Final Report

Research Project Title:
Measuring the acoustic detection range of large whales from an ocean glider to improve an acoustic whale alert system for use by the offshore marine industry in Atlantic Canada

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Summary

There is significant concern about the risk that offshore marine industries pose to endangered whales. These concerns were exacerbated by the unprecedented number of North Atlantic right whale deaths in 2017. Using a novel passive acoustic monitoring (PAM) system to alert ocean users to whale presence in near real-time can provide an effective mitigation strategy. Our research group is pioneering such a system in Atlantic Canada. The system uses autonomous ocean-going gliders and a specialized PAM system to detect, classify, and report whale calls back to shore at intervals of approximately every 2 hours ('near-real time'). When right, fin, humpback or sei whales are detected, the location of the glider can then be relayed to nearby vessels or platforms so they may take necessary precautions (e.g., reduce speed, avoid the area, suspend operations, etc.). A major limitation of most PAM systems, including ours, is the uncertainty in whale detection range relative to the glider. Determining detection range uncertainty is essential to effectively use PAM systems to monitor the presence and general locations of endangered whales and provide that information to nearby vessel/platform operators.

The primary objectives of the proposed research were to 1) evaluate the range-dependent accuracy of the near-real time whale alert system on a mobile platform (glider), and 2) determine species-specific detection range thresholds that can be applied to upcoming glider PAM deployments on the Scotian Shelf.

Over a 4 week period (28 Feb to 30 Mar) in the spring of 2017, we deployed a PAM-equipped Slocum glider and a hydrophone array alongside an extant PAM buoy at a shallow (30m) site approximately 15 km Southwest of Martha's Vineyard, USA. Issues from storm-induced noise and array movement restricted the analysis to high-quality right whale upcalls within the first two weeks of the deployment. During that time, the array recorded nearly 350 right whale upcalls, 75 of which we were able to localize using a normal mode back-propagation technique. We then conducted a call-by-call comparison between calls detected on the array and those detected by the glider or buoy to determine the probability of detection for each platform. Logistic regression analysis determined the 50% detection range (i.e., the range at which 50% of calls are correctly identified) for right whale upcalls was ∼6.5km for the buoy, and ∼10.5km for the glider, though the latter relationship was not statistically significant.

Further work must be done before these results can be generally applied to other areas. We are also continuing to refine and improve the signal processing techniques so that we may localize more calls and reduce the uncertainties in the detection probability functions. A third goal will be to use localization results to quantify aspects of whale acoustic ecology, including movement patterns, individual calling rates, source levels, and calling depths.

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1 Introduction

1.1 Background

North Atlantic right whales (NARWs) are at the brink of extinction. The latest published assessment, which includes data up to 2015, suggests that the population is in decline and numbers approximately 458 individuals, of which only about 100 are breeding females (Pace, Corkeron, and Kraus 2017). Unfortunately, we know those numbers have been further reduced. Since June of 2017, 18 NARWs have been found dead, 12 of which were in Canadian waters. Of the 6 Canadian carcasses where cause of death could be confidently determined, 4 were killed from vessel strike and 2 from entanglement in fishing gear (Daoust et al. 2017). A mortality event of this magnitude has not been documented since these whales were actively hunted.

Mitigation of anthropogenic impacts on NARWs and other at-risk species is critical, but challenging given the cryptic nature of whale behaviour and the limitations of conventional visual surveys. Using near real-time passive acoustic monitoring (PAM) to alert ocean users to whale presence in near real-time can provide an additional mitigation option. The Woods Hole Oceanographic Institution (WHOI) has developed a PAM system incorporating a low-frequency detection and classification system (LFDCS) that detects, classifies and reports the sounds of at-risk baleen whales (right, fin, sei, and humpback) in near real-time from autonomous platforms, including moored buoys and ocean gliders. The relayed information can be used by ocean users to dynamically plan their activities and minimize potential risk to endangered species.

Our research group has been using Slocum gliders equipped with the LFDCS system on the Scotian Shelf and in the Gulf of St Lawrence since 2014. The whale alert system has already demonstrated its usefulness as a mitigation strategy when the Royal Canadian Navy used near real-time alerts from our gliders to inform safe sonar and vessel operation activities during their international training exercise ‘Cutlass Fury’ on the Scotian Shelf in September 2016. Our collaborators, and the developers of the technology, at WHOI have demonstrated the success of the system in similar collaborations with the US Navy and Coast Guard. We envision the same alerts being provided in support of offshore industry and enforcement agencies on the Scotian Shelf through operational AIS-based delivery system using an Aid to Navigation (ATON) transceiver to be made operational within the next year.

A limitation of the LFDCS is the sound detection range uncertainty from the monitoring platform. The system currently relays only the position of the platform when a whale was detected and identified. This is a substantial limitation because the detection range may vary by an order of magnitude depending on the environmental conditions, signal type, source levels, PAM platform, etc. A more sophisticated and useful system that incorporates sound-range uncertainty will provide an estimate of the area wherein the detected call most likely originated.

1.2 Scientific Objectives

The primary objectives of the proposed research were to 1) evaluate the range-dependent accuracy of the near real-time whale alert system on a mobile platform (glider), and 2) determine species-specific detection range thresholds that can be applied to upcoming glider PAM deployments on the Scotian Shelf.

