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14. ABSTRACT
This report documents the development and implementation of a density estimation methodology for quantifying blue and fin whale abundance from passive acoustic data recorded on sparse hydrophone arrays. Data from the Comprehensive Nuclear Test Ban Treaty Organisation were used, as well as recordings from Ocean Bottom Seismometers. The method relies on estimation of bearings to calling animals, as well as estimates of the source levels of the animals' calls and information about how often animals call. All of these topics were addressed during the project.

15. SUBJECT TERMS
Passive acoustic monitoring, animal density estimation, blue and fin whales, sparse hydrophone arrays

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Large Scale Density Estimation of Blue and Fin Whales (LSD)

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LONG-TERM GOALS

Effective management and mitigation of marine mammals in response to potentially negative interactions with human activity requires knowledge of how many animals are present in an area during a specific time period. Many marine mammal species are relatively hard to sight, making standard visual methods of density estimation difficult and expensive to implement; however many of these same species produce vocalizations that are relatively easy to hear, making density estimation from passive acoustic monitoring data an attractive, cost-effective alternative. A particularly efficient passive acoustic monitoring design is a “sparse array”, where sensors are distributed evenly over a large area of interest – however a consequence of this design is that each vocalization cannot be heard at multiple sensor locations, restricting the choice of methods that can be used to estimate density. Nevertheless, sparse array methods have been developed and demonstrated (Marques et al., 2011, Küsel et al., 2011; Harris, 2012; Harris et al., 2013). While these studies represent an important step forward in making the methods more generally applicable at reasonable cost, they have some drawbacks: they either are only applicable to small local ocean areas, or they require unrealistic assumptions about animal distribution around the sensors, or both. The goal of this research is to develop and implement a new method for estimating blue and fin whale density that is effective over large spatial scales and is designed to cope with spatial variation in animal density utilizing sparse array data from the Comprehensive Nuclear Test Ban Treaty Organization International Monitoring System (CTBTO IMS) and Ocean Bottom Seismometers (OBSs).

OBJECTIVES

This effort develops and implements a density estimation methodology for quantifying blue and fin whale abundance from passive acoustic data recorded on sparse hydrophone arrays in the Equatorial Pacific Ocean at Wake Island. It builds on previous work with sparse arrays of OBSs. Density estimation methods developed in the Pacific Ocean at Wake Island can then be applied to the same species in the Indian Ocean at the CTBTO location at Diego Garcia.

Specific objectives are as follows:

1. Develop and implement methods for estimating detection probability of vocalizations based on bearing and source level data from sparse array elements.
2. Validate using OBS data, where additional independent information on detectability is available.
3. Use all available and relevant data to develop multipliers for converting calls-per-unit-area to blue and fin whale density – i.e., estimates of average call rate.
4. Estimate the regional density and spatial distribution of blue and fin whales in the Equatorial Pacific Ocean, using CTBTO data from Wake Island.
5. Estimate regional density and spatial distribution of blue and fin whales in the Indian Ocean, using CTBTO data from Diego Garcia.

APPROACH

Researchers at the University of New Hampshire (formerly of ARL Penn State) are working collaboratively with the Centre for Research into Ecological and Environmental Modeling (CREEM) at the University of St. Andrews. The St. Andrews team provides expertise in density estimation techniques from passive acoustic datasets, while collaborators at UNH provide the long-term data series and expertise in marine mammal biology, acoustic processing, ambient sound, and sound propagation. This project leverages multiple research products from previous and current funding from ONR, Navy Living Marine Resources (LMR) Program, NOAA, JIP, and the UK Defense Science and Technology Laboratory (DSTL). Low frequency (1-120 Hz), continuous data recorded by the CTBTO IMS for over or close to a decade at Diego Garcia (2002-present: Indian Ocean), and Wake Island (2007-present: Equatorial Pacific Ocean) have been acquired under an ONR YIP Award N000141110619 to Miksis-Olds. A near real-time portal has been opened between ARL PSU and the AFTAC/US NDC (Air Force Tactical Applications Center/ US National Data Center) to continue to download data from these two locations. The density estimation method development builds on the work of Danielle Harris (PhD work funded by UK DSTL; Cheap DECAF project funded by ONR N00014-11-1-0615) and Len Thomas (DECAF project, funded by NOAA and JIP through NOPP).

