draft ratio parallels increase in source levels from bow to 15˚. Source levels were recorded at 5 m depth at frequencies 1-2500 Hz.

3.5 Implications for mysticete detection of oncoming ships

Assuming sufficient signal strength, North Atlantic right whales should be physically capable of acoustically detecting all studied ship classes. North Atlantic right whales located in near sea surface waters may experience greater difficulty localizing oncoming ships than when they are located in deeper waters. This risk is the combined result of lower SLs at the surface in shallow locations, BNEASZs, and masking from ambient noise. As a consequence, the range of detection for a ship may be too close for a North Atlantic right whale to execute a successful avoidance maneuver.

Future studies should model the 3-D acoustic environment created by several oncoming ship classes in high-risk areas. Additional research could also focus on examining North Atlantic right whale behavior relative to ship class to ascertain if patterns of avoidance vary with ship class, hull design and/or propulsion method. Further research should also seek to develop a method for reducing and/or eliminating the presence of bow null effect acoustic shadow zones for different ship types. While it is important to understand the physical environmental properties and the ship design properties that contribute to bow null effect acoustic shadow zone formation, developing a method for eliminating these shadow zones and/or maximizing ship acoustic signature intensity at the bow could provide North Atlantic right whales increased opportunity to acoustically detect and avoid oncoming ships. If a ship's acoustic signature could be made significantly louder from the bow to 15˚ only, such a solution might provide North Atlantic right whales with an extended opportunity to accurately localize the presence of oncoming ships, potentially reducing North Atlantic right whale ship strike mortality.

CHAPTER 4

AN ACOUSTIC METHOD FOR REDUCING NORTH ATLANTIC RIGHT WHALE SHIP STRIKE MORTALITY

4.1 Chapter Abstract

International rates of baleen whale ship strike mortality are rising, corresponding to an increase in commercial shipping traffic. Baleen whales possess reduced chemosensory systems and environmentally limited vision, suggesting baleen whale detection of oncoming ships is auditory. The presence of observed bow null effect acoustic shadow zones in front of oncoming ships likely contributes to observed high rates of baleen whale ship strike mortality. Here, we present an acoustic method to reduce and/or eliminate the presence of bow null effect acoustic shadow zones from ship acoustic signatures. Our method utilizes a dual speaker system attached to a ship's bow to project pre-recorded vessel noise ahead of oncoming ships. This method was tested on five motor vessels in an outdoor environment to ascertain the feasibility of utilizing acoustics to increase the opportunity for baleen whales to accurately detect and/or localize oncoming ships, potentially reducing future instances of baleen whale ship strike mortality.

4.2 Introduction

Baleen whales are protected from commercial hunting by an international whaling moratorium (ICRW, 1946); however, anthropogenic causes remain the largest known cause of mortality for many baleen whale populations (Carillo & Ritter, 2010, Kraus et al., 2005). Specifically, ship strike mortality is the leading known cause of North Atlantic right whale mortality, and a significant cause of finback, blue, gray, humpback, sei and minke whale mortality (NOAA, 2011, Van Waerebeek et al., 2007, Panagaida et al., 2006). While it is not known how baleen whales detect the presence of oncoming ships, it is likely they primarily utilize acoustic cues. Baleen whales have underdeveloped olfactory systems, and visual cues are unreliable in an oceanic environment (Wartzok & Ketten, 1999).

There is no published audiogram for any baleen whale. Current literature assumes baleen whales should be capable of detecting audio signals in the frequencies and intensities they are heard vocalizing (Nowacek et al., 2004). In fact, given what is known about ship acoustic signatures at source (Arveson & Vendettis, 2003), baleen whales should be capable of acoustically detecting oncoming ships (Parks, 2003). Contrary to this, baleen whales have been observed turning into the paths of transiting parallel ships (Terhune & Verboom, 1999).

Recent studies have demonstrated that propagation of a ship's acoustic's signature is complex. Research has recorded the presence of bow null effect acoustic shadow zones located at the surface, directly ahead of oncoming ships, in a variety of oceanic environments (Allen et al., 2012, Gerstein & Blue, 2005, Arveson & Vendettis, 2003). Although the size and intensity of observed acoustic shadow zones vary with ship size, ship speed, and ship length to draft ratios, bow null effect acoustic shadow zones have been observed for all ship types recorded to date (Allen et al., 2012, McKenna et al., 2012, Gerstein & Blue, 2005). We suggest the presence of bow null effect acoustic shadow zones may impair the ability of a baleen whale to accurately detect and/or localize an oncoming ship, contributing to this observed behavior and the resulting observed high incidence of baleen whale ship strike mortality. Although the whale possesses the potential acoustic sensitivity to detect such a signal, propagation of that signal to the whale is inhibited.

This paper discusses the development of an acoustic method for reducing baleen whale ship strike mortality by utilizing pre-recorded vessel noise transmitted ahead of oncoming ships via a dual speaker system to overcome or reduce bow null effect acoustic shadow zones. Our system was designed for attachment to a variety of test ships via a floating platform pushed ahead of vessels. It was deployed and tested on five ships in the Bar Harbor, Maine shipping channel during June 2013. While no baleen whales were sighted in the test area during that time, minke whales are often observed utilizing this area as a feeding ground July to October, making the test location appropriate to the design's purpose.

The remainder of this paper is organized as follows. Acoustic hardware discusses the function of the dual speaker sound source and the requirements that drive the acoustic components described; attachment platform design discusses the reasons for developing a transferable attachment method, the platform designed, its hardware requirements, and its impacts on the overall acoustic method developed; calibration results describes the initial calibration testing of the design in the Bar Harbor, Maine shipping channel and the adjustments made to the design as a result; and sea trial results summarize the extent to which this acoustic method reduced the presence of observed bow null effect acoustic shadow zones on five ships in the Bar Harbor, Maine shipping channel.

4.3 Acoustic Hardware

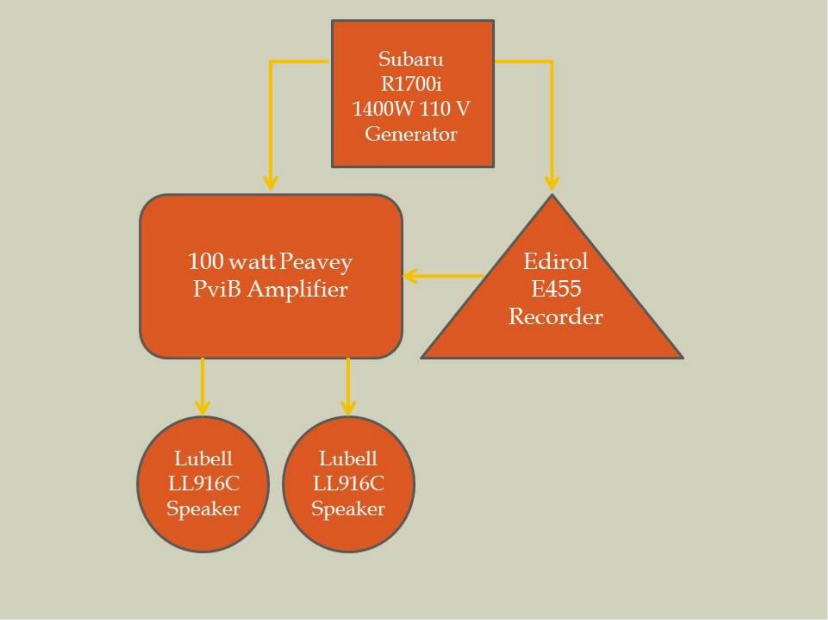


Figure 4.1 Block Diagram of Acoustic Hardware and Power Flow.

A pair of calibrated underwater speakers (Lubell model LL916C, Columbus, OH) were connected to a 100 watt amplifier (Peavey model Pvi4B 110, Meridian, MS) via two speaker cables (HOSA model 16 AWG, Buena Park, CA). For specifications, see Tables 4.1 and4.2. Pre-recorded ship noise 20-5000 Hz was played back through the speakers via a recorder (Edirol model R-44, Los Angeles, CA) on a repeating two minute loop. A 1400 watt generator (Subaru model R1700i, Lake Zurich, IL) provided the 110 volt AC current needed to power all components. For power system structure, see Figure 4.1.

Feature	Description
Output power	75 watts/8 ohms
Channel equalization	±15 dB @ 5 kHz
Master equalization	±15 dB @ 60 Hz
Power consumption	110 watts
Dimensions (w x l x h)	0.24 x 0.49 x 0.15 m
Input impedance	1000 ohms

Table 4.1. Amplifier Specifications.

Feature	Description
Type	Piezoelectric drive piston
Frequency response	20 Hz – 200 kHz
Output level	92 dB/μPa/m @ 50Hz 142 dB/μPa/m @ 200Hz
Cable	7.62 m 18/3 PVC
Maximum cable voltage	20 V rms 100% duty cycle
Weight	6.80 kg in air 1.36 kg in water
Transducer size (2r x l)	0.23 x 0.15m

Table 4.2 Speaker Specifications.

Although not shown in this prototype, we used a pair of speakers so that in its final design speakers could be flush mounted to either side of a ship's hull, reducing drag and helping to maintain fuel economy. In this prototype, we adjusted the speakers' orientation to match the approximate shear and draft of each test ship hull (see Figure 4.2), approximating a test of a hull-mounted solution without damaging test ships or requiring through-hull connections.

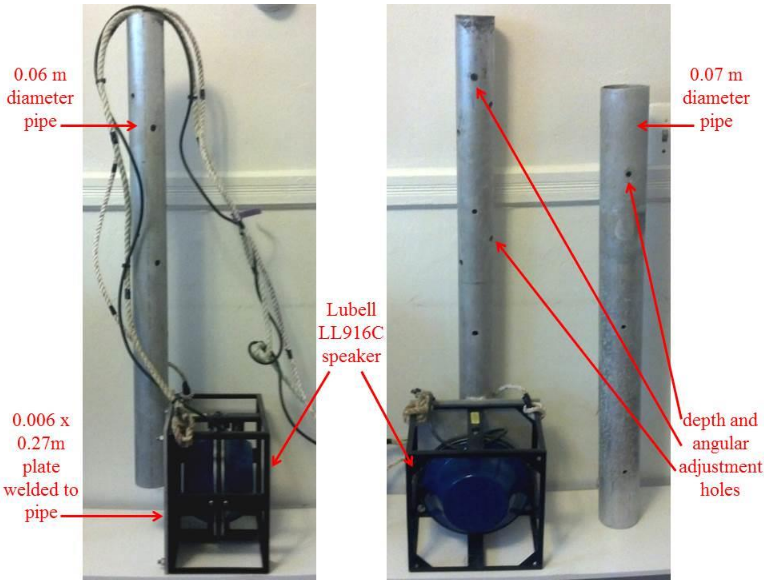


Figure 4.2. Vertical and Angular Speaker Orientation Adjustments. Speakers are bolted to aluminum plates welded to 0.06 m diameter pipe. The 0.07 m diameter pipe was bolted to the attachment platform. The 0.6 m diameter pipe slid inside and underneath the 0.07 m diameter pipe. A bolt slid through holes in both pipes to allow for depth and angular speaker adjustment.

4.4 Attachment Platform Design

An issue central to initial field testing of our prototype was for it to be transferable to a variety of ships. We thus designed a floating platform to accommodate variations in hull drafts and bow shears. Our platform allowed secure attachment of the speakers at a variety of depths and angles with a degree of standardization that would have been unachievable had we attached the speakers directly to each hull. The platform also provided flexibility, adapting to differences in bow to waterline height, ship draft, and bow width. For platform specifications, see Table 4.3.

Feature	Description
Overall length	2.38 m
Overall width	0.66 m
Overall depth	1.23m
Bow width	0.33 m
Bow length	1.02 m
Keel length	2.47 m
Keel width	0.05 m
Keel depth	0.15 m
Minimum speaker depth	0.31 m
Maximum speaker depth	2.14 m
Distance between speaker centers	1.33 m
Testable speaker angles	0 degrees 20 degrees right of center 20 degrees left of center
Testable speaker depths	0.31 m 0.61 m 0.91 m 1.22 m 1.52 m 1.83 m 2.14 m
Platform extensions length	1.23 m
Minimum distance between platform extensions	0.44 m
Maximum distance between platform extensions	1.71 m

Table 4.3 Attachment Platform Specifications.

The introduction of a platform also presented challenges. As this acoustic method is primarily concerned with reducing bow null effect acoustic shadow zones for frequencies less than 500 Hz, the platform needed to be less than 2.4 m long in order to avoid moving the test speakers more than one wavelength ahead of the test ship bow. As a result of the moment induced on the speakers during test runs, downward force was required on the rear of the platform at speeds greater than 3 knots to prevent platform rollover. In addition, an extension was required that could be fitted to each hull width to reduce lateral platform sway (see Figure 4.3). To increase platform tracking ability, a false "keel" was laid onto the bottom. Finally, to reduce noise introduced by platform improvements, thin rubber sheets were placed between all metal and/or wooden platform components. Fire hose was glued to the exterior of the 0.06 meter diameter pipe to reduce rattling between the angular and depth adjustment pipes. For additional prototype photos, see Appendix C.

Figure 4.3 Prototype Attached to Test Ship Rhumbline Underway at 4.2 Knots. The adjustable platform extensions are located below the rub rails, providing downward force on the rear of the platform thereby increasing platform stability.

4.5 Calibration Results

The speaker/platform complex was anchored to the middle of the Bar Harbor, Maine shipping lane on May 31, 2013. The generator and the electronic components transmitted a single frequency recording increasing from 20-2500 Hz, 1/3 octave at a time, with each tone having a 2 second duration. A calibrated vertical hydrophone array was deployed to obtain received levels (RLs) for both speakers at a series of locations shown in Figure 4.4. The array consisted of three omnidirectional C54XRS hydrophones with flat frequency response range of 6 Hz - 203 kHz and calibrated sensitivity of -20 dB re: 1 V/µPa. Each calibration listening location was located 50 meters from the anchored speaker/platform complex. Calibration tests were conducted with the speakers located 0.3 – 2.2 m below the surface, and at angles from 0-30˚, approximating differences in hull depth and bow shear, respectively. Source levels (SLs) were calculated as in Allen et al. (2012).

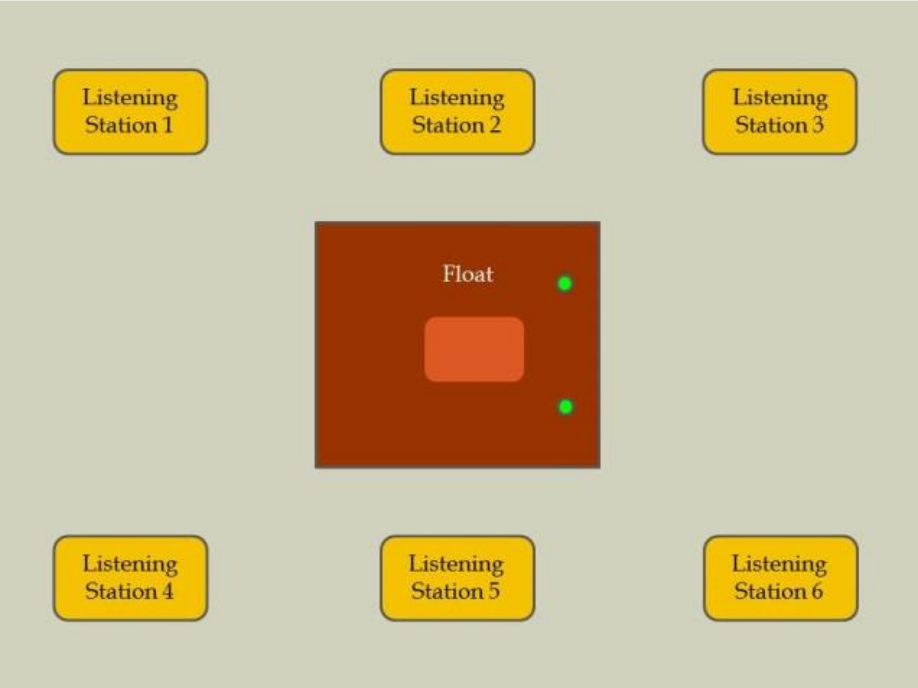


Figure 4.4 Calibration Listening Locations Relative to Acoustic Components on Anchored Test Platform. Each listening location was 50 m from the test platform.

As a result of the speaker calibration testing, the low frequency (20-200 Hz) master equalization was set 4 dB higher on the port speaker to account for a reduction at frequencies 20-50 Hz relative to that recorded from the starboard speaker. In addition, speaker depths during test ship trial runs were allowed to range from 0.9 -2.2 m below the surface corresponding with differences in ship draft. Speaker calibration tests conducted at depths less than 0.9 m resulted in reduced source levels at frequencies below 250 Hz.

4.6 Sea Trial Design and Results

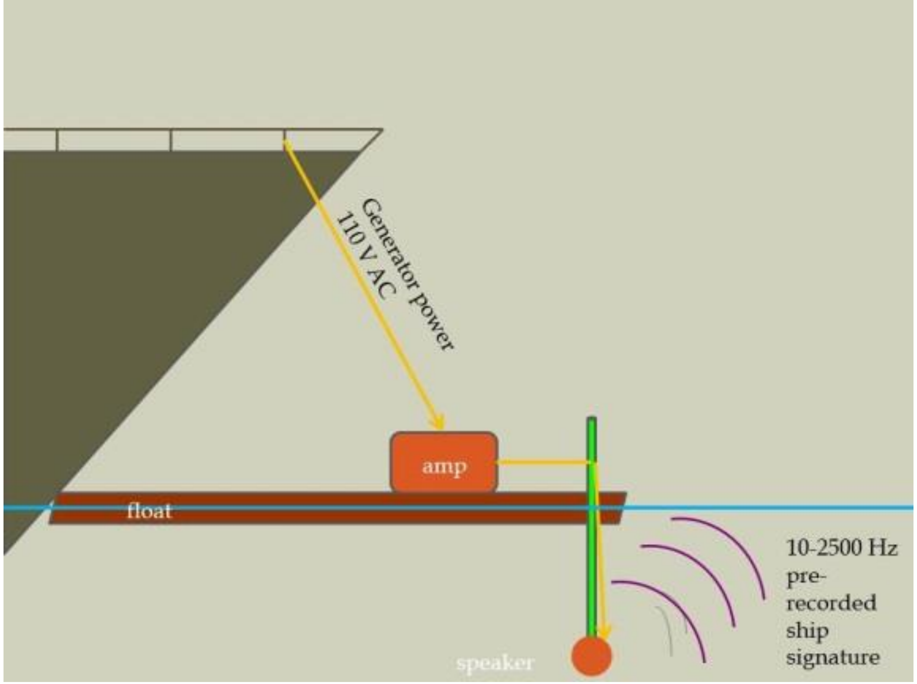


Figure 4.5 Platform and Speaker Attachment to Test Ships.

For each test, the platform was attached to the bow of the ship as shown in Figures 4.3 and 4.5. The supportive limbs were manually adjusted to the angle of each test ship's bow. When a bow rub rail was present, the supportive limbs were positioned directly below the rub rail to increase platform stability (see Figure 4.3). All lines were secured to the test ship as shown in Figures 4.3 and 4.6.

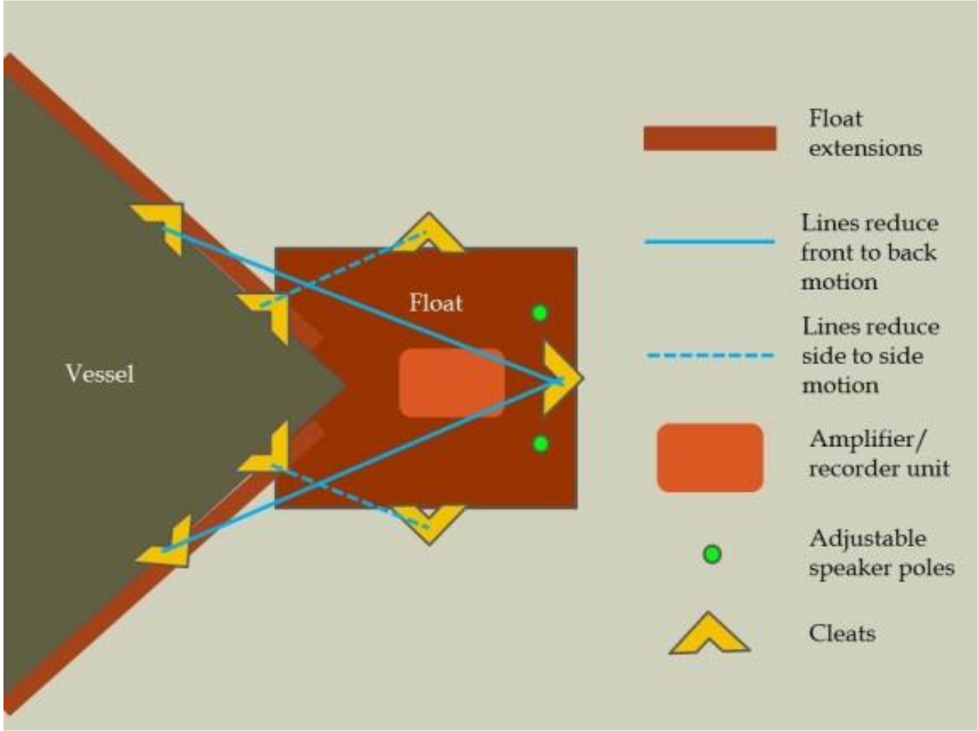


Figure 4.6 Platform and Speaker Attachment to Test Ships via Stabilizing Lines.