2 Methods

2.1 Study site

We deployed collocated horizontal and vertical line arrays of hydrophones and a Slocum electric glider at an extant monitoring buoy 15 km SW of Noman's Island, MA, USA from 28 Feb to 30 Mar 2017. The water depth was approximately 30 meters at the array, and remained relatively flat to a range of 15 km with the notable exception of a steep shoal near Noman's Island approximately 8-10 km NE of the deployment site (Figure 1).

2.2 Near real-time acoustic monitoring

Both the Slocum glider and monitoring buoy were equipped with digital acoustic monitoring instrument (DMON) hydrophones running the low-frequency detection and classification system (LFDCS; Baumgartner and Mussoline 2011) to facilitate near real-time monitoring of 4 species of baleen whales (right, fin, sei and humpback whales; e.g. Baumgartner and Mussoline 2011; Baumgartner, Fratantoni, et al. 2013). Briefly, the LFDCS algorithm produces smoothed spectrograms of the audio data, removes spurious broadband noise and continuous tonal noise, then uses a contour-following algorithm to create pitch tracks of tonal sounds from the spectrogram (Figure 2). It then sends a subset of these pitch tracks back to shore via iridium approximately every 2 hrs where they can be manually reviewed and scored by a trained analyst (Baumgartner and Mussoline 2011; Figure 3).

2.3 Acoustic array and localization

The vertical line array (VLA) contained 4 hydrophones with approximately 2 meter spacing between each element. These were all sampled at 8 kHz continuously for the entire deployment. The VLA also had two temperature loggers and a temperature-pressure logger positioned at intervals along the extent of the array to measure the water column structure, depth, and array tilt at 0.5 Hz throughout the entire deployment. The horizontal line array (HLA) contained 8 hydrophones with nearly 8 meter spacing between element. These were all sampled at 4 kHz continuously for the entire deployment. The HLA also had a single temperature-pressure sensor to record bottom water properties for the full deployment.

The HLA and VLA were deployed concurrently to facilitate call localization using a recently-developed normal mode back-propagation method (Lin, Newhall, and Lynch 2012; Newhall et al. 2012). The great benefit of this method is that it allows 3-d localization of low-frequency signals from a single station, as opposed to the distributed arrays used for conventional arrival time difference methods. The general steps of this localization workflow are to 1) isolate the call in the array data (Figure 4A), 2) use a normal mode model (Kraken; Porter 2016) and Pseudo-Inverse mode filter to isolate the modal arrivals of a given call at the VLA, (Figure 4C) 3) use the estimated group