The CTBTO IMS instrument configuration of hydrophone triads suspended in the deep sound channel allows for call bearing and, in some cases where the vocalizing animal is close, localization (Harris 2012; Samaran et al., 2010). This, together with received level, allows the distribution of animals to be estimated without requiring randomly placed multiple instruments. With over a decade of time series data, bearings and received levels of a large number of calls can be estimated. These data, coupled with estimates of call source levels and sound propagation models in the study area, are being used to estimate the distribution and density of calling whales in the monitored area. A detailed detector characterization gives the probability of detection as a function of signal-to-noise ratio (SNR), and hence we are able to estimate probability of detection for each received call. Spatio-temporal variability in the efficiency of the automatic detector is also addressed. Call "abundance" at the location of each call is then estimated with a Horvitz-Thompson-like estimator, where each detected call is scaled by its associated probability of detection to account for undetected calls also produced at that location (Borchers et al., 2002; Thompson 2012). The resulting estimates are smoothed in space with a Generalized Additive Model (GAM) to give an estimated density surface (Wood, 2006). Taken together, this represents a novel approach to density estimation that has wide applicability.

Density estimation from passive acoustic recorders relies heavily on the detection of vocalizations above the noise and knowledge of the acoustic coverage (or active acoustic space) of each passive acoustic sensor. Sound propagation characteristics and ambient noise dynamics are site specific and highly time dependent, so an acoustic propagation model that incorporates the changing acoustic and oceanographic conditions is applied to calculate the acoustic coverage over time for each sensor. Noise level is likely the most variable factor affecting the range of acoustic detection. Sound levels at Wake Island over the past 5 years show frequency-dependent seasonal patterns (Miksis-Olds et al., 2015), so a seasonal component is included in the optimal acoustic coverage model. SNR detection thresholds are assessed on a subset of calls each year and monitored over the duration of the dataset to assess any long-term changes. There is evidence that tonal blue whale calls are decreasing in frequency over time (McDonald et al., 2009), which is why it will be necessary to verify SNR detection thresholds and adjust detectors as needed.

In addition to understanding the time-varying environmental components influencing call detection, use of the most appropriate source levels is critical to computing accurate detection ranges and final density estimations. Localized calls (from nearby animals) on a given CTBTO array provides a distribution of regional source level estimates. This is preferable to source level estimates taken from the literature. The developing density estimation method is also highly dependent on call rate inputs, which are used in the development of species specific multipliers for converting the number of detected calls to the estimated number of animals. Blue and fin whale call production rates are best estimated from tagged animals, and DTag (digital acoustic tag) data are available for blue and fin whales through ongoing ONR projects, where we are currently communicating with the project PIs to acquire realistic call rate information.

Quantifying uncertainty in estimates is as important as obtaining the estimates themselves. Our inputs to the acoustic modeling include a distribution on source and noise levels. Uncertainty in these inputs is cascaded through the acoustic modeling, and combined with variance estimates for detector performance and call rates to provide a robust estimate of uncertainty in density. An example of this kind of uncertainty propagation is given by Harris (2012, Chapter 6).

The use of bearing data is a new density estimation methodology, and we will use OBS array data in a pilot study. An array of 24 instruments was deployed off the coast of Portugal for 12 months in 2007/2008. Each OBS has a sampling rate of 100 Hz and many fin whale calls have been detected (Harris, 2012). Both range and bearing to each call can be estimated using the OBS array (Harris et al., 2013), providing an ideal dataset with which to compare the new method with an existing robust density estimation method. Using this array, density results obtained using bearing data can be directly compared with density results obtained using standard distance sampling.

WORK COMPLETED

Objective 1: Method Development

Since the start of the project in FY14, the density estimation approach detailed above using bearing and SNR data to estimate abundance and density has been developed, tested via simulation and applied to several datasets. The method for has been developed using R, an open-source statistical software package (R Core Team, 2018). Both a simulation and analysis tool have been created. The simulation tool allows users to run simulations specific to their study site, study species, and detection process. This allows an assessment of the size of the monitored area, given the signal of interest's source level, local transmission loss properties, and the efficiency of the automatic detector ahead of data collection. The simulation tool also allows users to assess the level of bias that may occur at the data analysis stage and at what monitoring range the bias is minimized. Simulations can be developed for different distributions of animals around the instrument. The analysis tool uses the same method implemented in the simulation code, but allows users to input their collected survey data.

All method development has been supported by extensive acoustic data processing by the UNH team. Over the course of the project, CTBTO data from both Wake Island and Diego Garcia have been processed to provide automatic detections of fin whales with associated received and noise levels, as well as bearing and source level estimates where possible. At Wake Island, ambient noise levels were also assessed in each minute for the whole dataset. Further, a subset of the Wake Island data was manually checked to assess detector performance (linking probability of detection to SNR). Site- and season-specific transmission loss data were also provided using the OASIS Peregrine parabolic equation model for both sites.