Received levels (RLs) were measured by obtaining calibrated vertical hydrophone array recordings of passing test ship acoustic signatures as detailed above. RL data were associated with transiting test ship track data determined by onboard GIS recorders accurate to ± 1 m. Ship orientation relative to the hydrophone array was calculated using directional compass observations. After each passage, vertical sound speed profiles were calculated using data from conductivity/temperature/depth (CTD) casts. Additional bathymetric topography and sediment characterization data were obtained from the Gulf of Maine 15 arc-second bathymetry database (Roworth & Signell, 2002) and the U.S. Geological Survey East Coast Sediment Texture Database (U.S. Geological Survey,

2004) respectively. The hydrophone array was suspended near the Bar Harbor shipping lane, with water depth range of 38.7-46.0 meters and a rocky sea floor (see Appendix A for chart information).

Ship GIS tracks were used to calculate ship speed and distance from the hydrophone array. All ships recorded passed the array on their starboard side. Test tracks were conducted so test ships passed within 50 meters of the vertical hydrophone array at their closest point of approach.

Source levels (SLs) were calculated as in Allen et al. (2012). SL calculations were made in 1 Hz bins from 1-2500 Hz for each ship recorded at hydrophone depths of 5, 15 and 25 meters. Source intensities in 1 Hz bins were integrated over frequency to compute the broadband pressure level at each depth. It is important to note that SL calculations reflect the oncoming ship's pressure variation above the ambient noise level; not the ship's absolute source level. As ship signal pressure is related to ship speed, all calculated SLs are for a specific ship speed.

An estimate of the root mean square error in the SL calculation can be obtained using the attenuation from a range of empirical values collected by Francois & Garrison (1982) and the ΔSL = root mean square error (dB) relationship:

$$\Delta SL = \pm\sqrt{\Delta RL^2 + (\tfrac{N\Delta r}{r})^2 + (\Delta\alpha r)^2 + (\alpha\Delta r)^2)}. \tag{4.1}$$

where SL = source pressure level (dB re 1μPa^2 @ 1m), RL = pressure level recorded by the hydrophone (dB re 1μPa^2/Hz), N = coefficient for geometric transmission loss (dB/m), r = ship range from the hydrophone array (m), and α = coefficient for absorption transmission loss (dB/m).

Ambient noise levels present during field testing were calculated utilizing spectral averages taken from field recordings in 1 Hz bins with a 0% overlap Hanning window every second for 15 minutes before and after ship passages. All 1 Hz bin spectral averages recorded at each hydrophone depth were averaged to calculate broadband (1-2500 Hz) ambient noise levels specific to each ship passage. Broadband ambient noise levels calculated during field testing ranged from 53-58 dB re 1µPa^2 (see Table 4.4).

Four trials were completed for every ship tested; two with the speaker/platform complex attached, but not operating, and two with the platform/speaker complex attached and operating (for test speeds, see Table 4.4). Stabilizing lines between the platform and the test ship were tightened between each trial. As a result of decreasing platform stability at speeds over 5.5 knots, all trials were run at 4.5-5.2 knots.

Figure 4.7 shows spectrogram and frequency source level calculations for two test ships with and without the speaker/platform complex operating. Figure 4.7 is representative of all test trials conducted. All five ships recorded exhibited reduced broadband SLs from the bow to 15˚ without the speaker/platform complex operating, indicative of bow null effect acoustic shadow zones. The average variation in broadband source level from the test ship bow to 15˚ was +5.3 ± 1.2 dB re 1µPa when recorded at 5 m depth. The same five ships recorded with the speaker/platform complex attached and operating exhibited an average -0.2 ± 0.9 dB re 1µPa variation in broadband source level from the bow to 15˚ when recorded at 5 m depth. While all bow null effect acoustic shadow zones were effectively eliminated during these trials, only one exhibited an elevation in broadband source level (-2.9 ± 0.8 dB re 1µPa) from the bow to 15˚ when compared to the rest of the angular broadband SLs recorded.

	Ship information						Maine DMR/USCG	Acoustic measurements								
Ship name	Ship length (m)	Ship draft (m)	Year built	Gross tonnage	Horse power	Propulsion type	Registration number	Ship speed null 1 (kts)	Ship speed test 1 (kts)	Ship speed null 2 (kts)	Ship speed test 2 (kts)	Source level @ 1m[c] null 1	Source level @ 1m[c] test 1	Source level @ 1m[c] null 2	Source level @ 1m[c] test 2	Ambient noise level[c]
Passenger Vessels																
Acadian*	19.8	1.2	1969	58	600	2 propellers	525499	4.6	4.8	5.2	5.1	122	138	125	146	53
Islander	17.7	1.1	1995	42	1140	2 propellers	907086	4.5	4.6	4.9	5.1	119	136	122	139	55
Fishing Vessels																
Julie B*	11.0	0.9	2001	37	300	1 propeller	975940	4.5	4.6	4.9	5.0	121	137	122	143	54
Rhumbline	12.1	1.1	2003	40	350	1 propeller	1151471	4.7	4.9	5.1	5.2	122	135	123	139	58
Frenchman Bay	11.6	1.0	2008	39	450	1 propeller	1107341	4.9	5.1	5.2	5.2	119	141	126	144	58

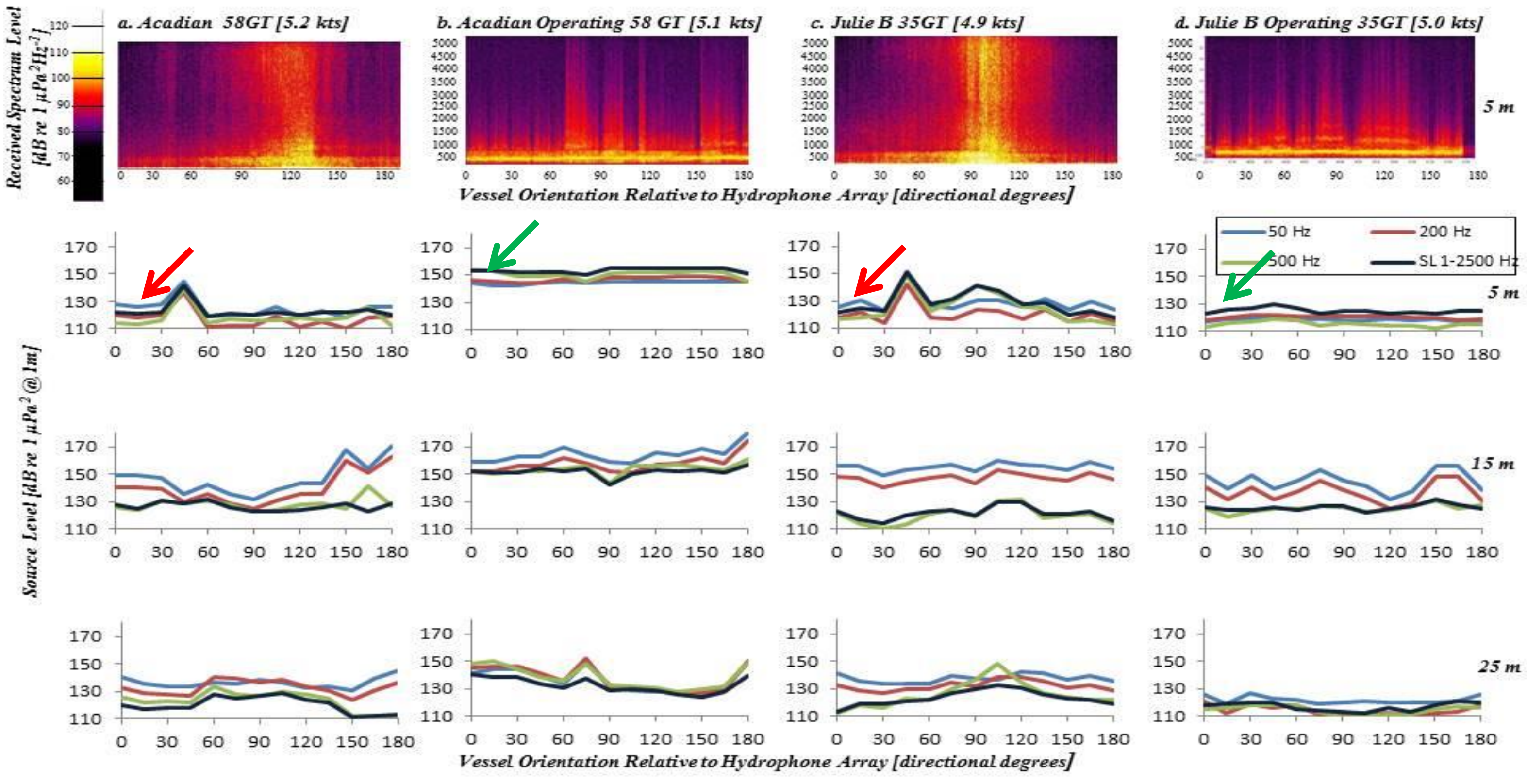
*Ships shown in Figure 4.7

[a] Maine Department of Marine Resources registration number

[b] United States Coast Guard registration number

[c] dB re 1μPa^2 (1-2500 Hz)

Table 4.4. Summary of Test Ship Characteristics.



*Hydrophone depth listed at the right.

Figure 4.7. Spectrum Levels During Close-Range Test Ship Passages at 5m Depth for Two Test Ships: Passages shown are for (a) twin-screw vessel, *Acadian*, (b) twin-screw vessel, *Acadian*, with speaker/platform complex operating, (c) single-screw vessel, *Julie B*, and (d) single-screw vessel *Julie B* with speaker/platform complex operating. Figures are centered relative to angular ship passage. Top figure series shows received level as color (dB re 1 μPa2/Hz) at hydrophone depth 5m using sequential 1 s spectral averages to form the long-term spectrogram (Hanning window, DFT length of 256 samples and 50% overlap). Presence of bow null effect acoustic shadow zones is indicated in top series with red arrows. Absence of bow null effect acoustic shadow zones is indicated by green arrows. Bottom figure series show calculated source levels (SLs) for hydrophone depths 5, 15, and 25 m.

By adding an additional source signal at the bow, this acoustic method changed oncoming ship sound radiation patterns from those of monopole sources into those of dipole sources. While the dipole source caused the bow-aspect signal to equal the stern-aspect signal of oncoming ships at frequencies below 500 Hz, it did not cause the bow-aspect signal to be substantially louder than the stern-aspect signal at these same frequencies. The results in Figure 4.7 indicate the theory of maximizing an acoustic signal at the bow of an oncoming ship will reduce bow null effect acoustic shadow zones. This result should increase the opportunity for baleen whales to detect an oncoming ship, but is unlikely to increase the opportunity for accurate localization of oncoming ships. The opportunity for accurate localization of the acoustic signal propagated by oncoming ships by baleen whales should be increased by making the bow-aspect of the oncoming ship substantially louder than any other aspect.

In order to accomplish this, future prototypes will focus on maximizing signal intensity and directionality below 500 Hz. This maximization will be accomplished by:

1) increasing the size of the speakers to increase low-frequency speaker directionality, and;
2) employing an array of at least four speakers, two forward facing and two rear facing, to increase low-frequency speaker directionality and intensity.

Increasing speaker size will increase the source-size-to-wavelength-size ratio, increasing the speaker directionality for frequencies less than 500 Hz. Employing an array of larger forward-facing speakers and slightly smaller rear-facing speakers with differing pre-configured source signal delays to each speaker will result in desirable constructive and destructive wavelength interference among array speakers, increasing low-frequency signal intensity and creating increased low-frequency signal directionality.

4.7 Conclusions

An acoustic method for eliminating the presence of bow null effect acoustic shadow zones has been designed and tested on five ships in an outdoor environment. Initial field tests indicate this is a viable method for eliminating the presence of bow null effect acoustic shadow zones at speeds of five knots or less, increasing the opportunity for baleen whales to detect oncoming ships.

Future testing of this method will maximize source signal intensity for frequencies below 500 Hz by increasing speaker size and utilizing a speaker array to create increased low-frequency signal directionality. These design alterations will make the bow-aspect of an oncoming ship the loudest acoustic aspect, increasing the opportunity for accurate baleen whale localization and avoidance.

When future designs meet these new design requirements, this acoustic method should increase the opportunity for baleen whales to accurately detect and localize oncoming ships, resulting in a reduction in baleen whale ship strike mortality across a variety of ship designs and ocean environments.

CHAPTER 5

CRITICAL HABITAT AND ITS IMPACT ON U.S. NORTH ATLANTIC RIGHT WHALE SHIP STRIKE REDUCTION POLICY

5.1 Abstract

Ship strike is the major anthropogenic source of mortality for severely endangered North Atlantic right whales. Two primary tools are given to U.S. wildlife managers by the Endangered Species Act post-listing to ensure species survival by reducing negative anthropogenic impacts: 1) creating a recovery plan and 2) defining and protecting critical habitat. This study reviews and analyzes the impact these strategies have had in reducing North Atlantic right whale ship strike mortality in U.S. waters from 1973 to 2011. Defining and protecting critical habitat poses distinct spatial and human-use overlap challenges when applied to highly migratory species. Managers should consider two different levels in designating critical habitat for highly migratory species such as the North Atlantic right whale: permanently protected critical habitat in areas where species take up seasonal residence, and temporarily protected migratory habitat to maintain functional migration corridors between seasonal residence critical habitat areas. Managers and stakeholders should also be aware that, given current definitions for North Atlantic right whale critical habitat, human-use overlap in critical habitat areas is inevitable. Instead of eliminating human-use in critical habitat, wildlife managers should apply a combination of adaptive human-behaviors, functional habitat definitions, and on-going habitat-use studies to reduce ship strike mortality, particularly for pregnant and nursing females. Ascertaining methods to effectively manage North Atlantic right whale critical habitat is particularly relevant as current regulatory actions aimed at reducing North Atlantic right whale ship strike mortality will be reviewed by the National Oceanic

and Atmospheric Administration in December 2013, offering wildlife managers an opportunity to adjust current ship strike mortality reduction strategies in order to improve the population growth rate.

5.2 Introduction

The primary aim of the Endangered Species Act of 1973 (ESA) is to reduce or eliminate the impact of commercial and federal activities on severely threatened or depleted species in the United States until those species recover to an extent that they no longer require federal protection to maintain a viable population (ESA, 1973). The ESA enables wildlife managers to define critical habitat; i.e., portions of habitat currently or historically occupied by a species that are inherent to its present-day survival (ESA, 1973). The ESA also limits wildlife managers, preventing all space occupied by a species from being designated as critical habitat (ESA, 1973; Suckling & Taylor, 2006). Designation of critical habitat can occur only after an economic cost/benefit analysis demonstrates the conservation benefits of such designation outweigh the economic costs, or if best available science indicates a habitat must be designated in order for an endangered species to recover (ESA, 1973; Czech & Krausman, 2001).

While designating critical habitat is useful for focusing negative anthropogenic impact mitigation efforts, this action does not specify management actions relative to that habitat, and does not create a habitat preserve (Suckling & Taylor, 2006). To assist in bridging this gap, the ESA enables managers to develop species-specific recovery plans delineating mitigation actions necessary to ensure survival and recovery (ESA, 1973). Recovery plans also define time frames for implementing management actions and estimation of associated costs (ESA, 1973). Finally, the ESA requires a review of each species recovery plan every 5 years to ascertain plan effectiveness (ESA, 1973; Czech & Krausman, 2001).

While the ESA has experienced some success, many more listed species have been extirpated than have recovered (Abbitt & Scott, 2001; Scott et al., 2006a). Reviewers have pointed to a reduction in ESA funding, a lack of managerial efficiency, and conflicting managerial priorities as potential reasons for lack of species recovery under ESA protection (Wallace, 2003; Reeves et al., 2007; Hildreth, 2008).

Improvements in species status have been linked to the creation of species recovery plans and definition of critical habitat (Suckling & Taylor, 2006). Most endangered species that improve status post-ESA listing have been sessile, sedentary, or have had limited ranges (Abitt & Scott, 2001; Scott et al., 2006b). Conversely habitat fragmentation has been implicated as a reason for the lack of recovery in many highly migratory species (Czech & Krausman, 2001; Scott et al., 2006b; Elvin & Taggert, 2008; Bearzi, 2012). Non-recovering endangered species often suffer from a lack of scientific understanding relative to population dynamics and habitat-use, preventing proactive management actions (Abbitt & Scott, 2001; Suckling & Taylor, 2006; Hinch & DeSanto, 2011). Although seasonal high-use areas are often protected habitat, migration corridors between these areas often do not receive similar protection (Czech & Krausman, 2001; Elvin & Taggert, 2008; Bearzi, 2012) leaving individuals vulnerable to negative anthropogenic impacts.

North Atlantic right whales, *Eubalaena glacialis,* herein after referred to as right whales (this paper does not discuss their Pacific counterpart, *E. japonica*), were listed as endangered following ESA enactment in 1973 and remain one of the most critically endangered marine species listed (NMFS, 2005; 2012; Kraus & Rolland, 2007). Right whales are a highly migratory species with the majority of current species range contained within 80 km of the shore along the U.S. and Canadian eastern seaboards (Kraus & Rolland, 2007; Asaro, 2012). Two major anthropogenic causes of mortality have been identified for this species post-listing; ship strike and entanglement in fishing gear. Ship strike mortality is currently the largest known cause of all right whale mortality (Kraus & Rolland, 2007; Moore et al., 2007; Van Der Hoop et al., 2013).

Right whales are further protected by additional legislation within US waters. The International Convention for the Regulation of Whaling (ICRW) banned commercial harvesting of right whales in 1949, and right whales are also protected under the Marine Mammal Protection Act (MMPA) of 1972 (ICRW, 1946; MMPA, 1972). While the ICRW, the MMPA and the ESA all prevent takes of right whales, only the ESA provides for habitat definition and protection (ICRW, 1946; MMPA, 1972; ESA, 1973).

In compliance with the ESA, the National Marine Fisheries Service (NMFS) published a right whale recovery plan in 1991 (NMFS, 2005). NMFS updated this recovery plan in July 2001 and August 2004 (NMFS, 2005). In compliance with recovery plan goals, the National Oceanic and Atmospheric Administration (NOAA) designated right whale critical habitat in 1994 (NOAA, 1994). Of the three areas designated within the U.S., two include feeding grounds located within the Gulf of Maine, and the third includes calving grounds located along the coast of Georgia and Florida (NOAA, 1994; NMFS, 2005).

In 1991 the recovery plan estimated the right whale population at a minimum of 350 individuals (NMFS, 2005). As of 2011, the NMFS right whale stock assessment estimates this population at a minimum of 396 individuals, indicating a minimum average of 2.3 individuals per year accruing in the population during this time (NOAA, 2011). The NMFS stock assessment report estimated a mean right whale population growth rate of 2.4% during 1990-2007 (NOAA, 2011). This low growth rate combined with a significant decrease in crude survival probability during 1980-1994 (Caswell et al., 1999) has contributed to stable and/or decreasing right whale population estimates (NMFS, 2005, 2012; NOAA, 2011).

Wildlife managers listed right whales as one of the first endangered species under the ESA, published right whale recovery plan over 20 years ago, designated right whale critical habitat more than 15 years ago, and as of yet right whales have not exhibited significant gains in population growth or survival rates. As such, this paper will examine the specific impact defining and protecting critical habitat has had on reducing right whale ship strike mortality during 1973-2011. This paper will focus on wildlife management actions taken to reduce negative anthropogenic impacts under the ESA within designated right whale critical habitat areas. Finally, this paper will develop recommendations to improve the efficiency of future critical habitat management methods, particularly for similar highly migratory species listed under the ESA.