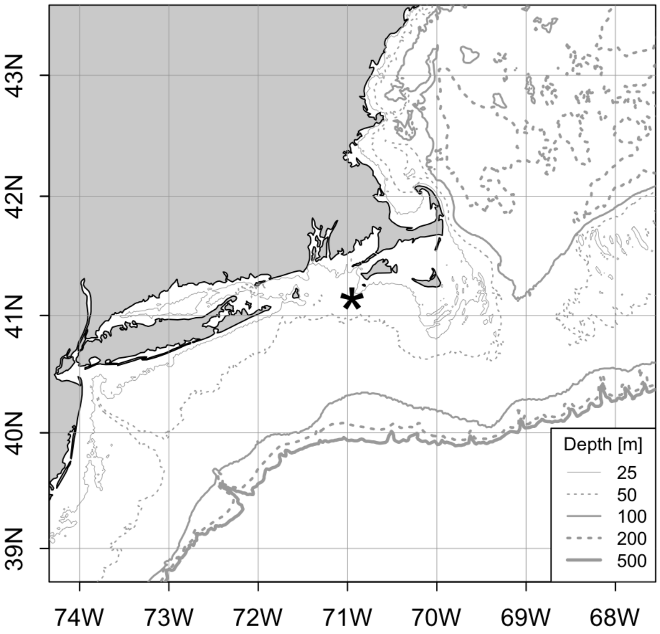

Figure 1: Study site (*) in 30m water depth ∼15 km SW of Nomans Island, MA, USA

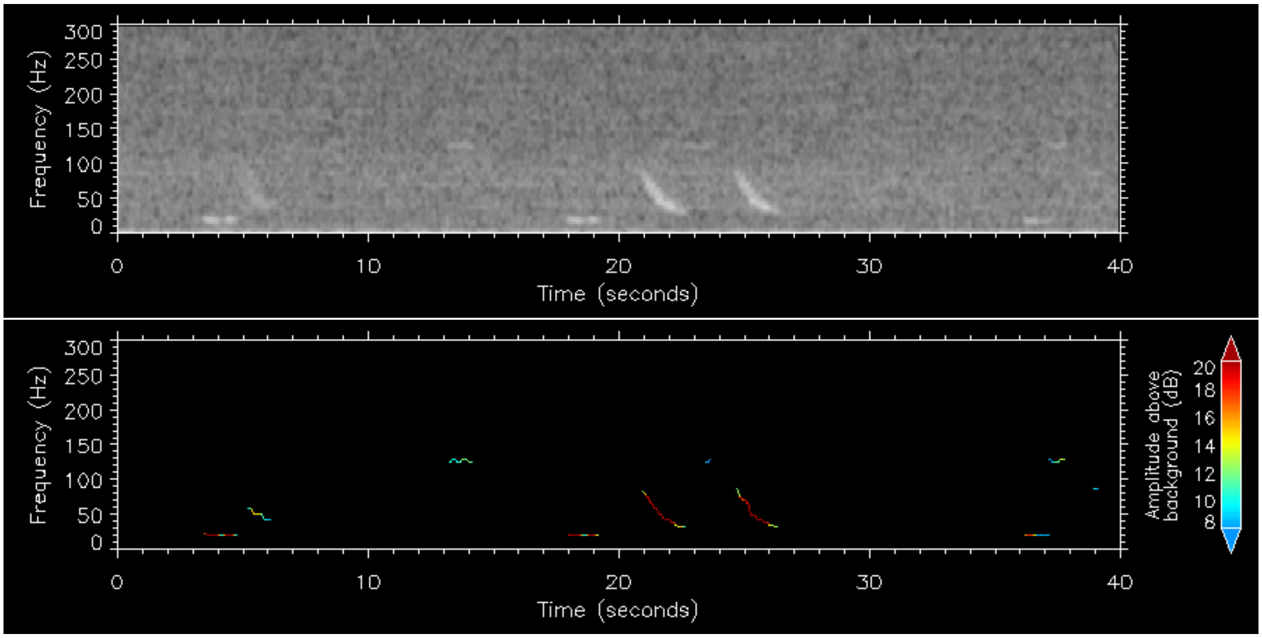

Figure 2: Spectrogram (top) versus pitch tracks (bottom) of sei whale calls (and several other tonal sounds) generated in real-time by the LFDCS

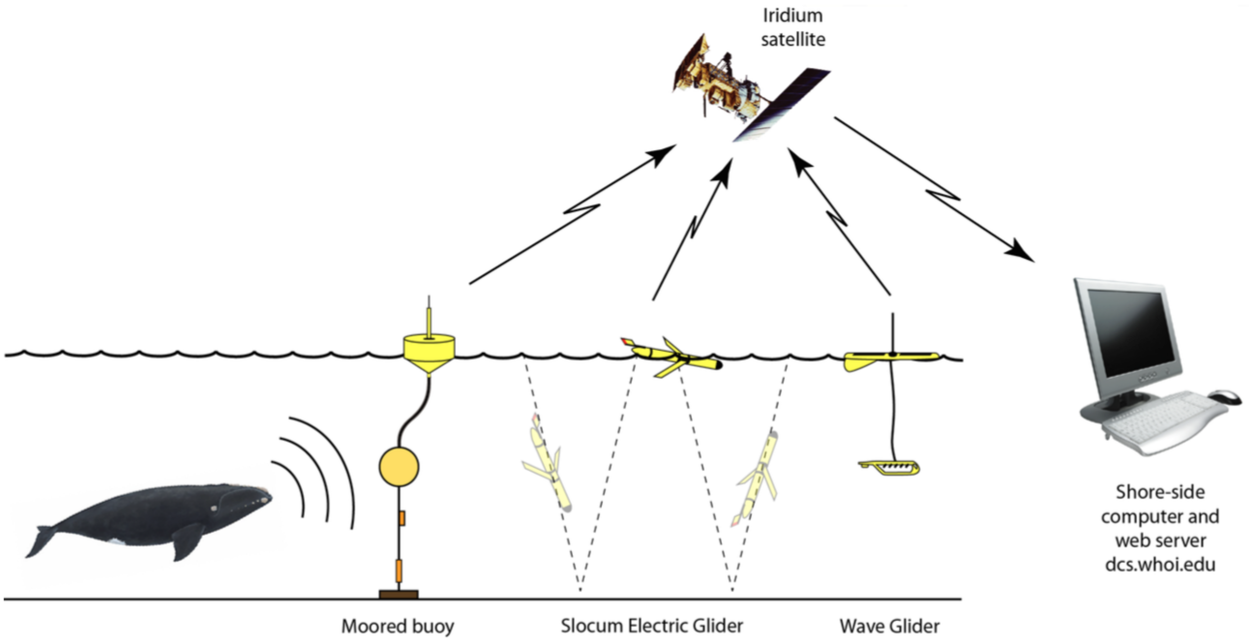

Figure 3: LFDCS platforms send pitch tracks and classification information back to shore for review

velocities of each modal arrival to beamform with HLA to determine the arrival angle (bearing) of the call (Figure 4B), 4) use the same mode model to estimate mode structures along the arrival path, then back-propagate the received signal along the arrival path until the two modes converge (Figure 4D). The range with greatest convergence represents the most probable range to the call (Figure 4E). For more detail on the methods see Lin, Newhall, and Lynch 2012, or see Newhall et al. 2012 for an application to sei whale localization.

2.4 Platform comparison and performance analysis

The benefits of a multi-channel system allow us to safely assume that the HLA/VLA will detect calls over a greater range than either of the two single hydrophone monitoring systems (e.g., the glider and buoy). As such, the HLA/VLA record was used as the ground truth for comparison between platforms. The full 12-channel acoustic record from the HLA/VLA was displayed as spectrograms and visually/aurally reviewed for whale calls. The pitch tracks from each LFDCS platform were independently analyzed for the presence of whale calls. The results from each monitoring platform were then scored based on their performance compared to the 'true' results from the HLA/VLA. Calls that were detected on the array, but missed on the buoy or glider were given a score of zero, while those detected on both were given a score of one. The series of scored pitch tracks, as well as the ranges to each localized call, were used to construct a logistic regression to quantify the range-dependent accuracy of each monitoring system.