Under Objective 1, work in FY18 has seen the revision, acceptance and publication of Harris *et al*., (2018). This paper details the developed method and demonstrates the approach using a pilot dataset from CTBTO data recorded at Wake Island between December 2007 and February 2008. During the revisions, part of the method concerning the estimation of the size and shape of the monitored area was adjusted. The monitored area was initially determined using simulated calls, which were subjected to a detection process based on the real detection scenario at Wake Island. Calls that were never detected by the hydrophone were considered to be acoustically masked from the hydrophone and their locations were omitted as part of the monitored area. However, this approach is subject to variation caused by the simulation i.e., the answer may change depending on the number and locations of the simulated calls. Therefore, a deterministic method was used instead, where the probability of detecting a call with a high source level in quiet noise conditions (defined by taking the 90th and 10th percentile from the source and noise level distributions used in the analysis, respectively) was estimated around the hydrophone. Locations where the detection probability fell below a threshold (0.1 was used in the pilot study) were considered to be masked and omitted from the monitored area. Key results from the paper are given below in the results section.

Objective 2: Validation study using Ocean Bottom Seismometers

Over the course of this project, under Objective 2, work has been ongoing to utilize the same OBS dataset analyzed during the Cheap DECAF project (N00014-11-1-0615). One of the challenges of the OBS data concerned range estimation outside a critical range from a given OBS instrument, determined by water depth. The algorithm used to estimate range returns spurious estimates for calls occurring outside the critical range. In particular, incorrect ranges could affect density estimation analyses using distance sampling. Therefore, a variety of selection criteria based on various metrics measured from detections were examined in the Cheap DECAF project to try to identify such calls and eliminate them from further analyses (Matias & Harris, 2015). In this project, further investigation of the selection criteria was continued, to try to minimize the number of criteria whilst eliminating calls outside the critical range.

In FY18, range estimates from OBS data were also re-estimated using (a) more detailed information about the sound speed profile and sediment properties at the deployment site and (b) an adjustment for differences in gain between the vertical seismometer channel and the hydrophone (as discussed in Matias & Harris, 2015). Further, a filtering step was removed that had been found to affect the measurement of the hydrophone amplitudes, which were needed for the bearing-only method.

The distance sampling analysis first reported in FY17 was re-run using the re-processed data. Using data from the hydrophone channel on OBS19 (the focal OBS instrument for the comparison study) from December 2007 – February 2008, absolute detection azimuths, source levels, noise levels and the SNR detector threshold (as part of the detector characterization analysis) were estimated. The bearing-only method was re-run for the same months of data as the distance sampling analysis. The same estimates of false positive proportion and call production rates, as well as monitoring effort, were applied to the results of both analyses to estimate animal density.

Objective 3: Developing Multipliers

Cue production rates

Cetacean acoustic cue (i.e, calls or clicks) production rates are difficult to estimate and likely vary between sites, species and seasons. Therefore, using estimates from the literature may be biased, leading to incorrect animal density estimates. As part of this project, spatio-temporal variation in cue rates was investigated using the most comprehensive cetacean dataset available, which was from acoustic tags deployed on Blainville's and Cuvier's beaked whales in several years at different sites. Though these are different species from the target species of this project, the conclusions of this study are relevant for any density analysis that relies on cue rates. Spatial variation in click production was detected in both species, and Cuvier's beaked whales also showed temporal variation (Warren *et al*., 2017).

During the project, the team has also liaised with other researcher working with call production rate data from blue and fin whales, including Ana Sirovic and John Calambokidis as they progress in their ONR funded work "Behavioral context of blue and fin whale calling for density estimation" (Award N000141410414).

In 2015, a paper on fin whale call production rates from the Southern California Bight in the Pacific was published (Stimpert *et al.*, 2015). As no call production rate data were available for fin whales occurring near Wake Island, we used the call production rate from Stimpert *et al.* (2015) to produce preliminary animal density estimates at Wake Island and in the OBS validation study. However, the resulting animal density estimates must be treated cautiously. The fin whale data from southern California were collected in summer months, and so it is possible that this call production rate is biased for fin whales calling near Wake Island in the winter months. It is also likely the incorrect call production rate to use for Atlantic animals recorded by the OBS instruments, so these animal estimates should be considered a rough indication at best.