5.3 Negative anthropogenic impact mitigation actions, 1970-1995

After listing right whales under applicable protected species acts in the 1970s, U.S. wildlife managers appointed the Northern Right Whale Recovery Team in 1987 (see Figure 5.1) (NMFS, 2005, 2012). As required by the ESA, this team published a recovery plan in 1991, in which anthropogenic mortality from ship strike and entanglement in fishing gear were identified as the two largest threats to species recovery (ESA, 1973; NMFS, 2005). Following ESA recovery plan recommendations, two regional implementation teams were formed; one for southeastern calving grounds (SEIT) in 1993 and one for northeastern feeding grounds (NEIT) in 1994 (NMFS, 2005). While both the SEIT and the NEIT included representatives from multiple stake-holder groups, the NEIT also included international representation from Canada's Department of Fisheries and Oceans (NMFS, 2005). In 1993 the SEIT began conducting seasonal aerial surveys in calving grounds to determine right whale habitat-use, gather population information, and to alert ships to the presence of right whales (NMFS, 2005).

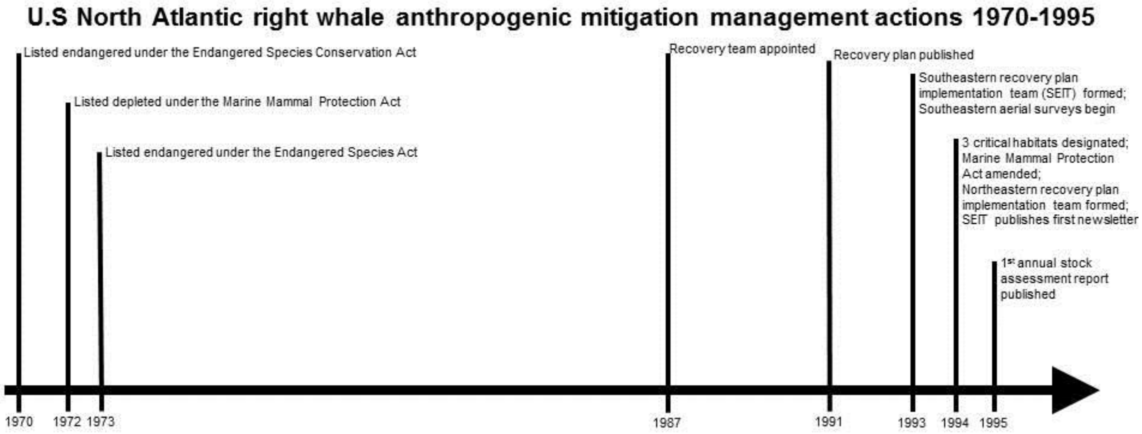


Figure 5.1. Timeline of Actions Taken by US Wildlife Managers to Protect North Atlantic Right Whales from Negative Anthropogenic Interactions from 1970 to 1995. Two distinct periods of activity occur; one in which North Atlantic right whales are listed under applicable legislative acts, and a second period following publication of the recovery plan in which basic stock assessment and habitat-use evaluations begin.

In 1994 critical right whale habitat was designated under the ESA, consisting of two feeding grounds within the Gulf of Maine and one calving ground along the coasts of Georgia and Florida (see Figure 5.2) (ESA, 1973; NOAA, 1994). Also in 1994, the SEIT published the first issue of a quarterly newsletter available to mariners and the public in an effort to educate both about the impact of ship strike mortality on the right whale population (NMFS, 2005). In 1995, the National Marine Fisheries Service (NMFS) published its first annual right whale stock assessment report (NMFS, 2006).

Although it took wildlife managers 18 years to publish a recovery plan post-ESA listing, once the recovery plan was published, additional anthropogenic impact mitigation actions followed at a quicker pace (see Figure 5.1) (NMFS, 2005). As ship strike remains the leading known cause of right whale mortality, and as major U.S. legislation aimed at reducing right whale ship strike mortality is due to expire in December 2013 pending review, this paper will focus on analysis of critical habitat definition impact on this issue only.

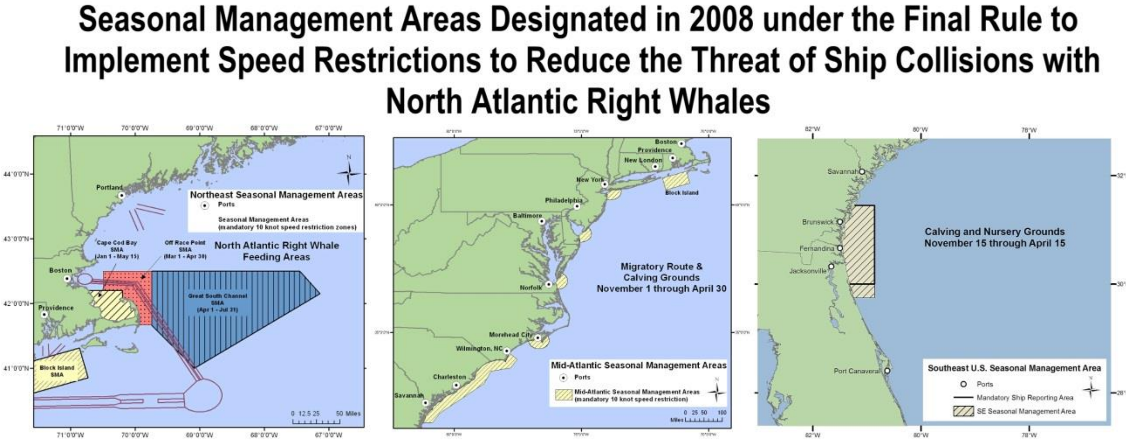


Figure 5.2. Seasonal Management Areas Designated in 2008 by the Final Rule to Implement Speed Restrictions to Reduce the Threat of Ship Collisions with North Atlantic Right Whales. Ships 65 feet long or greater must reduce their speed to 10 knots or less when transiting these areas. SMAs designated in the left and right panels overlap with critical North Atlantic right whale habitat designated under the Endangered Species Act in 1994 (reproduced by permission; NOAA North Atlantic Right whale ship strike reduction website [NOAA, 2013]).

5.4 Ship strike mitigation actions, 1996-2011

After the formation of the NEIT in 1994, the NEIT developed Habitat and Ship Strike Subcommittees (NMFS, 2005). In 2000, the SEIT and NEIT elevated the Ship Strike Subcommittee to a full Committee, enlisting the participation of stakeholders from both implementation teams (NMFS, 2005). Following recommendations of the Ship Strike Committee, NMFS began a three-pronged approach to reducing right whale ship strike mortality in 1996, which evolved into the Right Whale Shipstrike Reduction Strategy in 2004 (see Figure 5.2). (NMFS, 2005, 2006). Management actions in the U.S. were divided into 3 categories: 1) efforts to educate mariners about the risks ship strike mortality poses to right whales; 2) efforts to inform mariners of the real-time or near real-time location of right whales; and 3) efforts to reduce the proximity of right whales and ships through rule-making and/or International Maritime Organization (IMO) collaboration (see Figure 5.3) (NMFS, 2005, 2006, 2012; Reeves et al., 2007).

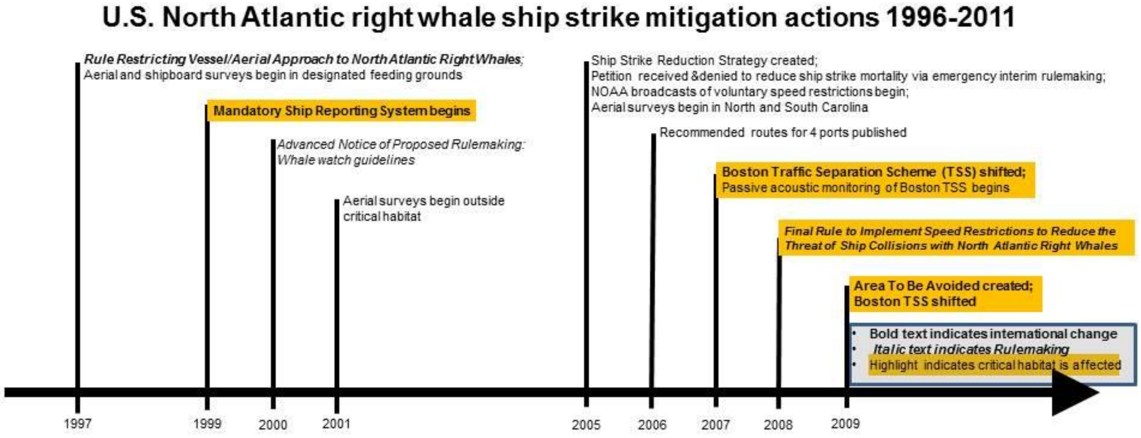


Figure 5.3. Timeline of Actions Taken by US Wildlife Managers to Protect North Atlantic Right Whales from Ship Strike Mortality from 1996 to 2011. Management strategy combines mariner education with communication of real-time whale locations, federal rulemaking, and international maritime routing measures to accomplish recovery plan objectives. Only final outcomes of the federal rulemaking process are listed here.

5.4.1. Mariner education

In 1996, NMFS launched an effort to educate mariners about right whale ship strike mortality vulnerability and about the locations of defined right whale seasonal residence critical habitat areas in U.S. waters (NMFS, 2005). In 1997, NMFS added this information to publications including U.S. Coast Pilots, Notice to Mariners, and Sailing Directions (NMFS, 2005, 2006). Also in 1997, NMFS and the U.S. Coast Guard collaborated to incorporate similar information into the International Safety Management Code (NMFS, 2005).

In 1998, the Ship Strike Subcommittee added information on mariner avoidance of right whales and on right whale seasonal habitat-use to the Cape Cod Canal Tide Tables (NMFS, 2005). The Subcommittee also produced a free mariner right whale education and avoidance training video, making this available to the maritime community in 1999 (NMFS, 2005). In 2001 the Ship Strike Committee held a workshop inviting mariners to assist wildlife managers in identifying voluntary right whale shipstrike avoidance measures (NMFS, 2005).

In 2005, NMFS contacted other government agencies including the U.S. Navy and the U.S. Coast Guard requesting they transit designated right whale critical habitat areas at speeds of 12 knots or less, except when their missions would be compromised by this speed reduction (NOAA, 2008). This was a request, not a formal mandate (NOAA, 2008).

In 2006, NMFS published and distributed fliers, brochures, and posters highlighting new voluntary recommended ship entry and exit routes into 4 U.S. ports in designated right whale critical habitat: Cape Cody Bay, Massachusetts; Brunswick, Georgia; Fernandina Beach, Florida; and Jacksonville, Florida (NOAA, 2008). Recommended routes reduced shipping traffic overlap with high seasonal concentrations of right whales, thus promoting a theoretical reduction in the probability of right whale shipstrike mortality (NOAA, 2008). Recommended routes were also published on NOAA nautical charts and posted on NOAA and NMFS websites (NOAA, 2008, 2013). Finally, advisories about the new recommended routes were broadcast via VHF and NOAA weather radio to local and regional mariners (NOAA, 2013).

In 2008, prior to and following passage of a rule requiring vessels 65 feet or greater to maintain speeds of 10 knots or less in Seasonal Management Areas, NMFS created and distributed “compliance guides” and an interactive compliance training CD (NMFS, 2012). NMFS further broadcast rule passage and compliance information via

NOAA weather radio, U.S. Coast Guard broadcasts, and the Mandatory Ship Reporting System (NMFS, 2012). Finally, NMFS updated right whale information in mariner publications to reflect the new rule and rule compliance requirements (NMFS, 2012).

In addition to other efforts, NMFS continually distributed right whale informational posters, brochures and placards to the maritime community documenting guidelines, rules and general right whale natural history (NMFS, 2005, 2006, 2012).

5.4.2 Direct efforts informing mariners of right whale locations

5.4.2.1 Aerial survey sightings

In 1997, NMFS initiated seasonal aerial surveys in critical habitat feeding grounds in the Gulf of Maine (see Figure 5.3) (NMFS, 2005; Reeves et al., 2007). Feeding ground aerial surveys were supported by opportunistic shipboard surveys conducted by various stakeholders while engaged in work or research in critical habitat feeding grounds (NMFS, 2005). Aerial surveys in calving and feeding grounds communicated real-time right whale locations to vessels encountered during the survey, and broadcasted near real-time right whale locations to mariners via NOAA weather radio, NAVTEX, and regional and local U.S. Coast Guard radio broadcasts (NMFS, 2005, 2006). In addition, Cape Cod Canal Traffic Controllers contacted individual vessels within the canal, informing them of real-time right whale locations reported by aerial surveys (NMFS, 2006). In feeding grounds, near real-time location of right whales reported by aerial surveys were used to update the NMFS sightings advisory system website, fax sightings reports to port authorities, harbor pilots, and shipping agents (NMFS, 2005). All of these efforts continue today.

In 2001, experimental aerial surveys for right whales began in areas outside of designated critical habitat (Reeves et al., 2007). These aerial surveys resulted in the incorporation of annual seasonal aerial surveys along the coasts of North Carolina and South Carolina beginning in 2004 (Reeves et al., 2007). In an effort to inform mariners of the presence of right whales and specify actions mariners could take to reduce the probability of right whale ship strike mortality, in 2005 NOAA began broadcasting voluntary speed restriction advisories along with right whale locations from aerial surveys (Reeves et al., 2007). In 2006, additional experimental aerial surveys included areas in the Gulf of Maine and along the coasts of New York, New Jersey and Rhode Island (NMFS, 2006). Although infrequent, these additional aerial surveys informed all ships encountered of real-time right whale locations and communicated right whale sightings to local broadcasting outlets (NMFS, 2006; Reeves et al., 2007).

5.4.2.2 Visual observers

The Ship Strike Subcommittee held a workshop in 1998 that developed a partnership with Bay Ferries, placing visual right whale observers onboard the company's high speed ferry transiting from Bar Harbor, Maine to Yarmouth, Nova Scotia to reduce the potential for right whale shipstrike mortality (NMFS, 2005). Right whale visual observers continued to operate on these ferries until service was cancelled in 2009 (Trotter, 2013).

5.4.2.3 Mandatory ship reporting system

In 1999, the International Maritime Organization (IMO) approved and implemented a U.S. Coast Guard proposal requiring all vessels over 300 gross tons entering right whale critical habitat to call into a shore-based station, a mandate still in operation today (see Figure 5.3) (NMFS, 2005, 2006). The ship calling then receives messages containing recent right whale sightings in the area, and information on detecting and avoiding right whales (NMFS, 2005, 2006). This Mandatory Ship Reporting System (MSRS) operates year-round in designated critical habitat feeding grounds and seasonally in designated critical habitat calving grounds (NMFS, 2006).

5.4.2.4 Passive acoustic monitoring

In 2007, NMFS deployed a real-time passive acoustic monitoring network to reduce the probability of right whale ship strike mortality near a liquid natural gas terminal and pipeline construction site in Massachusetts Bay (Bettridge & Silber, 2009). In this on-going strategy, bottom-mounted acoustic buoys detect vocalizing right whales, triangulate an approximate right whale location, and transmit this information via satellite phone to transiting liquid natural gas ships (Bettridge & Silber, 2009). Transiting ships involved in terminal construction or transporting liquid natural gas are required to maintain speeds of 10 knots or less when transiting within 5 nautical miles of the detecting acoustic buoy (Bettridge & Silber, 2009). This system was expanded to include a second passive acoustic monitoring network in the Boston Traffic Separation Scheme (TSS) in 2008 (Bettridge & Silber, 2009). Right whale vocalizations detected by this network are communicated to local shipping traffic via the Boston TSS Sightings Advisory System (Bettridge & Silber, 2009).

In 2012, NOAA launched the Whale Alert Application, linking right whale vocalizations detected by passive acoustic monitoring networks in the Boston TSS to mariner cell phones and tablets (NMFS, 2012). The Whale Alert Application is free, although mariners must sign up for the app and pay any associated cellular service charges (NMFS, 2012).

5.4.3 Rulemaking and IMO Collaboration

5.4.3.1 Rulemaking

Following Ship Strike Committee recommendations, NMFS published an interim final rule in 1997 prohibiting ships and aircraft from approaching within 500 yards of a right whale (see Figure 5.3) (NOAA, 2004). Exceptions to this prohibition include when doing so endangers the lives onboard; the ship; or the aircraft; when ships are restricted in their ability to maneuver; when ships are actively disentangling a right whale; or when ships or aircraft are conducting permitted right whale research (NOAA, 2004). Thus, NMFS hoped to reduce ship strike mortality by limiting ship proximity to right whales (NOAA, 2004; NMFS 2005, 2012).

In 2000, NOAA published an advanced notice of proposed rulemaking, soliciting comments on the appropriateness of codifying a set of right whale watching regulations to reduce the potential for right whale ship strike mortality (NOAA, 2000; NMFS, 2005). NMFS later decided not to pursue separate whale watching guidelines; instead relying on the 500 Yard Approach Rule and the Ship Strike Reduction Rule speed restrictions to reduce right whale ship strike mortality from this potential source (NOAA, 2004; 2008).

In May 2005, NMFS received a petition from multiple stake-holders calling for emergency rule-making in order to immediately reduce right whale ship strike mortality occurring inside critical right whale habitat areas (NOAA, 2005). This petition requested NMFS create emergency regulations to reduce shipping traffic speed to 12 knots or less, or re-route shipping traffic transiting right whale critical habitat (NOAA, 2005). NMFS denied this petition, fearing that enacting such emergency rules would limit the amount of public input to those rules and slow down efforts to create a more permanent and comprehensive ship strike reduction rule (NOAA, 2005).

Following Ship Strike Committee recommendations and the Ship Strike Reduction Strategy, NOAA published a Final Rule to "Implement Speed Restrictions to Reduce the Threat of Ship Collisions with North Atlantic Right Whales" (Ship Strike Reduction Rule) in 2008 (NOAA, 2008). This rule required vessels 65 feet or longer to maintain speeds of 10 knots or less when transiting through a series of Seasonal Management Areas (SMAs) surrounding U.S. ports and designated critical habitat areas (see Figure 5.2) (NOAA, 2008). SMAs are located in permanent geospatial areas and are effective annually when right whales are known to occupy or are thought to transit through these areas (NOAA, 2008). SMAs overlap feeding and calving critical habitat off the southeastern US coast, in Cape Cod Bay, and in the Great South Channel (NOAA, 2008).

The Ship Strike Reduction Rule also outlines the process undertaken for NOAA to designate Dynamic Management Areas (DMAs) surrounding right whales sighted outside of SMA locations (NOAA, 2008). Vessels transiting DMAs are advised, but not required, to re-route around DMAs or maintain speeds of 10 knots or less when transiting through DMAs (NOAA, 2008). Unlike SMAs, DMAs are triggered by right whale sightings (NOAA, 2008). DMA size is dependent upon the density of right whales located in or near a single sighting (NOAA, 2008). DMAs are effective for 15 days, but may be extended if right whales continue to be present (NOAA, 2008).

Federal vessels, including military vessels, are exempt from the Ship Strike Reduction Rule, as are police and search-and-rescue vessels engaged in a mission where adhering to the speed restrictions within the Ship Strike Reduction Rule compromises that mission (NOAA, 2008). In addition, the Ship Strike Reduction Rule is set to expire on December 9, 2013, 5 years after the rule was passed (NOAA, 2008). The Ship Strike Reduction Rule is set to expire in an effort to mitigate the negative economic impacts of enacting and enforcing this Rule, should the Ship Strike Reduction Rule prove ineffective at reducing right whale ship strike mortality inside critical habitat (NOAA, 2008). This was a deliberate expiration, as there was a degree of scientific uncertainty as to how effective the Ship Strike Reduction Rule may be at the time when it was enacted (NOAA, 2008).

5.4.3.2 IMO Collaboration

In 2007 the IMO approved a U.S. proposal to shift and narrow the east-west leg of the Boston TSS to reduce overlap between shipping traffic and right whales in a critical feeding habitat feeding, thus reducing the probability of right whale ship strike mortality (NMFS, 2012; Silber et al., 2012). In 2009, the IMO approved a second U.S. proposal to shift and narrow the north-south leg of the Boston TSS for the same reasons (NMFS, 2012; Silber et al., 2012). New Boston TSS lane locations were updated on navigational charts and the U.S. Coast Guard TSS list (NMFS, 2012).

In 2009, the IMO also approved a U.S. proposal designating a seasonal voluntary Area To Be Avoided (ATBA) in critical feeding habitat near the Great South Channel (NMFS, 2012; Silber et al., 2012). This ATBA was then added to navigational charts (NMFS, 2012).