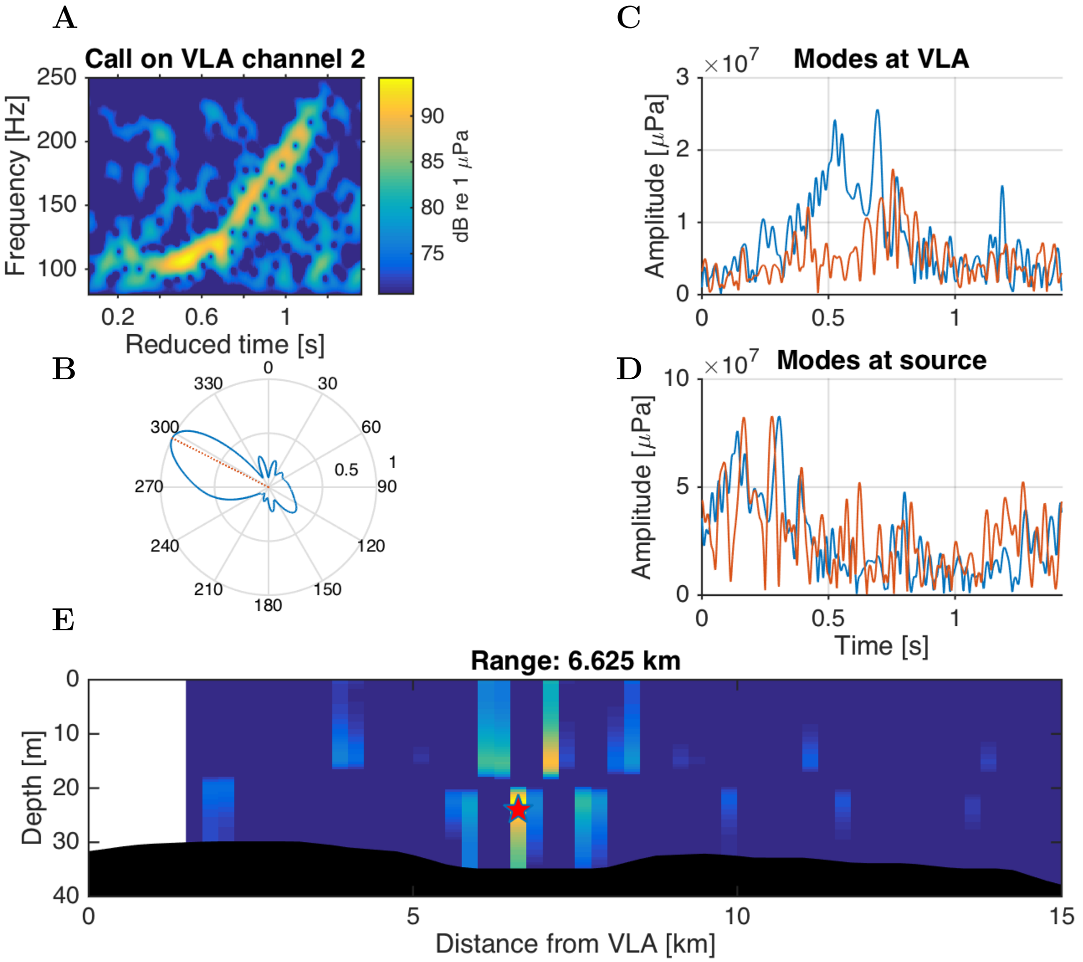

Figure 4: Example localization workflow for a single call showing the call spectrogram [A], beam pattern (blue) and arrival angle (red line) [B], received amplitudes of mode 1 (blue) and 2 (red) [C], back-propagated amplitudes of the same modes [D], and a normalized probability map of the back-propagation results [E]

3 Results

3.1 Storm-induced challenges

On two occasions (2-3 Mar and 14-15 Mar), storm-induced noise prevented effective acoustic analysis. On recovering the HLA after the study period, it became evident that the energetic input from storms was sufficient to move the array from its original position. We presume that this movement occurred during the second, more powerful storm event between March 14-15. Because of this movement, and the resulting uncertainty in the position of each hydrophone, we were unable to beamform to determine the arrival angle of incoming calls after March 14th. Wave action contributed to persistent acoustic energy below approximately 100 Hz on the VLA, which made call detection more difficult and occasionally prevented accurate localization (Figure 5).

3.2 Localization

The normal mode back-propagation technique requires 1) the excitation of 2 or more acoustic modes, and 2) sufficient dispersion of these modes such that they can be reliably filtered at the receiver. The cutoff frequency for mode 2 at the study site was approximately 80 Hz, which prevented localization of any calls with substantial energy at lower frequencies. This meant that right whale upcalls and (some) humpback whale calls were amenable to localization, but fin whale 20 Hz pulses and sei whale downsweeps were not. We chose to focus on right whale upcalls because they are highly stereotyped and reliably detected by the LFDCS, and because right whales are of substantial conservation importance. The requirement of modal dispersion imposed a minimum range limit of approximately 1.5 km for right whale upcalls. Calls originating from within this range did not exhibit sufficient modal dispersion to localize.