Fin Whale Source Level

Throughout the project, source levels of fin whales have been estimated at both Wake Island and from the OBS data.

In FY18, during the review process of the newly published pilot and simulation study (Harris et al., 2018), questions related to the source level estimations from the Wake Island data were raised. To address the reviewer comments, and because accurate source levels are critical to the density estimation methods, a more detailed analysis of the final whale source levels within the pilot data was conducted.

Source level is a vital parameter for animal density estimates from passive acoustics data and directly relates to successfully completing Objectives 3-5. Based on the results of the additional source level analysis in the pilot study, more in-depth analysis of fin whale source levels was conducted for the full Wake Island dataset from 2007-2013. Analysis of fin whale source levels at Wake Island from 2007-2013 included: 1) verification of the false alarm rate of the automatic detector to ensure fin whale source levels were not biased by false alarms, 2) down selecting of automatically detected calls and associated estimated source levels by only including those calls with an associated bearing, 3) calculating each estimated source level by applying spherical and Peregrine modelled transmission loss, and 4) assessing the any relationships between source level, bearing, and range.

Objective 4: Density and spatial distribution of whales at Wake Island in the Pacific Ocean

The full dataset at Wake Island (2007 – 2013) was used to estimate fin whale density in each year. Year-specific source level and noise level distributions and false positive proportions were estimated. The same detector characterization model was used across years due to similarity of the relationship between detection probability and SNR across years and sample size limitations. The transmission loss model was also assumed to be the same across years, though model outputs from both fall and winter were averaged, to reflect that the analysis was conducted over both seasons.

Objective 5: Seasonal distribution of whales at Diego Garcia in the Indian Ocean

Progress continues to be made in applying the methodology used with fin whales at Wake Island to both fin and blue whales at Diego Garcia. Last year seasonal fin whale detections from Diego Garcia recordings were assessed during the literature-documented seasonal migration period from Aug-Nov in the years 2007-2009. The full Diego Garcia year-round dataset (2007-2013) was processed this year for fin whale calls, as numerous detections outside the historical migration period indicated fin whale vocal presence in initial detection records.

Effort has also been made this year to apply the methods developed with fin whales to Sri Lankan blue whales. Initial simulations conducted during method development were based on Sri Lankan blue whale calls (reported on in FY15). However, previously ONR funded work under Award N000141110619 showed that the dominant frequency of the most salient Unit 3 song component had decreased in frequency over the decade analyzed. These results impact application in the developed density estimation methods because the same automatic detector cannot be used each year, as in the case with fin whales. To examine this further for future automatic detectors in support of density estimation, the rate of decrease in the Unit 3 call was quantified using a regression analysis. In addition, the frequency characteristics of a second song component (Unit 2) was assessed over the same time period.

RESULTS

Objective 1: Method Development

Key results from the recently published paper are:

- Analyses of simulated animal distributions showed that the method could achieve estimated densities with less than 2% bias.
- Analysis of the pilot study data gave a call density estimate of 0.02 calls.hr^{-1}.km^{2} with a coefficient of variation (CV) of 15%.
- Applying a tentative call production rate from the literature (Stimpert *et al*., 2015) gave an estimate of 0.54 animals/1000 km^{2} (CV: 52%). Note that the uncertain call production rate estimate lead to an increased overall variance associated with the density estimate.
- The predicted monitored area around the CTBTO hydrophone was much more restricted than originally anticipated given that the hydrophone is moored in the deep sound channel. Further, the monitored area was not circular or continuous, highlighting the important of determining the size and shape of the monitored area in passive acoustic surveys.
- Calling animals detected around Wake Island showed a non-uniform spatial distribution, with the majority of the detections being measured between 90 and 180 degrees.

Objective 2: Validation study using Ocean Bottom Seismometers

Further analysis of the OBS selection criteria suggested that two values, SNR and coherency of the signal on the vertical and horizontal OBS channels, were valuable in (1) removing false positive detections (SNR) and (2) identifying calls produced outside the critical range (positive coherency values indicated calls from within the critical range). These criteria were used to re-process the OBS dataset.

The distance sampling analysis was conducted in program Distance 7 (alpha 1). A multiple covariate distance sampling analysis was run using OBS depth as a covariate in the statistical model that predicts detection probability as a function of range (the detection function). This allowed the appropriate average detection probability to be estimated specifically for OBS19. A hazard rate detection function was selected using Akaike's Information Criterion to inform model selection. A quantile-quantile plot (QQ plot) was also used to assess model goodness-of-fit. Based on the QQ plot, the distance data were truncated at 3500 m. The estimated average probability of detecting a fin whale call within 3500 m of OBS19 was estimated to be 0.87.