5.5 Critical habitat: Where does it fit?

Two feeding grounds and a calving ground were identified as right whale critical habitat in 1994 (NOAA, 1994). Although originally listed endangered as the northern right whale, NFMS separated the northern right whale into two reproductively distinct stocks, North Atlantic right whales and North Pacific right whales in 2008 (NOAA, 2006). These two stocks are separate species as noted above (Committee on Taxonomy, 2012). Additional critical habitat has been designated for North Pacific right whales, while right whales retain the original critical habitat identified in 1994 (see Figure 5.4) (NOAA, 2003, 2006, 2010).

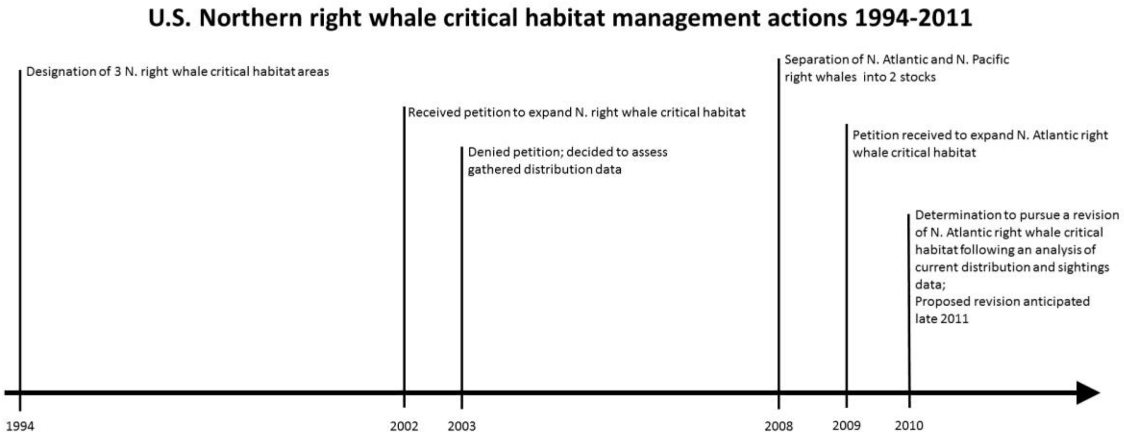


Figure 5.4 North Atlantic Right Whale Critical Habitat Designations and Alterations under the Endangered Species Act from 1994 to 2011. Critical habitat has not been revised for this stock since it was designated in 1994, although two petitions to expand critical habitat have been received.

Once critical habitat has been defined under the ESA, it does not mean that a preserve has been created, or that habitat protection has been conferred (ESA, 1973; Suckling & Taylor, 2006). Instead, it is up to wildlife managers to determine what levels of protection areas of critical habitat need for a species to maintain a recovering population growth rate (ESA, 1973; Suckling & Taylor, 2006). However, it remains an important first step in targeting areas of interest that require particular management oversight.

The question of what constitutes appropriate critical habitat protection is complex for highly migratory species (Boyd et al., 2008; Elvin & Taggert, 2008). Because these species require large spatial areas in order to feed, reproduce, and care for their young, eliminating all human impacts from an area may be economically and/or culturally impossible (Harwood, 2001; Fahrig, 2002; Boyd et al., 2008). This is particularly the case for right whales, whose identified critical habitat areas overlap several major U.S. shipping ports including Boston, Massachusetts and Jacksonville, Florida (NOAA, 1994; Kraus & Rolland, 2007). Further, right whales estimated migratory habitat overlaps nearly every U.S. east coast shipping port (NOAA, 1994; Kraus & Rolland, 2007). Thus, eliminating shipping traffic completely from right whale critical habitat as a strategy to reduce ship strike mortality remains unlikely because of competing economic pressures.

Following the designation of right whale critical habitat, U.S. wildlife managers provided education and right whale detection support to assist mariners operating in these areas in avoiding right whale ship strike mortality (NMFS, 2005). Informational pamphlets and newsletters about right whale critical habitat-use became available to the maritime community immediately following critical habitat designation, and continue today (Reeves et al., 2007; NMFS 2005, 2012). In 1999 the Mandatory Ship Reporting System became active in all three identified right whale critical habitat areas (see Figure 5.2) (NMFS 2005, 2006). This system originally requested mariners slow down or route around right whale critical habitat, and communicated known locations of individual right whales to local mariners (NMFS, 2005). Unfortunately, MSRS monitoring showed low voluntary compliance rates (Ward-Geiger et al., 2005). This, along with a continued increase in right whale ship strike mortalities, led to a series of vessel re-routing and vessel speed reduction measures (Silber & Bettridge, 2010; Silber et al., 2012). Results from habitat-use studies conducted in critical habitat led NOAA to establish recommended routes for vessel travel into and out of 4 ports in 2006 to reduce right whale/shipping use overlap (Merrick, 2005; Nichols & Kite-Powell, 2005; Bettridge & Silber, 2008). Results from additional habitat-use studies conducted in critical feeding habitat also resulted in narrowing and rotating the east-west and north-south legs of the Boston TSS to reduce right whale/shipping use overlap in 2007 and 2009 (Merrick, 2005; Silber et al., 2012). The 2008 Ship Strike Reduction Rule was enacted, requiring vessels larger than 65 feet to maintain speeds of 10 knots or less when transiting through identified seasonal critical habitat and port areas (NOAA, 2008).

Although it may be too soon to statistically determine what effect the Ship Strike Reduction Rule and various vessel re-routing measures have had on right whale ship strike mortality, the current literature indicates the overall location of large whale ship strikes along the east coast has not changed significantly during 1970-2009 (Elvin & Taggert, 2008; Silber & Bettridge, 2010; Pace, 2011; Van Der Hoop et al., 2013). If anything, the probability of large whale entanglement and ship strike in the U.S.

increased from 1990-2009 (Van Der Hoop et al., 2013). This probability may have increased as a result of increasing amounts of shipping traffic, as a result of increased right whale ship strike mortality reporting, and/or as a result of lack of compliance with current regulations (Van Der Hoop et al., 2013). Of note, the highest numbers of ship strike mortalities are found in the mid-Atlantic region of the U.S.; a region not currently designated as right whale critical habitat (Jensen & Silber, 2003; Nelson et al., 2007; Henry et al., 2011; Van Der Hoop et al., 2013).

5.6 Dealing with habitat fragmentation: Can whales and vessels co-exist?

In the case of right whales, it appears the current designation of critical habitat has led to habitat fragmentation; i.e., a phenomenon where portions of habitat necessary to species' survival has been reasonably protected, but a pathway from one of these protected portions to the next has not been protected (Andrén, 1994; Harwood, 2001; Boyd et al., 2008; Elvin & Taggert, 2008; Hinch & DeSanto, 2011). Thus, individual right whales experience relative safety only in designated critical habitat areas, and experience higher mortality rates outside of those areas, which may, at least in part, account for slow, if any, population recovery.

Given that removing all shipping traffic from right whale habitat is not economically viable, U.S. wildlife managers must find effective solutions to the question: How can right whales and ships co-exist sustainably?

The ESA tasks U.S. wildlife managers with creating recovery plans and identifying critical habitat areas so that a species is able to maintain population growth rates at levels that allow that species not to require further federal protection in order to sustain a viable population (ESA, 1973). Historically, wildlife managers identified right whale critical habitat that accounted for feeding and calving, but did not designate any critical habitat to assist individual right whales in migrating between those two critical life activities (NOAA, 1994; Harwood, 2001; Elvin & Taggert, 2008; Hinch & DeSanto, 2011). Part of this hesitation may lie in reluctance to bring about negative economic impacts through critical habitat protection, or perhaps in a lack of understanding concerning right whale migratory habitat-use (ESA, 1973; NOAA, 2003; Reeves et al., 2007; Firestone, 2009; Schick et al., 2009).

Initial attempts by wildlife managers to reduce right whale ship strike mortality involved reasonable first strategies: designate well understood right whale critical habitat, attempt to build voluntary consensus actions that reduce right whale ship strike mortality, and when that fails, utilize rulemaking to reduce right whale shipstrike mortality by regulating enforceable commercial actions inside designated right whale critical habitat. However, as it is clear these strategies have not been enough to reduce right whale ship strike mortality to potential biological removal (PBR) levels necessary to ensure species recovery required under the ESA (Elvin & Taggert, 2008; NOAA, 2011; NMFS, 2012; Van Der Hoop et al., 2013), managers should continue their efforts with a combination of the following approaches.

1) Designate right whale critical migratory habitat based upon best available science.
2) Continue to conduct migratory habitat-use studies using the best available technology.
3) Define the difference between protection levels required for migration and seasonal residence habitat areas.

4) Develop short-term and long-term solutions specific to migration and seasonal residence habitat areas to accelerate a reduction in right whale ship strike mortality.

5.6.1 Designate critical migratory habitat based upon best available science

There may be resistance to designating critical habitat if wildlife managers do not feel they understand how right whales use migratory habitat (ESA, 1973; NOAA, 2003, 2010; Firestone et al., 2008; Firestone, 2009; Schick et al., 2009). Although designation of critical habitat under the ESA does not automatically confer habitat protection (ESA, 1973; Suckling & Taylor, 2006), it does focus managerial efforts (NMFS, 2005). Thus, for highly migratory endangered species near human disturbances, designation of critical habitat areas essential to feeding, breeding, calving or nursing without subsequent designation of any migratory corridor connecting these habitats results in habitat fragmentation, and slows the overall population recovery process (Harwood, 2001; Fahrig, 2002; Boyd et al., 2008; Hinch & DeSanto, 2011). Indeed, doing so may concentrate anthropogenic threats, such as ship strike, outside designated critical habitat, increasing the probability that individuals within a species will be subjected to these impacts along a migration corridor (Fahrig, 2002; Boyd et al., 2008; Hinch & DeSanto, 2011).

Best available science has produced models, but no direct evidence of right whale migratory habitat-use since the late 1990s (Mate et al., 1997; Kenney et al., 2001; Knowlton et al., 2002; Firestone et al., 2008; Firestone, 2009; Schick et al., 2009). Further, designating critical habitat that does not include a migration corridor has not significantly reduced anthropogenic mortality for right whales. As most large whale ship strikes along the east coast of the U.S. continue to take place along the right whale migration corridor (Glass et al., 2010; Henry et al., 2011; NOAA, 2011), designating right whale critical migratory habitat based on current understanding of right whale migration habitat-use is a logical and imperative next step.

5.6.2 Continue to conduct migratory habitat-use studies using the best available technology.

In part, migratory critical habitat has not been designated because wildlife managers do not understand exactly when right whales migrate, and through which exact pathways (Kenney et al., 2001; Reeves et al., 2007; Firestone et al., 2008; Schick et al., 2009; Hinch & DeSanto, 2011). There may be no predictable annual answer to these questions, in part because variability in the marine environment may influence and change the timing and availability of right whale prey (Harwood, 2001; Kenney et al., 2001; Boyd et al., 2008; Hinch & DeSanto, 2011; NMFS, 2012) or navigational cues that guide migration. For example, pregnant right whales might not migrate to calving grounds until their own biological needs have been met (Garrison, 2007), and thus right whale migration timing and routes may change considerably from year to year.

In addition, the majority of consistent right whale aerial, ship board, and acoustic monitoring surveys have been conducted inside designated critical habitat (Reeves et al., 2007; NMFS, 2005, 2006, 2012). This has limited the availability of financial resources required to conduct these surveys in right whale migration habitat (Reeves et al., 2007; Firestone, 2009; Silber et al., 2009), resulting in a prolonged lack of understanding about right whale migration habitat-use.

Wildlife managers should re-examine the utility of satellite tagging, or other similar long term tracking technology, to help better understand right whale migration habitat-use (Reeves et al., 2007; Schick et al., 2009; Silber et al., 2009). Although current tag attachment methods may be invasive (Mate et al., 1997; Baumgartner et al., 2005; Mate et al., 2007; Silber et al., 2009), alternative attachment methods are being developed which may allow for less invasive long-term tagging (Kamino, 2013). In addition, the right whale population is small enough that tagging tracks from a few migrating females could provide a significant increase in understanding migration timing, migration routing, and preferred migration habitat (Reeves et al., 2007; Firestone, 2009; Schick et al., 2009). It is important to monitor the right whale migration both from a feeding ground to a calving ground, and from a calving ground to a feeding ground (Schick et al., 2009); although impacts of the latter scenario may be prohibitive, as tag attachment may negatively impact mother/calf proximity (Garrison, 2007). With the development of less invasive attachment methods, wildlife managers may want to weigh the consequences of tagging and tracking a few individual right whales against the potential benefits of better understanding right whale ship strike vulnerability during migration.

Wildlife managers should also consider reducing the amount of aerial surveys flown in feeding and calving critical habitat, and consider increasing passive acoustic monitoring in those areas to more cost-effectively monitor right whale seasonal resident critical habitat-use (Reeves et al., 2007; Silber et al., 2009). The limited funding released by this exercise might be better reprioritized to gain a more complete understanding of right whale migratory habitat-use.

Knowledge gained about migratory habitat-use from these efforts should assist in designating and revising right whale migration corridor critical habitat (Firestone, 2009; Schick et al., 2009). Knowledge gained should also enable wildlife managers to ascertain where and when right whales are most vulnerable to migration ship strike mortality (Reeves et al., 2007, Firestone, 2009; Schick et al., 2009). This knowledge should inform future ship strike mitigation actions.

5.6.3 Define a difference between protection levels required for migration and seasonal residence habitat areas.

The ESA enables wildlife managers to designate critical habitat, but does not limit wildlife managers by defining what constitutes habitat protection (ESA, 1973; Suckling & Taylor, 2006). Accordingly, highly migratory species may benefit from two distinctly different levels of habitat protection: permanently protected feeding, breeding, calving, and nursing seasonal residence habitat combined with temporarily protected migration habitat.

	Seasonal Residence Habitat	Migratory Habitat
Definition	• Allows limited amounts of low-impact human use • Allows maximum, blanketed species protection • Permanent protection allows for least management flexibility	• Allows most human uses • Allows minimum, directed individual-responsive protection • Temporary protection allows for maximum management flexibility
General Migratory Species Application	• Uses human- behavior modification as main protection tool • Uses only proven management tools • Rules apply to fixed spatial areas during fixed seasons, reducing stakeholder confusion • Standardized species seasonal habitat-use location information is obtained • Location information obtained is communicated through long-term broadcasting outlets	• Uses a combination of human-behavior modification and experimental technology as main protection tools • Uses proven and potential management tools • Rules and recommendations are applied for short periods of time and space • Standardized and opportunistic individual location information obtained • Near real-time location information is communicated through short-term broadcasting outlets
North Atlantic Right Whale Application	• Mandatory vessel re-routing, vessel speed restrictions, and onboard visual observers • Blanket restriction of recreational activities that have been shown to negatively impact right whales • Continuous seasonal passive acoustic monitoring combined with periodic aerial surveys to verify known habitat-use and assist with population studies	• Limited mandatory vessel re-routing and vessel speed restrictions, combined with satellite tagging technology, and aerial surveys • Use of experimental technology on government vessels to better locate individual right whales and/or to alert right whales to the presence of oncoming ships • Ongoing use of technology, surveys, and verified opportunistic sightings to ascertain migration timing, routing and preferred habitat

Table 5.1. Differences Between Seasonal Residence Critical Habitat and Migratory Critical Habitat Protection. These differences have been applied to potential ship strike reduction measures for migratory species in general, and North Atlantic right whales specifically, inside each habitat-type.

Permanently protected seasonal residence feeding, breeding, calving, and nursing grounds should limit the amount of human use within these designated critical habitats to ensure species recovery (see Table 5.1). Limiting human-use should be aimed at eliminating identified anthropogenic threats to a species within these critical habitats, yet minimizing negative economic impacts by encouraging reasonable, low-impact human uses (Vanderlaan et al., 2009; Wiley et al., 2011). Seasonal residence critical habitats should use human-behavior modification as a means to maintain adequate annual population growth rates. Proven anthropogenic impact mitigation methods and technology should be used inside seasonal residence critical habitats in order to reduce unintended impacts from new anthropogenic impact reduction technology and strategies (Silber et al., 2009). Further, seasonal residence critical habitats should remain in consistent locations and be valid during consistent portions of the year to reduce stakeholder confusion. Designated seasonal residence critical habitats should make use of rulemaking once mitigation needs are shown. Seasonal residence critical habitat areas and the rules governing human-use inside them should be evaluated for effectiveness every 10 years, and adjusted if needed to allow for management flexibility and endangered species protection stability.

Critical migration habitat should allow for more human-use than seasonal residence critical habitat areas, but should provide directed protection for migrating endangered species. Limiting human-use in these areas should involve reducing identified anthropogenic threats only in portions of migration habitat currently in use. Because individuals do not normally take up long-term residence in migration corridors (Mate et al., 1997; Firestone et al., 2008), migratory critical habitat should allow for flexible individual protection, thus reducing negative economic impacts by allowing for maximum sustainable human-use. A combination of human-behavior modification and permitted experimental technology should be used to reduce spatial overlap between humans and endangered species. Restrained use of rulemaking is required; instead the focus should be on obtaining accurate endangered species location information and communicating location information to stakeholders efficiently to prevent negative anthropogenic impacts. Rulemaking should encourage the use of temporary, short-term protection zones within the migratory habitat. Managers should also provide incentive for increased reporting of negative anthropogenic impacts in these areas in order to better understand endangered species habitat-use and anthropogenic impact vulnerability.

5.6.4 Develop short- and long-term right whale ship strike reduction solutions specific to migration and seasonal residence critical habitat areas

Rulemaking is a long, complex process composed of many steps, most of which require public notification and comment (ESA, 1973, NOAA 1994, 2000, 2005, 2008; Reeves et al., 2007). As a result, wildlife managers in the U.S. cannot be expected to designate critical habitat for an endangered species in one day, and adequately protect it the next (Reeves et al., 2007). However, NOAA and NMFS have received several petitions from stakeholders requesting revisions of right critical habitat and use of emergency interim rulemaking in order to more effectively reduce right whale ship strike mortality during 2000-2011 (NOAA, 2002; 2005; 2010). Those agencies have denied each petition (NOAA 2003; 2005; 2010). Regardless of outcome, this series of petitions highlights stakeholder frustration stemming from an important oversight in current right whale ship strike mortality reduction strategies: a lack of development and implementation for short- and long-term right whale ship strike mitigation solutions (Reeves et al., 2007).

Accordingly, wildlife managers should apply the migratory and seasonal residence critical habitat labels to establish a series of both short- and long-term management goals to accelerate a reduction in right whale ship strike mortality. Short-term solutions may be phased out once long-term solutions become available. For highly endangered species such as the right whale, a dearth of interim solutions may lead to reduced population growth rates (NOAA, 2005; Reeves et al., 2007) and in extreme cases, prevent the species from maintaining a viable population long enough to benefit from more ideal long-term solutions (Fujiwara & Caswell, 2001).

5.6.4.1 Long-term right whale ship strike reduction goals for seasonal use critical habitat areas

While it is not economically possible or desirable to eliminate shipping activity in designated right whale critical habitat (Reeves et al., 2007; Silber et al., 2009), it should be possible to limit shipping traffic. Specifically, the mandatory routing changes to the Boston TSS and the 2008 Ship Strike Reduction Rule speed restrictions are a well-conceived beginning. Requiring vessels entering and exiting critical habitat to utilize routes that minimize overlap with known right whale concentrations should reduce ship strike mortality (Vanderlaan et al., 2009; Lagueux et al., 2011; Silber et al., 2012). Also limiting vessels greater than 65 feet in length transiting feeding and calving critical habitat to speeds of 10 knots of less in the seasons when right whales are known to frequent those areas should allow some human-use while limiting the manner to more sustainable “safe” speeds (Vanderlaan et al., 2007; NOAA, 2008). Wildlife managers should at a minimum expand current speed limitations to include all vessels not involved directly in a search and rescue operation, police operation, or other military or law enforcement operation when following such a speed restriction would directly impact the success of that operation.

Commercial, military and public service vessels choosing to transit through feeding and calving critical habitat areas should be required to post trained right whale look-outs while transiting critical habitat areas, and to utilize proven supplementary right whale detection technology, such as infra-red detectors (Silber et al., 2009) or the Whale Alert App (NMFS, 2012) when that technology is made available. Right whale-trained lookouts should hold certification from an appropriate maritime industry, U.S. Navy or U.S. Coast Guard training course. These measures are similar in nature to right whale ship strike avoidance measures resulting from Section 7 ESA consultations between NMFS and various government agencies (Bettridge & Silber, 2008).