A total of 341 separate right whale upcalls were detected on the HLA/VLA over the two week period between 28 Feb and 14 Mar. The LFDCS on the glider and buoy convincingly pitch tracked 340 and 196 right whale upcalls, respectively, during the same period. Of the 341 calls detected on the array, 75 could be accurately localized. These 75 calls occurred throughout the monitoring period, but most (51) occurred on March 8th (Figure 6). The ranges to these calls ranged from 1.6km to 14.9 km on the buoy (median = 4.4 km), and from 0.7km to 15.2 km on the glider (median = 5.2 km; Figure 7).

3.3 Platform performance

The 75 localized calls were compared across platforms to determine range-dependent accuracy of the LFDCS. The buoy detected 41% (31/75) of calls while the glider detected 33% (19/58) of calls received by the array. Several calls (n=17) occurred during periods of noise caused by the activation of the glider buoyancy engine or air pump (i.e., when the glider was inflecting or at the surface) and were removed from the glider analysis. Figure 8 shows the distribution of calls detected (open circles) and missed (crosses) by each platform. Logistic regression analysis suggested that the 50% detection range (i.e., the range at which 50% of calls were detected) for the glider and buoy were 10.5 and 6.5 km, respectively, though the result for the glider was not statistically significant (Figure 9).

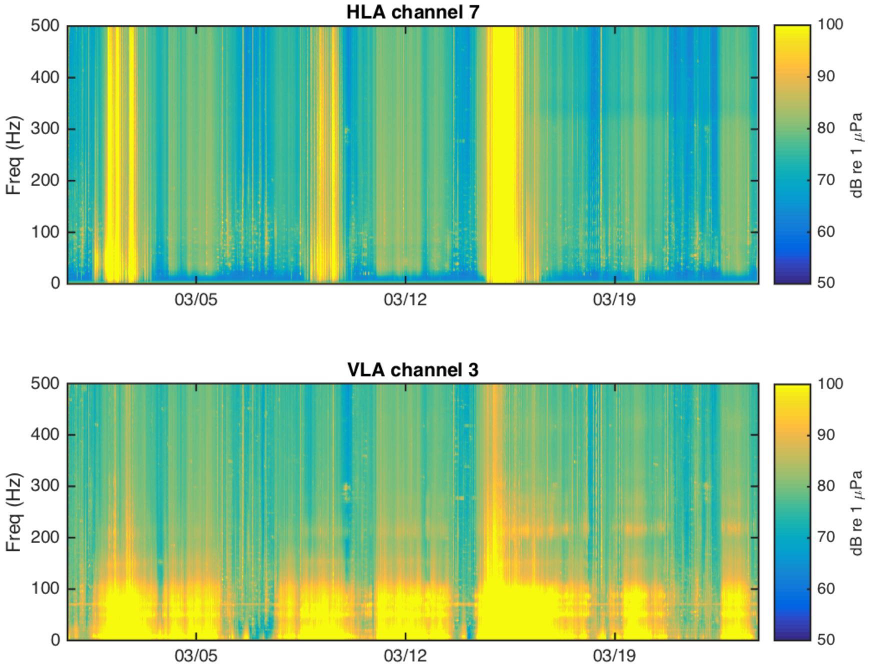

Figure 5: Acoustic energy received at the HLA (channel 7; top panel), and the VLA (channel 3; bottom panel) during the study period. Yellow banding across the full frequency range (most obvious on the HLA) indicates storm-induced noise.

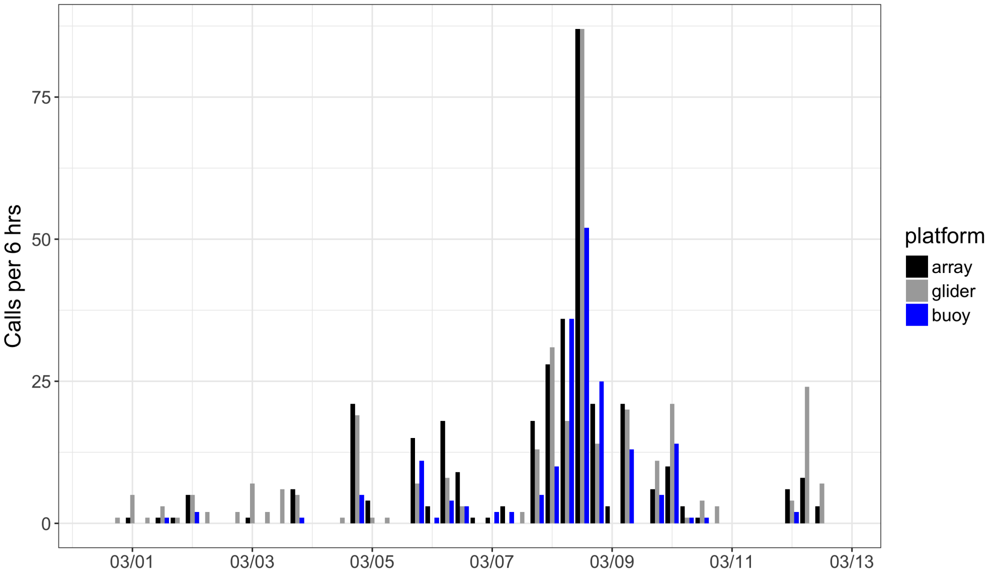

Figure 6: Detections of right whale upcalls from the WHOI array acoustic record (n=341) and the pitch track records from the DMON-LFDCS glider (n=340) and buoy (n=196)

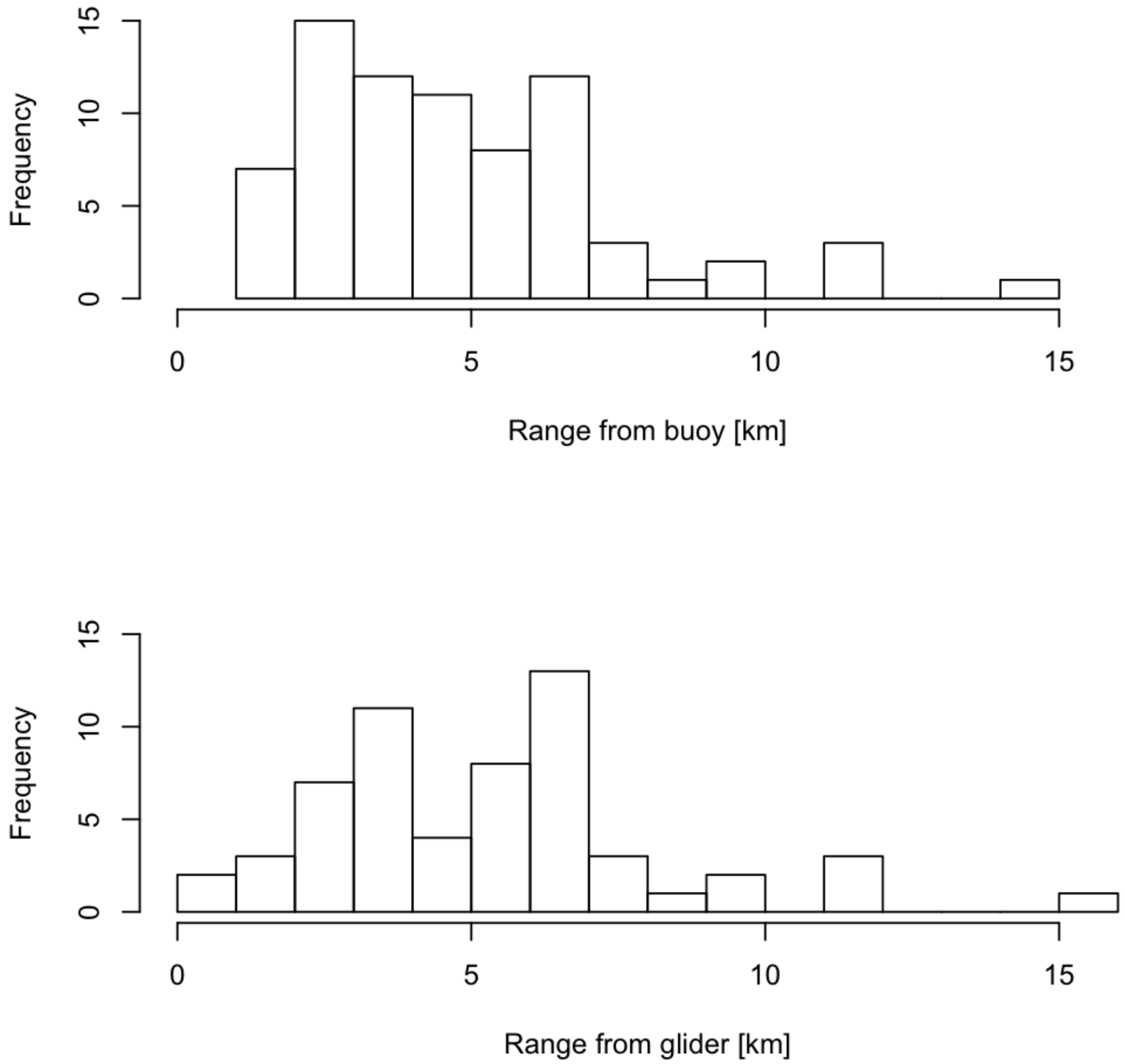

Figure 7: Distribution of ranges from the LFDCS buoy (top; n=75) and LFDCS glider (bottom; n=58) to calls localized by the HLA/VLA