Finally, wildlife management agencies responsible for right whale ship strike reduction should also invest in compliance monitoring and enforcement (Reeves et al., 2007). Compliance with current routing measures seems to be increasing, but directing additional efforts towards monitoring and enforcing compliance with reduced vessel speed measures should be considered (Silber & Bettridge, 2010; Lagueux et al., 2011; McKenna et al., 2012). Vessels not compliant with current rules should be fined, and personnel charged accordingly to increase rates of compliance inside seasonal use critical habitat areas.

5.6.4.2 Short-term right whale ship strike reduction goals for seasonal use critical habitat areas

Short-term solutions to reduce right whale ship strike mortality should assist in preparing stakeholders for future long-term solutions. As such, a large-whale observer training program should be developed in partnership with maritime academies, maritime continuing education institutions, U.S. Coast Guard training programs and U.S. Navy internal training programs. Any new approved right whale detection technology, and relative use training, should be integrated into these courses. Use of this training program should be encouraged by offering participant incentives. A right whale visual detection training program for U.S. Navy forces and U.S. Coast Guard forces operating in right whale critical habitat areas has already been developed and is currently being used (Bettridge & Silber, 2008), but this program should be expanded to offer commercial training as well.

A recreational boater education campaign on the perils of ship strike for right whales, right whale field identification, and right whale critical habitat locations should be developed and established. Recreational boaters should be encouraged to follow the same speed restrictions valid for vessels greater than 65 feet in right whale critical habitat areas. Also, recreational boaters should be encouraged to route around right whale critical habitat areas or to utilize sailing vessels instead in an effort to limit right whale ship strike mortality. Finally, incentives, including observer immunity to any associated prosecution, should be used to encourage recreational boaters to report right whale ship strikes observed in order to gain an understanding of right whale ship strike vulnerability. The 2008 Report of a Workshop to Identify and Assess Technologies to Reduce Ship

Strikes of Large Whales noted that an assessment of ship strike mitigation methods for smaller craft had not been undertaken, but that smaller craft also hit and kill whales (Silber et al., 2009). Further, Jensen & Silber note at least one right whale calf death from ship strike included propeller scars from a twin engine (Jensen & Silber, 2003), while Henry et al note at least one adult female right whale serious injury from a 43 foot power yacht where the yacht partially severed the left fluke (Henry et al., 2011). Therefore, engaging smaller craft in ship strike mitigation strategies should assist in accelerating a reduction in right whale ship strike mortality.

A competitive grant program should be developed to encourage members of the shipping industry, educational institutions, and other stake-holders to work together in order to develop better right whale detection technology within a specific time frame. Ship strike reduction technology requirements identified by the 2008 Report of a Workshop to Identify and Assess Technologies to Reduce Ship Strikes of Large Whales should be included in this program (see Table 5.2) (Silber et al., 2009). These requirements should be separated into those that must be met within the grant period, and those requirements for which a solution is foreseeable, but not necessarily met within the grant period. This program should be utilized to accelerate the development of right whale ship strike mortality mitigation technology.

Required characteristics of ship strike reduction technology	Desired characteristics of ship strike reduction technology
• It should work with multiple detection systems. • It should have the ability to be fine-tuned to area or vessel-type. • It should operate in real-time, but detect a whale or warn a whale in time for the appropriate ship strike avoidance action to occur. • It should require minimal ESA and/or MMPA permits to test and operate	• It must introduce no, or minimal negative effects to marine organisms and the surrounding habitat. • It must involve the least amount of time involvement for mariners while underway. • It must not inject increasing amounts of ambient noise into the surrounding marine environment. • It must not significantly increase vessel fuel consumption. • It must not confer permanent significant economic costs to the shipping industry.

Table 5.2. Required and Desired Characteristics of Developing Right Whale Ship Strike Reduction Technology. As identified in a workshop held by the National Oceanic and Atmospheric Administration in 2008 (Garrison, 2007).

5.6.4.3 Long-term right whale ship strike reduction goals for migratory corridor critical habitat areas

Although right whales need to transit through a migration corridor, they likely do not need to stay long in such areas. As a result, slowing vessels down near port entries within the migration corridor at specific seasons, as is done in the Ship Strike Reduction Rule (NOAA, 2008), is an appropriate restriction in this area, as long as compliance is enforced. However, that speed restriction be expanded again to include all vessels not involved directly in a search-and-rescue operation, police operation, or other military or law enforcement operation where following such a speed restriction would directly impact the success of that operation.

Further, the Dynamic Management Area (DMA) system proposed in the Ship Strike Reduction Rule (NOAA, 2008) is a good attempt at protecting migrating right whales. While wildlife managers should make speed restrictions inside DMAs mandatory, wildlife managers should also trigger a DMA lasting a maximum of 3 days following each right whale sighting in the migration corridor. DMA speed restrictions should be mandatory as compliance monitoring consistently shows a lack of compliance with voluntary shipping traffic speed restrictions (Silber & Bettridge, 2010; Lagueux, 2011; McKenna et al., 2012). Further, speed restrictions inside DMAs should be enforced to ensure this change has a measureable effect. This will allow DMAs to provide immediate protection for each right whale sighted, but also allow DMAs to more closely reflect satellite tagging observations that show tagged right whales outside feeding areas range 90-131 km in a single day (Mate et al., 1997). Thus, this change will enable each DMA to provide time-responsive protection to individual migrating right whales while also allowing for maximum human-use of the area.

Additionally, as new ship strike mitigation technology and methods become available, U.S. wildlife managers might examine testing and implementing it first in migration zones. As right whales do not need to establish long residence times in migration zones (Mate et al., 1997; Knowlton et al., 2002; Schick et al., 2009), technology aimed at better identifying right whale locations in real-time, or alerting right whales to the presence of oncoming ships may be a viable human/whale overlap solution in these areas, allowing for maximum human and whale use. Further, as right whales are likely to be less concentrated in migration zones (Reeves et al., 2007; Firestone et al., 2008; Schick et al., 2009), these technologies assist the mariner/whale detection process while minimizing the economic impact that further vessel re-routing and speed restrictions may cause.

5.6.4.4 Short-term right whale ship strike reduction goals for migratory corridor critical habitat areas

Limited aerial surveys should be conducted in suspected migration corridor areas (Reeves et al., 2007). Although this may be initially expensive, sightings from these surveys should inform current population status work, inform regional mariners directly of near real-time right whale locations and contribute to managers' understanding of right whale migratory habitat-use (Reeves et al., 2007; Firestone, 2009; Silber et al., 2009).

A recreational boater education program should be developed incorporating right whale field identification, right whale habitat-use, right whale vulnerability to ship strike, and actions mariners can take to avoid right whales encountered. Given that mariner education has been touted as a cost-effective right whale ship strike mitigation strategy (Moore, 2009), it should be extended to recreational boaters. This program should include information on how and where to report any right whales sighted in migration areas in an effort to collect opportunistic migration corridor habitat-use data. Cost-effectiveness of endangered species management strategies has become a subject of review during the last decade (Reeves et al., 2007). Given that pregnant and nursing right whales likely migrate in small numbers (Firestone, 2009; Schick et al., 2009), are likely to be hard to visually detect (Silber et al., 2009), and are likely to transit large areas in a single day (Mate et al., 1997; Schick et al., 2009), making effective use of potential opportunistic right whale observers in the migration zone may significantly improve managers' understanding of right whale migratory habitat-use. In order to better utilize recreational boater sightings, recreational boaters should be encouraged to take opportunistic photos of right whales sighted from an appropriate distance, and to log approximate GPS locations and dates seen. Building and integrating a free “whale reporting photo app” for smart phones should be considered to encourage recreational boater opportunistic sighting reporting and to streamline sightings data collection. Increased sightings reported by opportunistic recreational boaters should be used to direct increases in aerial and/or ship board surveys to optimize right whale migratory habitat-use data gained versus funding spent.

Finally, wildlife managers should reconsider utilizing permitted field tests of alarm technology and infrared whale detection technology on “trial” vessels (Reeves et al., 2007). Neither of these technologies is without risk, but allowing engineering and animal testing to go forward in a migration area ensures: 1) that technological development is continuing at an adequate pace should an emergency interim solution become imperative, and 2) that the unquantified risks of utilizing new technology can be quantified by testing the technology on a very small number of endangered individuals (Reeves et al., 2007; Silber et al., 2009) in an area where the long-term consequences of displacing those individuals is minimal. Further, wildlife managers should consider permitting such technology on government “test” ships to ensure that adequate testing occurs before any technological solution is approved and applied on a wider level. Use of government vessels as testing vehicles makes sense as several large naval bases overlap with right migratory habitat (Knowlton et al., 2002; Firestone, 2009). Further government vessels not required to abide by the Ship Strike Reduction Rule (NOAA, 2008) may have increased need of an alternative ship strike mitigation method. Finally, as the largest numbers of known large whale ship strike occur in right whale migratory habitat (Glass et al., 2010; Henry et al., 2011; Van Der Hoop et al., 2013) there is a reasonable chance of learning more about close whale/vessel interactions here. Additional benefits of utilizing government vessels as testing vehicles include streamlining federal funding resources and encouraging increased inter-agency awareness, communication and cooperation to reduce right whale ship strike mortality.

5.7 Conclusions

U.S. wildlife managers have designated right whale feeding and calving seasonal residence areas as critical habitat, and provided right whale ship strike protection in those critical habitat areas through mariner education, communication of known real-time right whale locations to mariners, vessel re-routing, and vessel speed restrictions. No significant reduction in right whale ship strike mortality has occurred following current critical habitat designation and ship strike mitigation strategy implementation (Vanderlaan et al., 2009; Pace, 2011; Van Der Hoop et al., 2013).

This lack of reduction in right whale ship strike mortality is a result of habitat fragmentation based on the current right whale critical habitat designated, and its protection. Although wildlife managers have protected known right whale seasonal residence areas, no migratory critical habitat has been identified or protected connecting seasonal residence areas, leaving individual pregnant and nursing right whales vulnerable to continued ship strike mortality. Given that statistical analysis indicates preventing the deaths of 2 female right whales per year could reverse negative population trends (Fujiwara & Caswell, 2001), identifying and protecting migration habitat for pregnant and nursing female right whales should enable right whale population recovery under the ESA.

Accordingly, wildlife managers should seek to extend the current Ship Strike Reduction Rule with small alterations to DMA triggering and time length in migration habitat. Wildlife managers should also supplement that extension by designating a small migratory corridor of critical right whale habitat based upon best available science, continue conducting studies on right whale migratory corridor use, define different levels of protection for critical right whale seasonal residence areas and migratory corridors, and implement both short-term and long-term ship strike reduction solutions in both habitat types. Pursuing these actions should accelerate a reduction in pregnant and nursing female right whale ship strike mortality.

CHAPTER 6

CONCLUSIONS

6.1 Acoustic shadow zone formation

This thesis is comprised of a series of articles intended to address different audiences across a variety of disciplines, all which must be considered when developing an acoustic method to reduce North Atlantic right whale ship strike mortality in U.S. waters. Accordingly, the following discussion explains how the development of each chapter contributed information to other chapters.

In order to better understand the acoustic landscape a North Atlantic right whale experiences during close whale/ship encounters, Chapter 2 developed a two-dimensional acoustic ray tracing model for seven high-risk locations in a known North Atlantic right whale feeding habitat. During the modeling effort, it became apparent that the presence of modeled acoustic shadow zones likely reduces the amount of time a North Atlantic right whale has to detect an oncoming ship. Further, the presence of acoustic shadow zones also may negatively impact the opportunity for North Atlantic right whales to accurately localize oncoming ships. Both of these consequences reduce the opportunity for successful avoidance of oncoming ships.

Acoustic shadow zones result from a combination of the following environmental factors:

1) changes in water column density, which influence sound velocity gradients and subsequent sound channeling;

2) the composition of reflective surfaces, which influence the amount of sound scattered, absorbed and reflected at the surface medium;
3) the composition of reflective barriers, which influence the angle of sound refraction through the barrier medium;
4) the rugosity of reflective surfaces, which influence the angle at which sound waves encountering the surface are reflected and/or refracted;
5) water column depth, which influences the directional radiation pattern of sound propagation.

Acoustic shadow zone formation is also influenced by the following source signal characteristics:

1) depth of the sound source, which influences the amount interference between direct sound spreading and phase-shifted reflection, or Lloyd's Mirror Effect, often resulting in less than expected signal intensity near the surface, and ;
2) sound source frequency, which affects the size of propagating wavelengths, influencing sound attenuation.

Characterization of the acoustic environment a whale experiences during close whale/ship encounters was modeled accounting for all of the factors listed above except for the composition of reflective barriers. The effects of reflective barrier composition on acoustic shadow zone formation should be explored in future modeling efforts. Results from the modeling indicate rugosity of the ocean floor is not likely a contributing factor to the formation of acoustic shadow zones. Instead, sound velocity profile minimums that create sound channel axes, composition of reflective surfaces and barriers, and water column depth likely have a greater influence on the formation and location of acoustic shadow zones present during close whale/ship encounters. Chapter 2 modeling results also indicate the formation of bow null effect acoustic shadow zones during July – September in 5 of the 7 modeled locations; this seasonality is doubtless a function of seasonal changes in vertical velocity profiles of the water column.

The work in Chapter 3 was undertaken to verify the results modeled from data collected in Chapter 2. A larger number of ship passages were observed *in situ*, across a variety of ship classes at one location within the larger modeled acoustic area. Differences in ships observed included differences in hull design, hull material, propulsion method, gross tonnage, approximate sound source depth, sound source intensity, and ship speed. Results from Chapter 3 indicate regardless of differences in ship construction, at 25 meters depth all ships exhibited increased peak broadband source levels (SLs) aft and minimum peak broadband SLs off the bow. Additionally, all ships recorded exhibited an increase in peak broadband SLs from the bow to 15 degrees indicating all observed ships exhibited bow null effect acoustic shadow zones. These results from Chapter 3 indicate that the modeling done in Chapter 2 may have under-estimated the extent to which bow null effect acoustic shadow zones are formed during Jul-Sep for ships transiting the northwestern Gulf of Maine.

The location of bow null effect acoustic shadow zones directly ahead of oncoming ships at the ocean surface paired with reported observations of North Atlantic right whales turning into the paths of parallel transiting ships (Terhune & Verboom, 1999) led me to conclude that these particular acoustic shadow zones were most likely to reduce the opportunity for North Atlantic right whales to detect and/or accurately localize oncoming ships, contributing to high observed rates of North Atlantic right whale ship strike mortality.

6.2 Bow null effect acoustic shadow zone formation

In the work described in Chapter 3, I examined observed variation in bow null effect acoustic shadow zones recorded among ships transiting *in situ*. In addition those already listed above for general acoustic shadow zone formation, bow null effect acoustic shadow zone formation is specifically influenced by the following factors:

1) ship draft, which influences source signal depth;
2) ship length and width, which influence the area a source signal must refract through or reflect around in order to propagate ahead of an oncoming ship;
3) hull material, which in this case is often the refraction/reflection barrier;
4) ship propulsion type, which influences source signal frequency and intensity;
5) placement of propellers, impellers, engines and/or generators relative to ship design, which influences source signal depth, refraction, and reflection, and;
6) ship speed; which influences source signal frequency and intensity.

Each ship recorded in Chapter 3 was constructed in a slightly different manner. Low *n* values prevented statistically significant comparisons of variations in bow null effect acoustic shadow zone intensities observed within ships of the same type. Further, the placement of propellers, impellers, engines and/or generators relative to ship design varied dramatically among the 24 ships observed, as they included V-, U-, and catamaran-style hulls as well as propeller, jet, and ADU propulsion systems. Further, to standardize comparisons between ships of varying types, only ship construction and propulsion information available from both Lloyd's Registry of ships and the Maine Department of Marine Resources Registered Fishing Vessels database were used. As a result, analysis of variation in bow null effect acoustic shadow zones observed was limited to differences in ship length, draft, gross tonnage, horsepower, propulsion type and speed at time of recorded ship passage.

Of these parameters, only an increase in ship length to draft (L:D) ratio exhibited a positive relationship to increasing SLs from the bow to 15 degrees. This was a limited analysis, but as two of the four ship types observed included only catamaran-style hulls this positive relationship may make sense. Catamaran-style hulls are typically characterized by shallower drafts than comparable V- and U-style hulls (see Figure 6.1b). Shallower draft ships generally have acoustic sound sources (in these cases impellers, engines, and generators) located nearer the surface than deeper draft vessels. While this could be expected to exacerbate the difference in broadband SLs observed from the bow to 15 degrees as a result of Lloyd's Mirror Effect (Gerstein & Blue, 2005; Medwin et al., 2005), it also reduces the area of hull material a source signal must refract through or reflect around in order to propagate ahead of the boat. Further, by creating two additional sound reflection surfaces in the form of the space between the two hulls (see Figure 6.1b), catamaran-style hulls may increase sound channeling at the surface, resulting in increased signal propagation ahead of the oncoming ship compared to V- and U-style hulled ships. Thus, while increasing L:D ratios in this study show a positive relationship with increasing broadband SLs from the bow to 15 degrees, differences in hull design are likely responsible for that observed relationship.

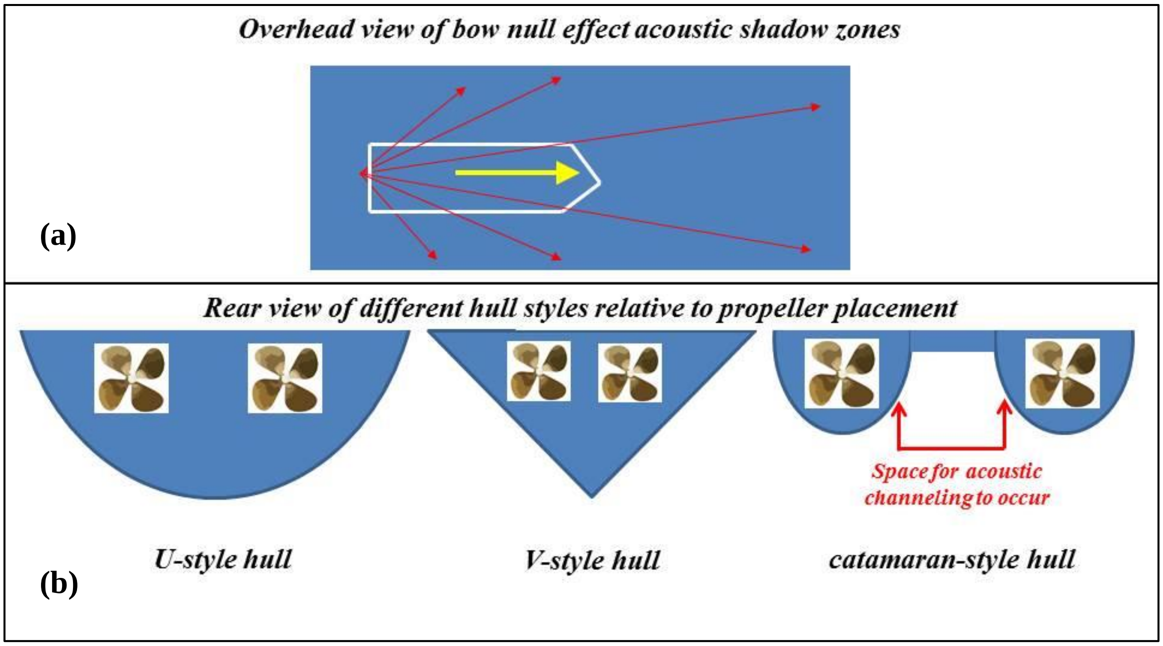


Figure 6.1 Formation of Bow Null Effect Acoustic Shadow Zones. **(a)** Top panel shows an overhead view of the formation of bow null effect acoustic shadow zones. Red sound rays originating from the ship's propellers refract through the hull material to propagate ahead of the ship, creating a surface acoustic shadow zone. **(b)** Bottom panel shows a rear view of the U-, V- and catamaran-style hulls with typical propeller placements. Because of its shape, the catamaran-style hull allows for a near-surface sound channel to form, reducing the presence of bow null effect acoustic shadow zones.

Although increases in broadband SLs have been correlated with increases in ship gross tonnage in some studies (Ross, 1976), an increase in ship gross tonnage did not show a definable relationship to increasing SLs from the bow to 15 degrees in Chapter 3, agreeing with the results of other studies (Heitmeyer et al., 2003; McKenna et al., 2012). Gross tonnage is a measure of the volume of cargo spaces within a ship that does not correlate directly with variations in ship design, ship mass or ship displacement (IMO, 1969). As bow null effect acoustic shadow zones are formed as a result of ship sound source signal refraction and reflection, and interaction with environmental variables conducive to sound channel formation, differences in ship design are more likely to influence the formation of bow null effect acoustic shadow zones.

Similar to the results of other recent studies (Heitymeyer et al., 2003; McKenna et al., 2012) no relationship was found between variations in ship speed and increasing SLs from the bow to 15 degrees in Chapter 3. It is important to keep in mind relationships, or lack thereof, reported in Chapter 3 result from comparisons among ships of different ship types. Like gross tonnage, increasing ship speed has been observed correlating to increasing broadband SLs in other studies (Ross, 1976; Arveson & Vendettis, 2000; Trevorrow et al., 2008). Unlike gross tonnage, future studies should explore this relationship among a larger number of ships within each specific ship type. At different speeds, different components of a ship's acoustic signature (propellers, impellers, engines, and/or generators) tend to dominate a ship's broadband source signal (Arveson & Vendettis, 2000; Trevorrow et al., 2008). Thus, different propagation patterns may dominate at different ship speeds, particular to each ship type.

Hull material was not evaluated as a potential influence on bow null effect acoustic shadow zone formation in Chapter 3, however future studies should assess this potential relationship. Acoustic impedance is a function of sound velocity and the density difference between propagation mediums (Medwin et al., 2005). In general, the closer the acoustic impedance values for two materials, the less the time-delay between source signal reflections (Norton & Karczub, 2003). Thus, assuming sound velocity is approximately equal, an increase in the density difference between a ship's hull material and the surrounding water column should result in an increase in observed broadband SLs from the bow to 15 degrees.

Likewise, although not evaluated as part of Chapter 3, future studies should examine the relationship between increasing stern width relative to increasing broadband SLs from the bow to 15 degrees. In general stern shape, including width, draft, and relative propeller placement, likely contributes to bow null effect acoustic shadow zone formation. When propellers are placed above the keel, low frequency sound generated by propeller revolution must refract through or reflect beneath the stern before propagating ahead of an oncoming ship (see Figure 6.1a). Therefore, any change in stern dimensions should result in a change in bow null effect acoustic shadow zone formation and/or shape.

6.3 Definition of design requirements

The limited verification of the modeled bow null effect in Chapter 2 by the observations in Chapter 3 led to the conclusion that the presence of bow null effect shadow zones located directly at the surface, ahead of oncoming ships, likely presented the most significant impediment to acoustic detection and localization of oncoming ships by North Atlantic right whales. In order to increase the opportunity for North Atlantic right whale detection and localization of oncoming ships, the results from Chapters 2 and 3 formed the design requirements for the prototype of an acoustic method to reduce North Atlantic right whale ship strike mortality developed and tested in Chapter 4.

Design requirements derived from the results of Chapters 2 and 3 included:

1) reducing and/or eliminating the presence of bow null effect acoustic shadow zones for a variety of ship types;

2) creating a testable prototype that would be transferable to multiple test ships of varying hull design;
3) creating a testable prototype that would not result in lasting changes or damages to test ship hulls, and;
4) creating a testable prototype that would have power independent of the test ship.

As the single factor likely most responsible for formation of observed bow null effect acoustic shadow zones was the propagation barrier provided by each ship's keel, I designed a prototype of a bow-mounted dual speaker array to eliminate that propagation barrier. I developed an attachment platform that enabled prototype testing to include broadcasting the test signal at a variety of depths and angles, closely modeling variation in test ship hulls without requiring permanent attachment to or modification of test ships. Finally I used a generator to standardize the speaker array power source, reducing potential variations in prototype signal intensity

Initial field-testing of this prototype eliminated an increase in broadband SLs from the bow to 15 degrees for all five ships tested, increasing the opportunity for North Atlantic right whales to detect oncoming ships. Future prototype modification should include increasing speaker size and developing an acoustic array employing constructive interference to maximize source signal intensity at frequencies below 500 Hz. These modifications will result in an increase in low frequency signal intensity and directionality at the bow aspect of oncoming ships. These improvements will make the bow the loudest aspect of an oncoming ship, increasing the opportunity for North Atlantic right whale to localize oncoming ships. Maximizing the opportunity for successful detection and localization of oncoming ships could result in an increase in successful ship avoidance by most baleen whales, although here my motivation is to specifically decrease annual rates of North Atlantic right whale ship strike mortality.

6.4 Interfacing the developed solution with current policy structure

Before applying any solution to negative anthropogenic impacts on a protected species and its protected habitats, current and evolving policy framework must be taken into account. Thus, Chapter 5 reviews existing U.S. North Atlantic right whale ship strike mortality reduction policy in the context of the Endangered Species Act of 1973, the more restrictive of the two protective acts applying to this population. As an extension of that review, Chapter 5 also suggests room for improvement in future North Atlantic right whale ship strike mortality reduction policy, defining a difference in protection levels for seasonal residence habitat areas and migration habitat areas. Chapter 5 concludes that while North Atlantic right whale seasonal residence critical habitat use is well understood, a lack of understanding regarding North Atlantic right whale migration habitat use has resulted in persistent ship strike mortality levels above the recommended potential biological removal (PBR) rates defined by regulatory agencies.

Current understanding of North Atlantic right whale migration habitat use is constrained by the expense required to obtain non-biased spatial habitat use assessments from aerial surveys, and the by limiting nature of data obtained from less expensive passive acoustic monitoring. While the prototype developed in Chapter 4 may not have a place in current U.S. North Atlantic right whale ship strike reduction policy, new technology may prove useful in reducing and/or eliminating North Atlantic right whale ship strike mortality in migration habitat regions where traditional habitat use surveys are cost prohibitive. Thus, future development of the prototype developed in Chapter 4 should be conducted in partnership with wildlife managers in the U.S. and/or Canada.

In partnership with wildlife managers in the U.S. and/or Canada, future *in situ* research should be conducted to observe North Atlantic right whale reactions to close ship encounters before testing the prototype developed in Chapter 4 on individual whales. Further study will help researchers define which acoustic stimuli North Atlantic right whales react to, what observed North Atlantic right whale critical ratios are, and whether North Atlantic right whales engaged in different behaviors react differently to close ship encounters, creating additional prototype modification requirements.

As it is imperative not to endanger individuals, future research on North Atlantic right whale behavior during close ship encounters should utilize a combination of existing long-term passive acoustic monitoring systems, existing long-term environmental monitoring buoys, existing ship Automatic Identification Systems, mariner accounts, and existing aerial survey observations inside shipping lanes to observe a large number of opportunistic North Atlantic right whale/ship encounters. Combining information from these sources should develop a clearer definition of the *in situ* acoustic environment of North Atlantic right whale/ship close encounters, the distances at which North Atlantic right whales react to close ship encounters, the intensity at which North Atlantic right whales react to close ship encounters, the locations and orientations of individual North Atlantic right whales relative to oncoming ships (subsurface, surface, etc.), the behaviors of individual North Atlantic right whales (feeding, transiting, logging, engaged in SAG, etc.) prior to the close ship encounters, and the reactions of North Atlantic right whales to oncoming ships.

Scientific take authorization permits could then be obtained to test the modified prototype developed in Chapter 4 on a similar non-endangered baleen whale species, North Atlantic minke whales (*Balaenoptera acutorostrata*), a species that likely has similar acoustic sensitivity. If prototype testing results in statistically significant minke whale avoidance behavior, additional scientific take authorization permits should be obtained to test the modified prototype on finback (*Balaenoptera physalus*), humpback (*Megaptera novaenagliae*), sei (*Balaenoptera borealis*) and eventually North Atlantic right whales. The reaction of all whales tested should be taken into account before any attempt is made to utilize this device as a North Atlantic right whale ship strike morality reduction method.

6.5 Thesis Conclusions

Thus, the following conclusions can be drawn from the results presented in this thesis:

1. Bow null effect acoustic shadow zones exist for all ship types that I modeled and observed in the Gulf of Maine, although an exhaustive review of this phenomenon across all ship types operating in this area is beyond the scope of this thesis. As bow null effect acoustic shadow zones exist at the surface and ahead of transiting

ships, these shadow zones likely reduce the opportunity for North Atlantic right whales to accurately detect and/or localize oncoming ships, contributing to observed high levels of North Atlantic right whale ship strike mortality.

2. Bow null effect acoustic shadow zones may be reduced by modifying ship length to draft ratios. Increasing length to draft ratios show a positive relationship to increasing broadband source levels from the bow to 15 degrees, indicating a change in ship hull design may result in a reduction in North Atlantic right whale ship strike mortality.
3. Bow null effect acoustic shadow zones can be eliminated via the use of hull-mounted dual speaker prototype, increasing the opportunity for North Atlantic right whales to detect oncoming ships.
4. Widespread use of a bow-mounted speaker array prototype to reduce North Atlantic right whale ship strike mortality is likely not a viable solution in all United States waters as a result of current U.S. ship strike mortality reduction policy under the restrictions imposed on wildlife managers by the Endangered Species Act of 1973.
5. Limited use of a modified bow-mounted speaker array prototype to reduce North Atlantic right whale ship strike mortality may be a viable short-term solution for permitted research ships, military ships, and/or federal ships transiting outside identified North Atlantic right whale critical habitat areas.
6. Utilizing the a modified version of the bow-mounted speaker array prototype for additional ships transiting areas where North Atlantic right whale ship strike mortality is known to occur, but also where North Atlantic right whale habitat use

is uncertain, may help reduce North Atlantic right whale ship strike mortality until a ship strike mortality reduction method less likely to impact North Atlantic right whale behavior is identified.

REFERENCES

Abbitt, R.J., & Scott, J.M. (2001). Examining differences between recovered and declining endangered species. *Conservation Biology, 15*(5), 1274-1284.

Allen, J.K., Peterson, M.L., Sharrard, G.V., Wright, D.L., & Todd, S.K. (2012). Radiated noise from commercial ships in the Gulf of Maine: implications for whale/vessel collisions. *Journal of the Acoustical Society of America, 132*(3), EL229-EL235.

Andrén, H. (1994). Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos, 71*(3), 355-366.

Arveson, P.T., & Vendittis, D.J. (2000). Radiated noise characteristics of a modern cargo ship. *Journal of the Acoustical Society of America*, *107*(1), 118-129.

Asaro, M.J. (2012). Geospatial analysis of management areas implemented for protection of the North Atlantic right whale along the northern Atlantic coast of the United States. *Marine Policy, 36*, 915-921.

Baumgartner, M.F., & Mate, B.R. (2005). Summer and fall habitat of North Atlantic right whales (*Eubalaena glacialis*) inferred from satellite telemetry. *Canadian Journal of Fisheries and Aquatic Science, 62*, 527-543

Bearzi, M. (2012). Cetaceans and MPAs should go hand in hand: a case study in Santa Monica Bay, California. *Ocean & Coastal Management, 60*, 56-59.

Best, P.B., Branadao, A., & Butterworth, D.S. (2001). Demographic parameters of southern right whales off South Africa. *Journal of Cetacean Research and Management*, *Special Issue 2,* 161-169.

Bettridge, S., & Silber, G.K. (2008). Update on the United States' actions to reduce the threat of ship collisions with large whales. *Prepared for the International Whaling Commission's Working Group on Ship Strikes and Presented at the International Whaling Commission's Conservation Committee 2008, Santiago, Chile, June 16, 2008. IWC/60/6612.*

Bettridge ,S., & Silber, G.K. (2009). Update on the United States' actions to reduce the threat of ship collisions with large whales. *International Whaling Commission 61st Annual Meeting, Maderia, Portugal, June 2009, IWC/61/CC14; Agenda Item 4*.

Bowlin, J.B., Speitsberger, J.L., Duda, T.F., & Freitag, L.F. (1992). Ocean Acoustical Ray-Tracing Software RAY. *Woods Hole Oceanographic Institute Technical Report*, *WHOI-93-10.*

Boyd, C., Brooks, T.M., Butchart, S.H.M., Edgar, G.J., da Fonseca, G.A.B., Hawkins, F., Hoffman, M., Sechrest, W., Stuart, S.N., & Van Dijk, P.P. (2008). Spatial scale and the conservation of threatened species. *Conservation Letters*, *1*, 37-43.

British Broadcasting Company. (2010). "Whale of a tale for couple yachting off Cape Town," *British Broadcasting Company News* published July 26. Retrieved from http://www.bbc.co.uk/news/world-africa-10712323

Brown, M.W., & Marx, M.K. (2000). Surveillance, monitoring and management of North Atlantic right whales, *Eubalaena glacialis*, in Cape Cod Bay, Massachusetts: January to mid-May 2000. *Division of Marine Fisheries, Commonwealth of Massachusetts, Final Report.*

Brown, M.W., Fenton, D., Smedbol, K., Merriman, C., Robichaud-Leblanc, K., & Conway, J.D. (2009). Recovery strategy for the North Atlantic right whale (*Eubalaena glacialis*) in Atlantic Canadian waters. *Species at Risk Act Recovery Strategy Series, Fisheries and Oceans Canada.*

Browning, C.L., Rolland, R.M., & Kraus, S.D. (2010). Estimated calf and perinatal mortality in western North Atlantic right whales (*Eubalaena glacialis*). *Marine Mammal Science*, *6*(4), 278-291.

Byington, R., Brown, E., Bruneel, T., & Perkins, G. (2011). U.S. Water Transportation Statistical Snapshot. *Office of Policy and Plans, Office of Congressional and Public Affairs, Maritime Administration, U.S. Department of Transportation*. Retrieved from http://www.marad.dot.gov/documents/US_Water_Transportation_Statistical_snapshot.pdf

Carrillo, M., & Ritter, F. (2010). Increasing numbers of ship strikes in the Canary Islands: proposals for immediate action to reduce risk of ship-whale collisions. *Journal of Cetacean Research & Management, 11*(2), 131-138.

Caswell, H., Brault, S., & Fujiwara, M. (1999). Declining survival probability threatens the North Atlantic right whale. *Proceedings of the National Academy of Science U.S.A.*, *96*, 3308-3313.

Committee on Taxonomy. (2012). List of marine mammal species and subspecies. *Society for Marine Mammalogy*, Retrieved from www.marinemammalscience.org

Czech, B., & Krausman, P.R. (2001). *The Endangered Species Act: history, conservation biology, and public policy.* Baltimore: John Hopkins University Press.

Dalsoren, S.B., Eide, M.S., Myhre, G., Endresen, O., Isaksen, I.S., & Fuglestvedt, J.S. (2010). Impacts of the large increase in international shipping traffic 2000-2007 on tropospheric ozone and methane. *Environmental Science & Technology, 44*, 2482-2489.

De Stephanis, R., & Urquiola, E. (2006). Collisions between ships and cetaceans in Spain. *Presented to the International Whaling Consortium Scientific Committee, St. Kitts and Nevis, West Indies, SC/58/BC5*. Retrieved from the Office of the *Journal of Cetacean Research & Management.*

Dolin, E.J. (2007). *Leviathan*. New York: W.W. Norton & Company.

Douglas, A.B., Calambokidis, J., Rafferty, S., Jeffries, S.J., Lambourn, D.M., & Norman, S.A. (2008). Incidence of ship strike of large whales in Washington State. *Journal of the Marine Biological Association U.K., 88*, 1121-1132.

Elvin, S.S, & Taggart, C.T. (2008). Right whales and vessels in Canadian waters. *Marine Policy, 32*, 379-386.

Endangered Species Act. (1973, amended 2002). United States.

Fahrig, L. (2002). Effect of habitat fragmentation on the extinction threshold: a synthesis. *Ecological Applications, 12*(2), 346-353.

Firestone, J., Lyons, S.B., Wang, C., & Corbett, J.J. (2008). Statistical modeling of North Atlantic right whale migration along the mid-Atlantic region of the eastern seaboard of the United States. *Biological Conservation, 141*, 221-232.

Firestone, J. (2009). Policy consideration and measures to reduce the likelihood of vessel collisions with great whales. *Boston College Environmental Affairs Law Review, 36*, 389-400.

Flagg, C.N. (1987). Hydrographic structure and variability. In Backus, R.M. (Ed.): *George's Bank*. (pp. 108-124). Boston: Massachusetts Institute of Technology Press.

Francois, R.E., & Garrison, G.R. (1982). Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America, 72*, 1879-1890.

Frasier, T.R., McLeod, B.A., Gillet, R.M., Brown, M.W., & White, B.N. (2007). Right whales past and present as revealed by their genes. In Kraus, S.D., & Rolland, R.M. (Eds.), *The Urban Whale*. (pp.200-231). Cambridge: Harvard University Press.

Fujiwara, M.,& Caswell, H. (2001). Demography of the endangered North Atlantic right whale. *Nature, 414*, 537-541.

Garbriele, C., Neilson, J., Jensen, A., & Straley, J. (2011). Summary of reported whale-ship collisions in Alaskan waters. *Presented at the 19th Biennial Conference on the Biology of Marine Mammals*.

Gaskin, D.E. (1991). An update on the status of the right whale, *Eubalaena glacialis*, in Canada. *Canadian Field Naturalist, 105*, 198-205.

Garrison, L.P. (2007). The big picture: modeling right whales in space and time. In Kraus, S.D., & Rolland, R.M. (Eds.), *The Urban Whale*. (pp.460-487). Cambridge: Harvard University Press.

Gerstein, E.R., & Blue, J.E. (2005). The acoustical causes of collisions between marine mammals and ships. In Medwin, H. (Ed.), *Sounds in the Sea*. (pp. 430-444). New York: Cambridge University Press.

Glass, A.H., Cole, T.V.N., & Garron, M. (2010). Mortality and serious injury determinations for baleen whale stocks along the United States and Canadian eastern seaboards, 2004-2008. *NOAA Technical Memorandum, NMFS-NE-214*.

Gulf of Maine Ocean Observation System, 2008. "Gulf Of Maine Ocean Observation System Historical Buoy Database". Retreived from http://www.gomoos.org/gnd/

Haar, L., & Cox, R. (1996). Port of Boston Economic Development Plan. *Massachusetts Port Authority*.

Hamilton, P.K., Knowlton, A.R., & Marx, M.K. (2007). Right whales tell their own stories: the photo-identification catalog. *In* Kraus, S.D., & Rolland, R.M. (eds.) *The Urban Whale*. Cambridge, MA: Harvard University Press. 75-104.

Hamilton, P.K., Kenney, R.D., & Cole, T.V.N. (2009). Right whale sightings in unusual places. *Right Whale News, 17*(1), 9-10.

Harwood, J. (2001). Marine mammals and their environment in the twenty-first century. *Journal of Mammalogy, 82*(3), 630-640.

Hatch, L., Clark, C., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., Thompson, M., & Wiley, D. (2008). Characterizing the relative contributions of large vessels to total ocean noise fields: a cast study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. *Environmental Management, 42*, 735-752.

Heitmeyer, R.M., Wales, S.C., & Pflug, L.A. (2003). Shipping noise predictions: capabilities and limitations. *Marine Technology Society Journal, 37*(4), 54-65.

Henry, A.G., Cole, T.V.N., Garron, M., & Hall, L. (2011). Mortality and serious injury determinations for baleen whale stocks along the Gulf of Mexico, United States and Canadian eastern seaboards, 2005-2009. *US Department of Commerce, Northeast Fisheries Science Center Reference Document 11-18*.

Henry, A.G., Cole, T.V.N., Garron, M., Hall, L., Ledwell, W., & Reid, A. (2012). Mortality and serious injury determinations for baleen whale stocks along the Gulf of Mexico, United States east coast and Atlantic Canadian provinces, 2006-2010. *US Department of Commerce, Northeast Fisheries Science Center Reference Document 12-11*.

Hildebrand, J.A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series, 395*, 5-20.

Hildreth, R. (2008). Place-based ocean management: emerging U.S. law and practice. *Ocean & Coastal Management*, *51*, 659-670.

Hinch, P.R., & De Santo, E.M. (2011). Factors to consider in evaluating the management and conservation effectiveness of a whale sanctuary to protect and conserve the North Atlantic right whale (E*ubalaena glacialis*). *Marine Policy, 35*, 163-180.

International Convention for the Regulation of Whaling [ICRW], with Schedule of Whaling Regulations. (1946) *62 Stat. 1716, 161 UNTS 72*.

International Maritime Organization [IMO]. (1969). International Convention on Tonnage Measurement of Ships. *IMO-713 E, London*.

IMO. (2007). Work Programme of the Committee and Subsidiary Bodies –Measures for minimizing the risks of collisions with cetaceans. *Marine Environment Protection Committee, MEPC 57/18/2*.

IMO. (2009). Report of the Marine Protection Committee. *Marine Environment Protection Committee, MEPC 59/24*.

International Whaling Consortium [IWC]. (2008). Third progress report to the Conservation Committee of the Ship Strike Working Group. *IWC Conservation Committee , IWC/60/CC3*.