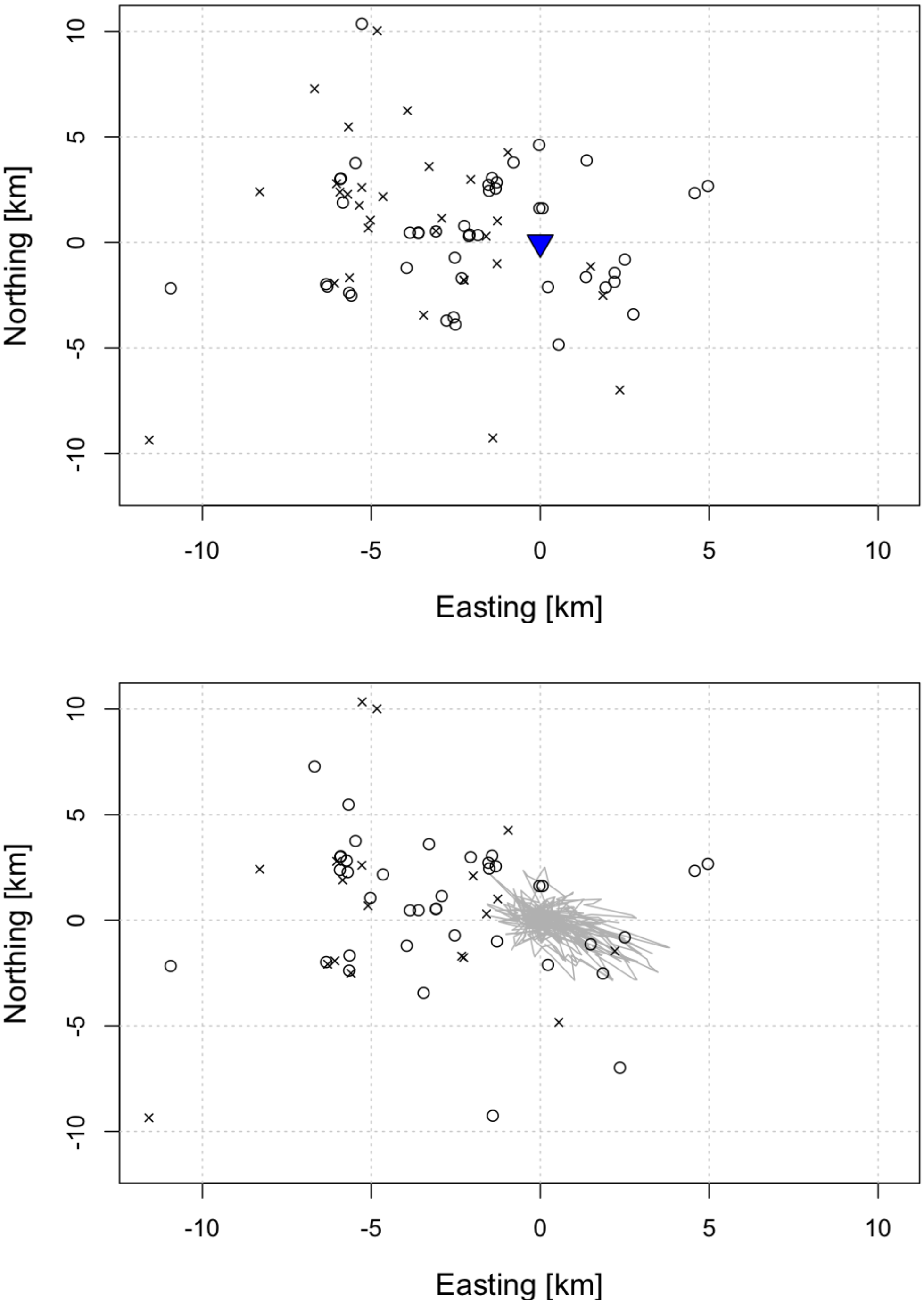

Figure 8: The spatial distribution of localized calls, with open circles and crosses indicating calls detected and not detected by the LFDCS platform, respectively. The top panel shows results from the buoy [blue triangle], while the bottom panel shows results from the glider [grey line]