Jacobsen, K., Marx, M., & Oien, N. (2004). Two-way trans-Atlantic migration of a North Atlantic right whale (*Eubalaena glacialis*). *Marine Mammal Science, 2*, 1-13.

Jensen, A.S., & Silber, G.K. (2003). Large Whale Shipstrike Database. *U.S. Department of Commerce, NOAA Technical Memorandum, NMFS-OPR-25*.

Kamino, K. (2013). Diversified material designs in biological underwater adhesives. In Thomopoulos, S., Birman, V., & Genin, G.M. (Eds.): *Structural Interfaces and Attachments in Biology*. (pp. 175-200). New York: Springer Science & Business Media.

Kenney, R.D., Mayo, C.A., & Winn, H.E. (2001). Migration and foraging strategies at varying spatial scales in western North Atlantic right whales: a review of hypotheses. *Journal of Cetacean Research and Management, Special Issue 2*, 251-260.

Kenney, R.D. (2007). Right whales and climate change: facing the prospect of a greenhouse future. In Kraus, S.D., & Rolland, R.M. (Eds.): *The Urban Whale*.(pp. 436-459). Cambridge: Harvard University Press.

Knowlton, A., Ring, J., & Russell, B. (2002). Right whale sightings and survey effort in the mid-Atlantic region: migratory corridor, time frame, and proximity to port entrances. *A Report Submitted to the National Marine Fisheries Service Ship Strike Working Group*. Retrieved from www.nero.noaa.gov/shipstrike/ssr/midatlanticreportrFINAL.pdf.

Kraus, S.D., Crone, M.J., & Knowlton, A.R. (1988). The North Atlantic right whale. In Chandler, W.J. (Ed.): *Audubon Wildlife Report 1988/89*. (pp.685-698). New York: Academic Press.

Kraus, S.D., Hamilton, P.K., Kenney, R.D., & Slay, C.K. (2001). Reproductive parameters of the North Atlantic right whale. *Journal of Cetacean Research and Management*, *Special Issue 2*, 231-236.

Kraus, S.D., Brown, M., Caswell, H., Clark, C., Fujiwara, M., Hamilton, P., Kenney, R., Knowlton, A., Landry, S., Mayo, C., McLellan, W., Moore, M., Nowacek, D., Pabst, D., Read, A., & Rolland, R. (2005). North Atlantic right whales in crisis. *Science, 309,* 561-562.

Kraus, S.D., & Rolland, R.M. (2007). Right whales in the urban ocean. In Kraus, S.D., & Rolland, R.M. (Eds.), *The Urban Whale*. (pp. 1-38). Cambridge: Harvard University Press.

Lagueux, K.M., Zani, M.A., Knowlton, A.R., & Kraus, S.D. (2011). Response by vessel operators to protection measures for right whales (*Eubalaena glacialis)* in the southeast U.S. calving ground. *Endangered Species Research, 14,* 69-77.

Laist, D.W., Knowlton, A.R., Mead, J.G., Collet, A.S., & Podesta, M. (2001). Collisions between ships and whales. *Marine Mammal Science, 17*(1), 35-75.

Mackenzie, K.V. (1981). Nine term equations for sound speed in the ocean. *Journal of the Acoustical Society of America, 70*, 807-812.

Mahaffey, C. A. (2006). *Qualitative GIS predictive modeling of ship strike in the Gulf of Maine*. Unpublished Masters, College of the Atlantic, Bar Harbor.

Marine Mammal Protection Act. (1972, amended 2004; 2007) United States.

Martin Associates. (2009). Port of Jacksonville Total Economic Impacts. *Jacksonville Port Authority*. Retrieved from http://www.jaxport.com/about-jaxport/overview/economic-impacts

Massachusetts Port Authority. (2012). Cruiseport Boston shatters passenger records in 2012. Retrieved from http://www.massport.com/news-room/News/CruiseportBostonShatters.aspx

Mate, B.R., Nieukirk, S.L., & Kraus, S.D. (1997). Satellite-monitored movements of the northern right whale. *Journal of Wildlife Management, 61*(4), 1393-1405.

Mate, B.R., Mesecar, R., & Lagerquist, B. (2007). The evolution of satellite-monitored radio tags for large whales: one's laboratory experience. *Deep-Sea Research II, 54*, 224-247.

Mayo, C.A, & Marx, M. (1990). Surface foraging behavior of the North American right whale, *Eubalaena glacialis*, and associated zooplankton characteristics. *Canadian Journal of Zoology, 68*, 2214-2220.

McKenna, M.F., Katz, S.L., Condit, C., & Walbridge, S. (2012). Response of commercial ships to a voluntary speed reduction measure: are voluntary strategies adequate for mitigating ship-strike risk? *Coastal Management, 40*, 634-650.

McKenna, M.F., Ross, D., Wiggens, S.M., & Hildebrand, J.A. (2012). Underwater radiated noise from modern commercial ships. *Journal of the Acoustical Society of America, 131*(1), 92-103.

McLellan, W.A., Meagher, E., Torres, L. Lovewell, G., Harper, C., Irish, K., Pike, B., & Pabst, A.D. (2004). Winter right whale sightings from aerial surveys of coastal waters of the U.S. Mid-Atlantic. *15th Biennial Conference on the Biology of Marine Mammals*, Greensboro, North Carolina.

Medwin, H. (1975). Speed of sound in water: a simple equation for realistic parameters. *Journal of the Acoustical Society of America, 58*(6), 1318-1319.

Medwin, H. (2005). *Sounds in the Sea*. New York: Cambridge University Press.

Merrick, R.L. (2005). Seasonal management areas to reduce ship strikes of northern right whales in the Gulf of Maine. *Northeast Fisheries Science Center Reference Document, 05-19.*

Moore, J.C., & Clark, E. (1963). Discovery of right whales in the Gulf of Mexico. *Science*, *141*(3577), 269.

Moore, M.J., Knowlton, A.R., Kraus, S.D., McLellan, W., & Bonde, R.K. (2005). Morphometry, gross morphology, and available histopathobiology in Northwest Atlantic right whale (*Eubalaena glacialis*) mortalities (1970-2002). *Journal of Cetacean Research & Management, 6*, 199-214.

Moore, M.J., McLellan, W.A., Daoust, P.Y., Bonde, R.K., & Knowlton, A.R. (2007). Right whale mortality: a message from the dead to the living. In Kraus, S.D., & Rolland, R.M. (Eds.), *The Urban Whale*. (pp.358-379). Cambridge: Harvard University Press..

Moore, M.J. (2009). Current issues facing North Atlantic right whales and stakeholders. *Boston College Environmental Affairs Law Review, 36*(2), 309-317.

National Marine Fisheries Service [NMFS]. (1991). Final recovery plan for the northern right whale *Eubalaena glacialis*. *U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Office of Protected Resources.*

NMFS. (2005). Recovery plan for the North Atlantic right whale (*Eubalaena glacialis*). *National Marine Fisheries Service, Office of Protected Resources*.

NMFS. (2006). Review of the status of North Atlantic right whales in the North Atlantic and North Pacific Oceans. *U.S. Department of Commerce NOAA Technical Memorandum*. Retrieved from http://www.nmfs.noaa.gov/pr/pdfs/statusreviews/rightwhale2006.pdf.

NMFS. (2012). North Atlantic right whale (*Eubalaena glacialis*) 5-year review: summary and evaluation. *U.S. Department of Commerce NOAA Technical Memorandum*.

National Oceanic and Atmospheric Administration [NOAA]. (1994). Designated Critical Habitat; Northern Right whale. *Federal Register, 59*(28793). Retrieved from http://www.nmfs.noaa.gov/pr/pdfs/fr/fr59-28805.pdf.30p.

NOAA. (1995). North Atlantic right whale stock assessment report. *Marine Mammal Stock Assessment Reports 1995; National Marine Fisheries Service*. Retrieved from http://www.nmfs.noaa.gov/prot res/PR2/Stock Assessment Program/sars.html

NOAA. (2000). Advanced Notice of Proposed Rulemaking for North Atlantic Right whale Protection. *Federal Register*, *65*(2), 270-272.

NOAA. (2002). Finding for a petition to revise critical habitat for Northern right whales. *Federal Register*, *67*(223), 69708-10.

NOAA. (2003). Finding for a petition to revise critical habitat for Northern right whales. *Federal Register*, *68*(167), 51758-63.

NOAA. (2004). Regulations governing the approach to North Atlantic right whales. *Federal Register*, *69*(229), 69536-37.

NOAA. (2005). Petition to initiate emergency rulemaking to prevent the extinction of the North Atlantic right whale; final determination. *Federal Register*, *70*(188), 56884-5.

NOAA. (2006). Revision of critical habitat for the Northern right whale in the Pacific Ocean. *Federal Register*, *71*(129), 38277-97.

NOAA. (2006). Proposed endangered status for North Atlantic right whales. *Federal Register*, *71*(248), 77704-16.

NOAA. (2008). Endangered fish and wildlife; Final Rule to implement speed restrictions to reduce the threat of ship collisions with North Atlantic right whales. *Federal Register*, *73*(198), 60173-91.

NOAA. (2010). Designating critical habitat for the endangered North Atlantic right whale. *Federal Register*, *73*(193), 61690-91.

NOAA. (2011). North Atlantic right whale stock assessment report. *Marine mammal stock assessment reports 2011; National Marine Fisheries Service.* Retrieved from http://www.nmfs.noaa.gov/prot res/PR2/Stock Assessment Program/sars.html

NOAA. (2012). North Atlantic right whale stock assessment report. *Marine mammal stock assessment reports 2012; National Marine Fisheries Service.* Retrieved from http://www.nmfs.noaa.gov/prot res/PR2/Stock Assessment Program/sars.html

NOAA. (2013). Reducing Ship Strike to North Atlantic Right whales. *Office of Protected Resources.* Retrieved from http://www.nmfs.noaa.gov/pr/shipstrike/

Nelson, M., Garron, M., Merrick, R.L., Pace, R.M.III, & Cole, T.V.N. (2007). Mortality and serious injury determinations for baleen whale stocks along the United States eastern seaboard and adjacent Canadian maritimes, 2001-2005. *Northeast Fisheries Science Center Reference Document 07-05*.

Nichols, O.C., & Kite-Powell, H. (2005). Analysis of risk to North Atlantic right whales (*Eubalaena glacialis*) from shipping traffic in Cape Cod Bay. *Final Report Submitted to NOAA Fisheries Northeast Fisheries Science Center, NOAA Award No. Na03NMF4720489*.

Norton, M., & Karczub, D. 2003. *Fundamentals of noise and vibration analysis for engineers*. (2nd ed.). New York: Cambridge University Press.

Nowacek, D.P., Johnson, M.P., & Tyack, P.L. (2004). North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. *Proceedings of the Royal Society of London B, 271*, 227-231.

Pace, R. (2011). Frequency of whale and vessel collisions on the US eastern seaboard: ten years prior and two years post ship strike rule. *Northeast Fisheries Science Center Reference Document 11-15*.

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., & Weinrich M. (2006). Mediterranean fin whales at risk from fatal ship strikes. *Marine Pollution Bulletin, 52*, 1287-1298.

Parks, S.E. (2003). Acoustic communication in the North Atlantic right whale (*Eubalaena glacialis*). *Ph.D. Thesis, Massachusetts Institute of Technology and Woods Hole Oceanographic Institute*.

Parks, S.E., Johnson, M., Nowacek, D., & Tyack, P.L. (2011). Individual right whales call louder in increased environmental noise. *Biology Letters, 7*, 33-35.

Parks, S.E., Warren, J.D., Stamieszkin, K., Mayo, C.A., & Wiley, D. (2012). Dangerous dining: foraging of North Atlantic right whales increases risk of vessel collisions. *Biology Letters, 8*, 57-60.

Reeves, R.R., Breiwick, J.M., & Mitchell, E. (1992). Pre-exploitation abundance of right whales off the eastern United States. *Northeast Fisheries Science Center Reference Document 92-05*.

Reeves, R.R., Rolland, R., & Clapham, P. (2001). Report of the workshop on the causes of reproductive failure in North Atlantic right whales: new avenues of research. *Northeast Fisheries Science Center Reference Document 01-16*.

Reeves, R.R., Read, A.J., Lowry, L., Katona, S.K., Boness, D.J. (2006). Report of the North Atlantic right whale program review. *Prepared for the Marine Mammal Commission 2007, Woods Hole, Massachusetts*.

Reeves, R.R., Smith, T.D., & Josephson, E.A. (2007). Near-annihilation of a species: right whaling in the North Atlantic. In Kraus, S.D., & Rolland, R.M. (Eds.), *The Urban Whale*. (pp.39-74). Cambridge: Harvard University Press.

Richardson, J., Greene, C.R., Malme, C.I., & Thomson, D.H. (1995). *Marine Mammals and Noise.* San Diego: Academic Press.

Ritter, F. (2010). Quantification of ferry traffic in the Canary Islands (Spain) and its implications for collisions with cetaceans. *Journal of Cetacean Research & Management, 11*(2), 139-146.

Rolland, R.M., Hunt. K.E., Doucette, G.J., Rickard, L.G., & Wasser, S.K. (2007). The inner whale: hormones, biotoxins and parasites. In Kraus, S.D., & Rolland, R.M. (Eds.), *The Urban Whale*. (pp.232-272). Cambridge: Harvard University Press.

Ross, D. (1976). *Mechanics of underwater noise*. New York: Pergamon Press.

Roworth, E., & Signell, R. (2002). "Gulf of Maine 15 arc second grid," in Construction of Digital Bathymetry for the Gulf of Maine. *Coastal and Marine Geology Program, U.S. Geological Survey, Open File Report 98-801*. Retrieved from http://pubs.usgs.gov/of/1998/of98-801/bathy/data.htm

Schick, R.S., Halpin, P.N., Read, A.J., Slay, C.K., Kraus, S.D., Mate, B.R., Baumgartner, M.F., Roberts, J.J., Best, B.D., Good, C.P., Loarie, S.R., & Clark, J.S. (2009). Striking the right balance in right whale conservation. *Canadian Journal of Fisheries and Aquatic Science, 66*, 1399-1403.

Scott, J.M., Goble, D.D., & Davis, F.W. (2006). Introduction. In Goble, D.D., Scott, J.M., & Davis, F.W. (Eds.), *The Endangered Species Act at Thirty*. (Vol. 1, pp. 3-15). Washington: Island Press.

Scott, J.M., Goble, D.D., Svancara, L.K., & Pidgorna, A. (2006). By the numbers. In Goble, D.D., Scott, J.M., & Davis, F.W. (Eds.), *The Endangered Species Act at Thirty*. (Vol. 1, pp. 16-35). Washington: Island Press.

Silber, G.K., Bettridge, S., & Cottingham, D. (2009). Report of a workshop to identify and assess technologies to reduce ship strikes of large whales. *Department of Commerce, NOAA Technical Memorandum, NMFS-OPR-42*.

Silber, G.K., & Bettridge, S. (2010). Vessel operations in right whale protection areas in 2009. *U.S. Department of Commerce, NOAA Technical Memorandum, NMFS-OPR-44*.

Silber, G.K., Vanderlaan, A.S.M., Arceredillo, A.T., Johnson, L., Taggart, C.T., Brown, M.W., Bettridge, S., & Sagarminaga, R. (2012). The role of the International Maritime Organization in reducing vessel threat to whales: process, options, action and effectiveness. *Marine Policy*, *36*, 1221-1233.

Suckling, K., & Taylor, M. (2006). Critical habitat and recovery. In Goble, D.D., Scott, J.M., & Davis, F.W. (Eds.), *The Endangered Species Act at Thirty*. (Vol. 1, pp. 75-89). Washington: Island Press.

Terhune, J., & Verboom, W. (1999). Right whales and ship noise. *Marine Mammal Science*, *15*, 256-258.

Todd, S.K., Allen, J.K., Mahaffey, C.M., Damon, J., Hamilton, P., & Kenney, R.D. (2009). An Acoustic Mysticete Shipstrike Mortality Risk Assessment for the Gulf of Maine. In *Proceedings of the 5th International Conference on Bio-Acoustics* (Volume 5, pp. 280-287).

Trotter, B. (2011). CAT ferry operator drops lease for MDI terminal. *Bangor Daily News* published March 19.

Trevorrow, M.D., Vasiliev, B., & Vagle, S. (2008). Directionality and maneuvering effects on a surface ship underwater acoustic signature. *Journal of the Acoustical Society of America*, *124*(2), 767-778.

United States Geological Survey [USGS]. (2004). "USGS East Coast Sediment Texture Database," *USGS Coastal and Maine Geology Program, Woods Hole Science Center, Woods Hole, MA.* Retrieved from http://pubs.usgs.gov/of/2000/of00-358/text/chapter2.htm

Urick, R.J. (1983). *Principles of Underwater Sound*. Los Altos: Peninsula Publishing.

Van Der Hoop, J.M., Moore, M.J., Barco, S.G., Cole, T.V.N., Daoust, P.Y., Henry, A.G., McAlpine, D.F., McLellan, W.M., Wimmer, T., & Solow, A.R. (2013). Assessment of management to mitigate anthropogenic effects on large whales. *Conservation Biology*, *27*(1): 121-133.

Vanderlaan, A.S.M., & Taggart, C.T. (2007). Vessel collision with whales: the probability of lethal injury based on vessel speed. *Marine Mammal Science*, *231*(1), 144-156.

Vanderlaan, A.S.M., Corbett, J.J., Green, S.L., Callahan, J.A., Wang, C., Kenney, R.D., Taggart, C.T., & Firestone, J. (2009). Probability and mitigation of vessel encounters with North Atlantic right whales. *Endangered Species Research, 6,* 273-285.

Van Waerebeek, K., Baker, A.N., Felix, F., Gedamke, J. Iniguez, M., Sanino, G.P., Secchi, E., Sutaria, D., Van Helden, A., & Wang, Y. (2007). Vessel collisions with small cetaceans worldwide and with large whales in the Southern Hemisphere, an initial assessment. *Latin American Journal of Aquatic Mammals, 6*(1), 43-69.

Waldick, R.C., Kraus, S., Brown, M., & White, B.N. (2002). Evaluating the effects of historic bottleneck events: an assessment of microsatellite variability in the endangered North Atlantic right whale. *Molecular Ecology, 11,* 2241-2249.

Wallace, R.L. (2003). Social influences on conservation: lessons from U.S. recovery programs for marine mammals. *Conservation Biology, 17*(1), 104-155.

Ward-Geiger, L.I., Silber, G.K., Baumstark, R.D., & Pulfer, T.L. (2005). Characterization of ship traffic in right whale critical habitat. *Coastal Management, 33,* 263-278.

Waring, G.T., Josephson, E., Maze-Foley, K., & Rosel, P.E. (2011). U.S. Atlantic and Gulf of Mexico marine mammal stock assessments 2010. *NOAA Technical Memorandum, NMFS NE 219.*

Wartzok, D., & Ketten, D. (1999). Marine Mammal Sensory Systems. In Reynolds, J.E., & Rommel, S.A. (Eds.), *Biology of Marine Mammals*. (pp. 117-175). Washington: Smithsonian Institution Press.

Wiley, D.N., Thompson, M., Pace, R.M. III, & Levenson, J. (2011). Modeling speed restrictions to mitigate lethal collisions between ships and whales in the Stellwagen Bank National Marine Sanctuary, U.S.A. *Biological Conservation, 144,* 2377-2381.

Williams, R., & O'Hara, P. (2010). Modeling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. *Journal of Cetacean Research & Management, 11*(1), 1-8.