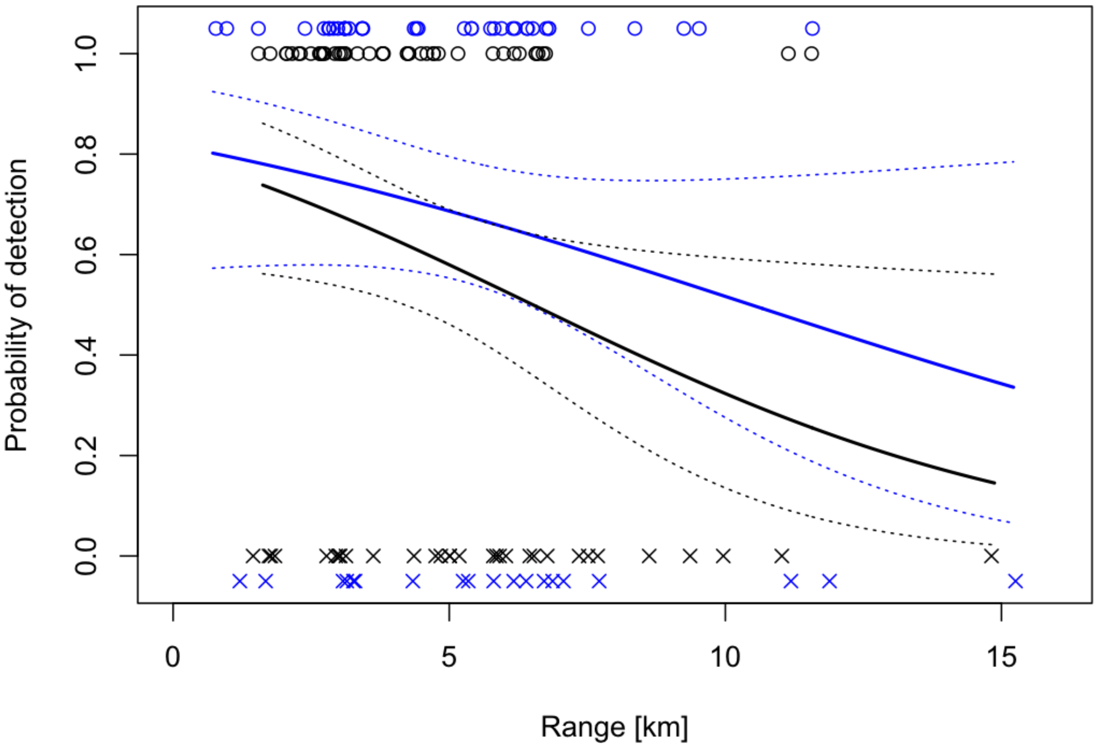

Figure 9: Probability of detection of right whale upcalls by the LFDCS as a function of range to the buoy (black; n=75) and glider (blue; n=58). The open circles and crosses indicate calls detected or undetected on either platform, respectively. Logistic regression analysis suggests detection probability for the buoy declines significantly with range (p = 0.033), but the relationship is not significant for the glider (p = 0.152). The regression model predictions are shown as solid lines, with 95% prediction intervals shown as dotted lines.

4 Conclusions, Recommendations, and Future Work

The results from this study have revealed new insights about the performance of the LFDCS and helped identify ways in which the system can be further improved. Despite challenges introduced by several powerful storms during the study period, we were able to successfully address our first objective of characterizing the range-dependent accuracy of the system for right whales. Even though gliders appeared to have a slightly greater detection range than the moored buoy, the two platforms were statistically indistinguishable, and had above a 50% chance of detecting a given right whale call out to a range of 6-10 km. The approximately equal performance of these platforms emphasizes the efficacy of the noise-abatement strategies used in the design of the buoy, and further highlights the potential for using buoys in areas where long-term, persistent monitoring is important. These results allow us to confidently continue to recommend the LFDCS as a viable real-time acoustic whale monitoring and risk mitigation tool.

We are continuing to pursue our second research objective of embedding range information within a whale alert message. This is currently feasible within the study area, but the detection probability functions derived here are not directly applicable to other areas. The generalization of these relationships requires substantial knowledge of the physical environment and whale acoustic behaviour that is difficult to acquire without measuring it directly. We are currently exploring the possibility of using a model-based approach to better understand how to apply what we have learned here to other areas.

A great deal more can be learned from this dataset. The first goal will be to use more advanced signal processing techniques to attempt to identify and localize more calls from periods compromised by storm-induced noise. Hopefully this will allow us to strengthen the probability of detection relationships, and better discriminate between the performance of the two platforms. A second goal will be to use this dataset to improve the performance of the LFDCS. An unexpected result that emerged from this work is that the empirical detection probability functions (Figure 9) do not reach a value of 1 at minimum ranges. The most likely explanation for this is that a factor other than range is responsible for missed detections. This dataset provides us with the ability to isolate, understand, and correct the factor(s) responsible for these missed detections, which will help us ultimately improve the performance of our detection system. A final goal is to use localization results to quantify unconstrained aspects of right whale acoustic ecology, including movement patterns, individual calling rates, source levels, and calling depths.

5 Dissemination and Technology Transfer

Our results are forthcoming and preliminary, but we have already taken several opportunities to disseminate the insights we have gained so far, and have plans to continue doing so as the results mature. The following are the upcoming and completed presentations that draw upon insights gained from this experiment:

Upcoming

1. Johnson HD. 'Measuring the acoustic detection range of large whales from autonomous platforms to improve an acoustic whale alert system'. Invited presentation for the 2018 OERA

webinar series. Halifax, Nova Scotia, October 2018

2. Johnson HD, M Baumgartner, Y-T Lin, A Newhall, D Barclay and CT Taggart. 'Calibrated passive acoustic monitoring: probability of North Atlantic right whale acoustic detection as a function of platform and environment'. Anticipated abstract submission for 2018 DCLDE workshop. Paris, FR June 2018

Completed

1. Johnson HD, M Baumgartner, Y-T Lin, A Newhall, and CT Taggart. 'Characterizing the range-dependent accuracy of a near real-time baleen whale monitoring system'. Poster presentation at the 2018 Ocean Sciences Meeting. Portland, Oregon USA February 2018
2. Johnson HD. 'Robots and whales: autonomous gliders as platforms for passive acoustic monitoring of marine mammals'. Oral presentation at the Passive Acoustic Monitoring workshop at the 22nd Biennial Conference on the Biology of Marine Mammals. Halifax, Nova Scotia October 2017

6 Publications

We are in the process of preparing the following manuscript that draws heavily on the results of this experiment, and also will comprise a chapter of H Johnson's PhD thesis at Dalhousie.

1. Johnson HD, M Baumgartner, Y-T Lin, A Newhall, D Barclay and CT Taggart.(*In preparation*). 'Calibrated passive acoustic monitoring: probability of North Atlantic right whale acoustic detection as a function of platform and environment'.

We will make all efforts to ensure that OERA is properly attributed and notified about any and all publications resulting from this project.

7 Expenditures of OERA Funds

We were successful in securing all the cash and in-kind contributions that were listed in our proposal. These contributions total $434,619, and are itemized in Table 1 (taken directly from the proposal).

Table 2 outlines the budgeted items and final project expenditures. No funds were spent on salary because Johnson's salary was covered by an external scholarship. No funds were allocated to dissemination because these results have not yet been submitted for publication. Additional travel funds were spent to enable Johnson to present these results at the 2018 Ocean Sciences Meeting in Portland, Oregon, USA. All of these deviations from the proposed budget were approved by the OERA program manager.

9 References

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