APPENDIX A: FIELD TEST AREA MAPS

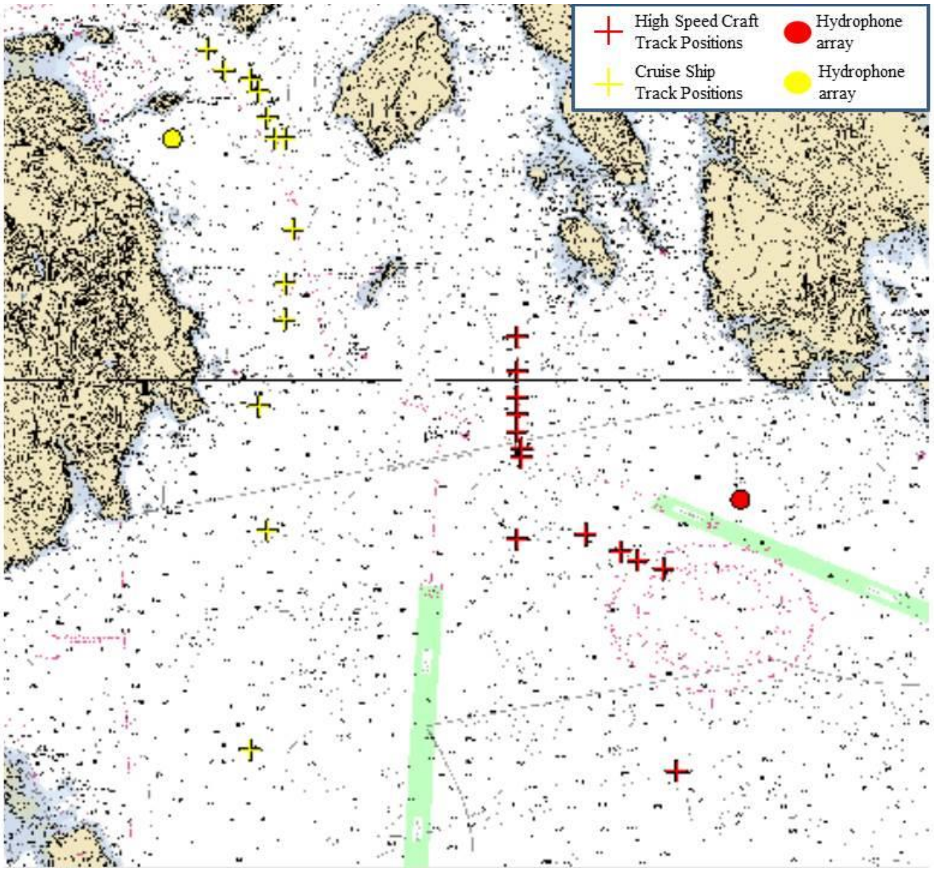


Figure A.1. Two Ship Tracks Recorded During Chapter 3 Field Work. Ship tracks are designated with crosses; position of the hydrophone array during each trial recording is designated with circles of the same color. A total of 79 ships were recorded during the course of the fieldwork, 24 of which were analyzed in Chapter 3. Frenchman Bay north and southbound recommended routes are highlighted on the chart in green.

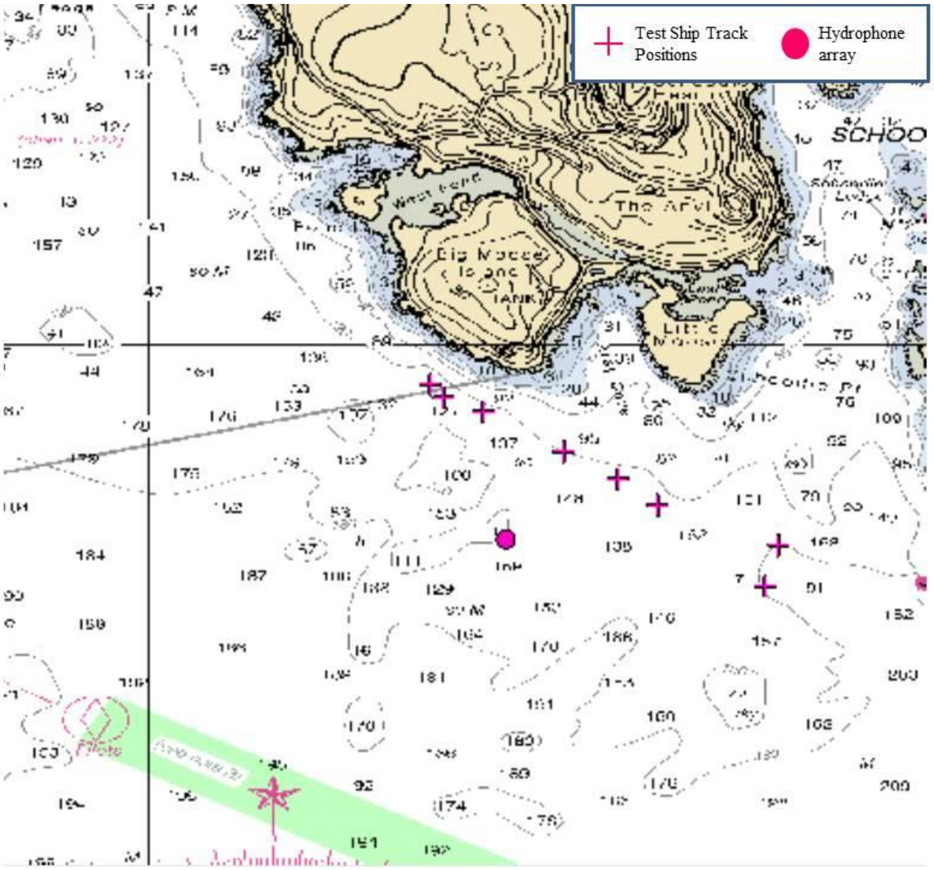


Figure A.2. Sample Test Ship Track from Prototype Field Testing in Chapter 4. A total of 5 ships were tested a minimum of 4 times, resulting in 35 different test tracks. The location of the hydrophone array is designated relative to test ship passage. Frenchman Bay northbound recommended route is highlighted on the chart in green.

APPENDIX B: CALCULATED RADIAL SOURCE LEVELS

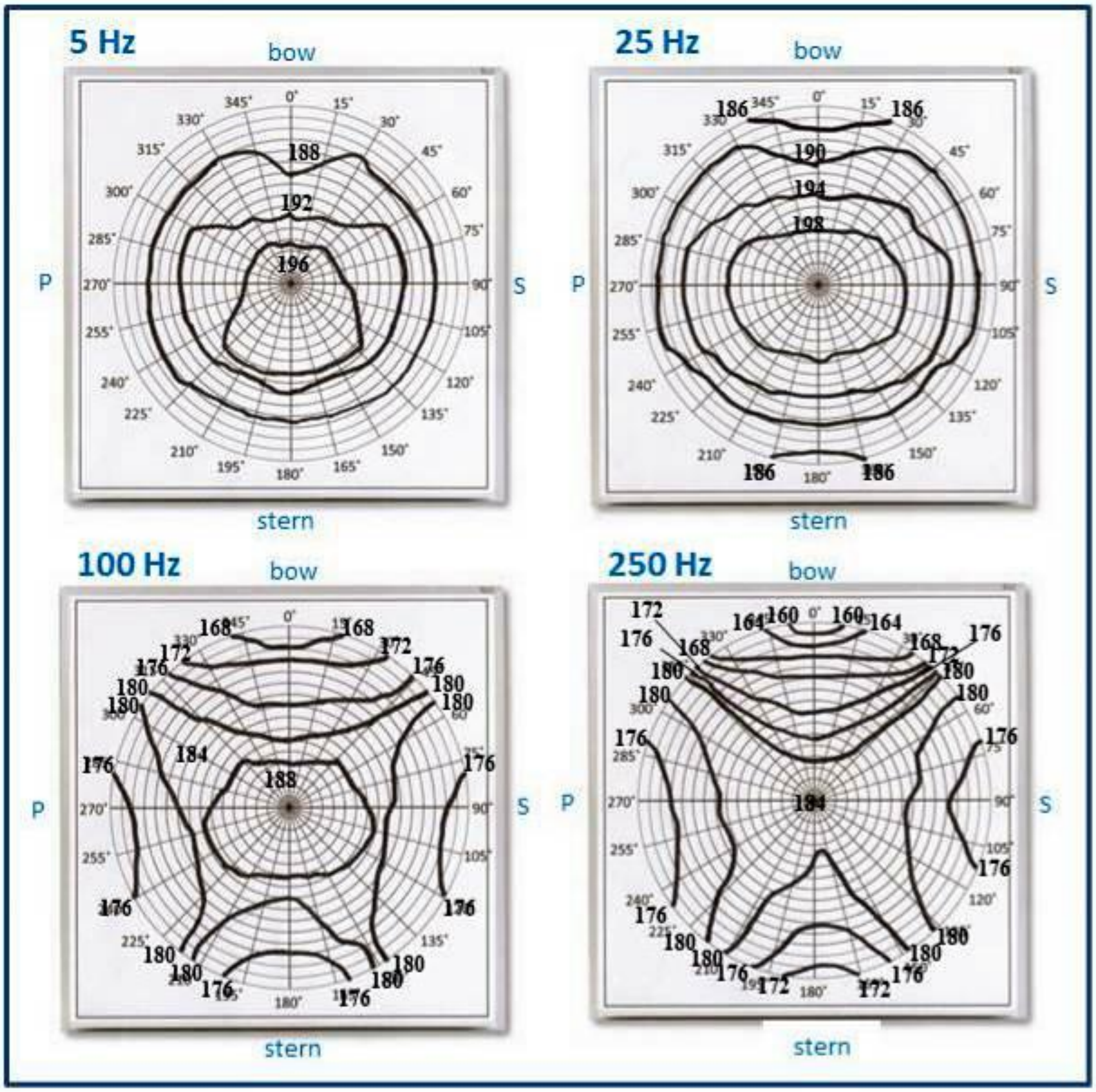


Figure B.1. Calculated Radial Source Levels for the Maasdam. Calculated radial source level (SL) change, or orbital sound spectra, are shown above for the Maasdam, a cruise ship transiting the Bar Habor, Maine shipping lane on August 12, 2009 at 10 knots.

The Maasdam was the only ship that passed the vertical hydrophone array on both the starboard and port sides at approximately the same speed during this study. Both passages were done within an hour, indicating environmental changes in Maasdam acoustic signature propagation were relatively low. Calculated radial SLs shown above are for 4 frequencies from 5 Hz – 250 Hz across a 50 m equidistant spherical plane at hydrophone depth 5 m. The ship acoustic source is located in the center of the spherical plane, and black rings indicate different calculated SLs at different recorded distances and angles.

Although the calculated radial SL change shown in the figure above was only calculated for a single ship (n=1), it demonstrates the sensory gradient a North Atlantic right whale may encounter as a result of the presence of the recorded bow null effect acoustic shadow zones in Chapter 3, better characterizing the acoustic field during close whale/ship interactions.

APPENDIX C: PROTOTYPE PHOTOS

Additional photos and explanation of the prototype developed and tested in Chapter 4.

Figure C.1. Front View of Attachment Platform. All acoustic and electronic components are attached. Poles allow speaker centers to be deployed at multiple depths and angles, approximating variations in test ship hull design.

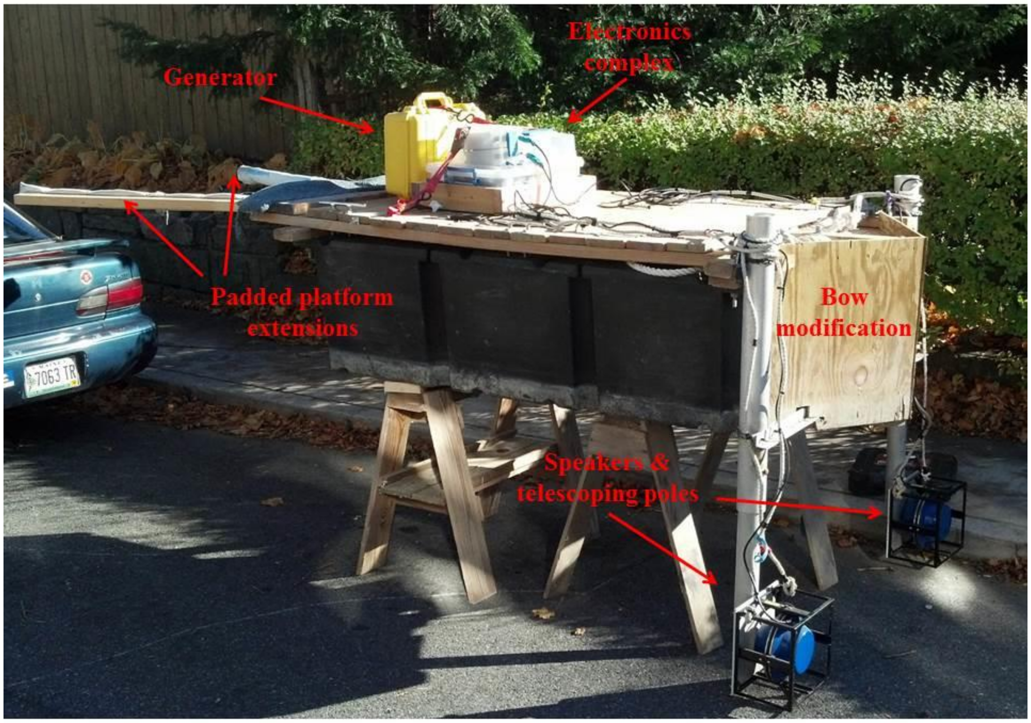


Figure C.2. Labeled Side View of Attachment Platform. All acoustic and electronic components are attached.

Figure C.3. Extended Side View of Attachment Platform. All acoustic and electronic components are attached.

Figure C.4. Top View of Attachment Platform. All acoustic and electronic components are attached.

Figure C.5. Close-Up of Platform Extensions. Platform extensions are padded and adjustable to the width of each test ship's bow. An additional notch is cut into the back of the platform, beneath the carpet padding.

Figure C.6. Attachment Platform Deployed with Speakers Attached. Platform extensions, generator, and electronics complex not yet attached.

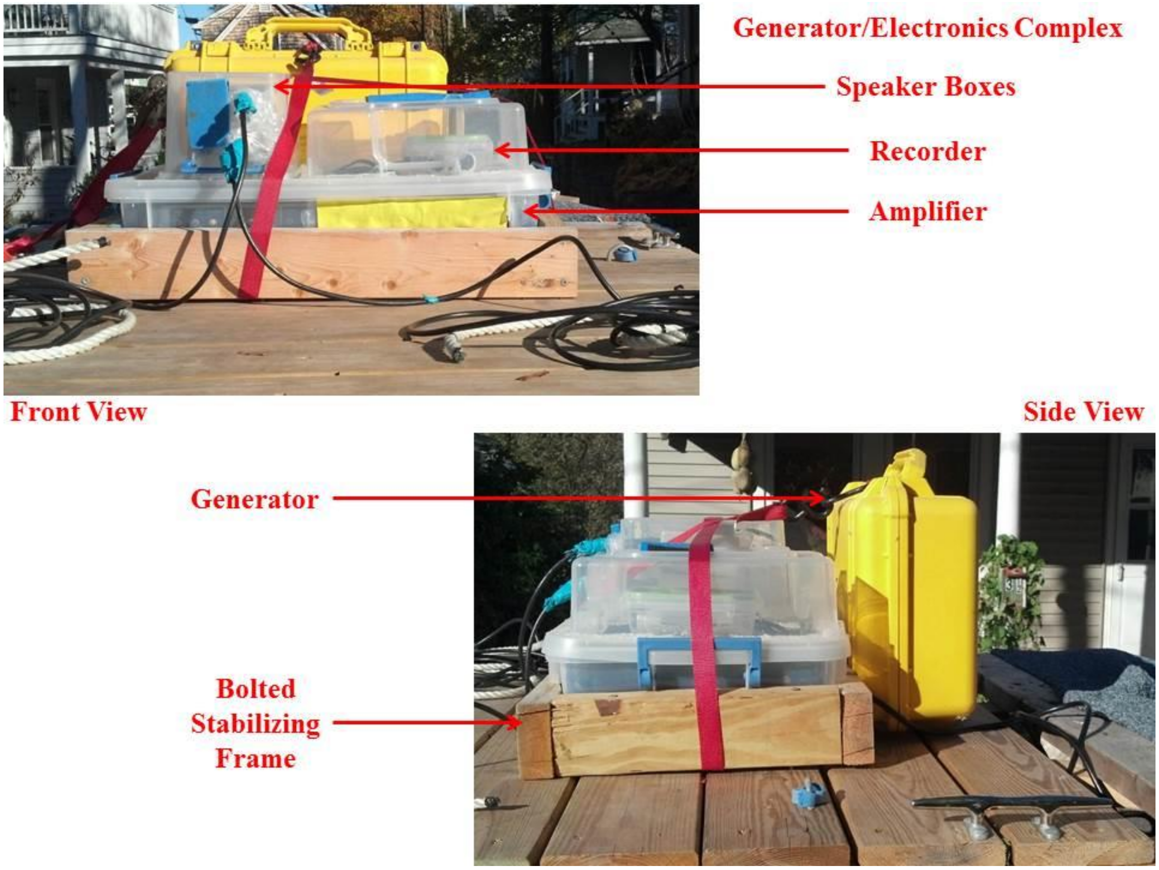


Figure C.7. Two Views of the Generator and Electronics Complex Secured to the Attachment Platform. The top view illustrates the location of each electronic component secured within the weather-resistant box. The bottom view illustrates the location of the secured generator and the electronic complex stabilizing frame bolted to the attachment platform deck.

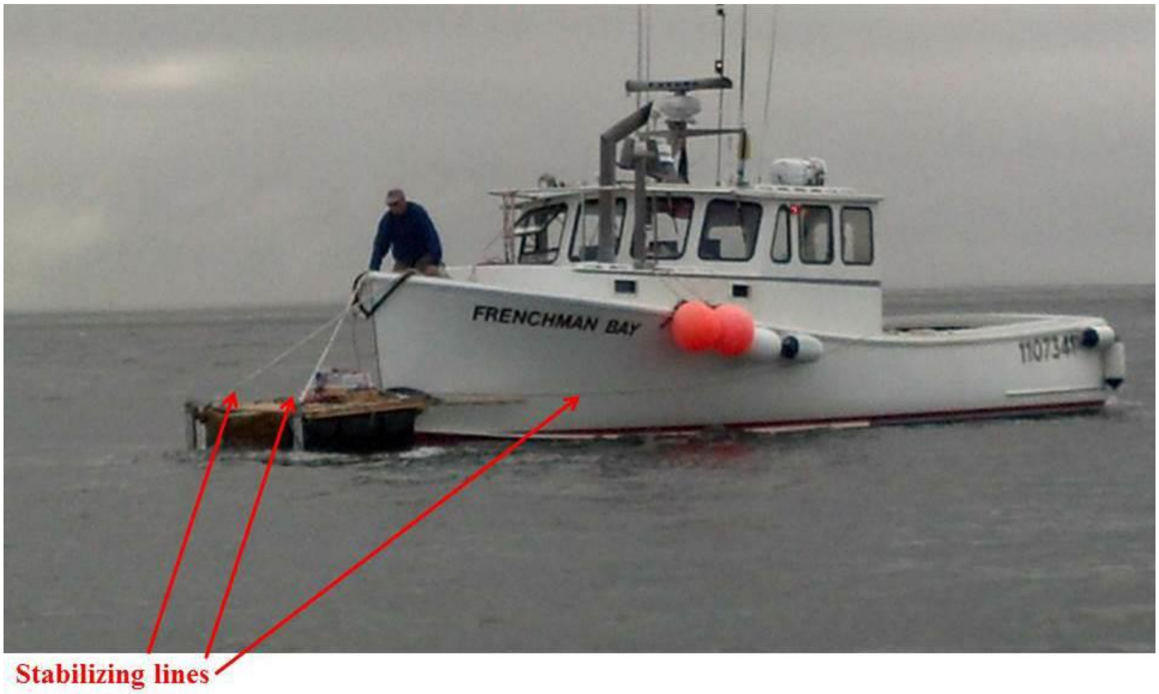


Figure C.8. Prototype Being Attached to Test Ship Frenchman Bay. Stabilizing lines are highlighted. Note that this test ship does not feature rub rails. As a result, the attachment platform tracks at an additional 0.6 meters depth compared to deployments on test ships that feature rub rails. This difference in speaker depth was accounted for during prototype testing.

BIOGRAPHY OF THE AUTHOR

Kaitlyn Allen Mullen was born in Richmond, Virginia on June 14, 1980. She was raised in Hanover County, Virginia and graduated from Patrick Henry High School in 1998. She attended Belmont University in Nashville, Tennessee and graduated in 1998 with a Bachelor’s degree in Music Business and Marketing. After touring as a singer/songwriter she moved to Maine to continue her education. Kaitlyn earned a second Bachelor’s degree in Marine Science at the University of Maine in 2006. She entered the interdisciplinary Ocean Engineering graduate program at The University of Maine in the fall of 2006. While a graduate student at the University of Maine, Kaitlyn also worked as a naturalist for the Bar Harbor Whale Watch Company and New Horizon Cruises, worked as a Marine Mammal Observer in the Gulf of Mexico, worked as a research associate with Allied Whale, and participated in marine mammal field work in the Gulf of Maine and the Cape Canaveral National Wildlife Refuge. As a result of her experiences, Kaitlyn earned her 100-ton master’s license in March 2010. She will likely continue working as a captain and naturalist after receiving her degree. Kaitlyn is a candidate for the Doctor of Philosophy degree, Interdisciplinary in Ocean Engineering from The University of Maine in December 2013.