The bearing-only method was run using the same detections, and their associated absolute azimuths and received levels on the hydrophone channel. Most of the detections occurred between 90-180 degrees (reported in FY17). Using root-mean-squared (RMS) amplitudes from the hydrophone channel on OBS19, source levels were estimated from 69 manually verified calls. Source levels ranged between 177 and 195 dB re 1 μPa^2 (mean averaged in dB 187.9 dB re 1 μPa^2). If the distribution was first averaged on the linear intensity scale, then the mean is 189 dB re 1 μPa^2.

The range of RMS noise levels associated with all fin whale calls, whether detected or not, was 101 – 125 dB @ 1 μPa^2. The mean and standard deviation, taken on the dB scale, were 110 and 3 dB @ 1 μPa^2, respectively (n = 1223). The RMS noise levels associated with the detected calls in the whole OBS19 dataset during the pilot period were between 96 and 120 dB @ 1 μPa^2.

A manually verified sample of fin whale calls across multiple OBS instruments throughout the pilot study period were assessed in order to estimate the detector characterization curve. The resulting predicted relationship between SNR on the hydrophone channel and the probability of being detected is given in Fig 1.

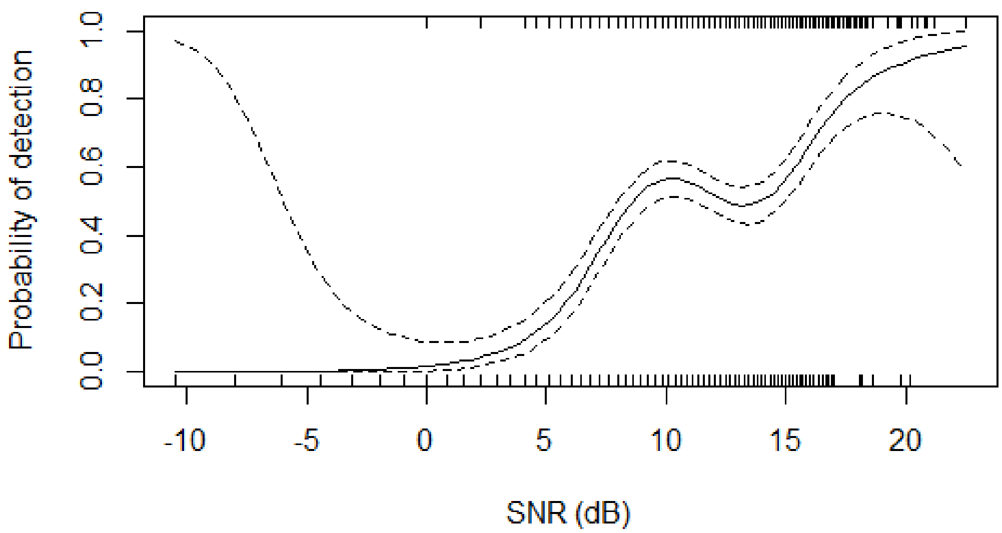

Figure 1. The predicted relationship between SNR (dB) on the hydrophone channel and probability of detection, modelled using a Generalized Additive Model.

The bearing-only method was run assuming a maximum detection range up to 6420 m, which is the nearest distance in the transmission loss model output to the critical range of OBS19 (6463 m). The results predicted that the average probability of detecting a fin whale call within this range was 0.08.

Both methods were used to estimate both call and animal densities. Both methods used the same false positive proportion of 0.15 (coefficient of variation, CV: 0.03) derived from a check of 322 manually verified detections from OBS19. The same monitoring effort of 2184 hours (Dec 07 – Feb 08) was used, as well as the call production rate estimated from data given in Stimpert *et al* (2015), which was 45 calls/hr (CV: 0.49), The bearing-only method density was predicted within 3500 m, to be comparable to the results from the distance sampling analysis.

Call density estimated using distance sampling was 0.36 calls/hr/km^2 (CV: 0.02, 95% confidence interval: 0.36 – 0.38). Call density estimated using the bearing-only method was 1.12 calls/hr/km^2. The predicted spatial distribution of calling animals is given in Fig 2. Animal density estimated using distance sampling was 8 animals/1000 km^2 (CV: 0.50, 95% confidence interval: 3 – 20). Animal density estimated using the bearing-only method was 24 animals/1000 km^2. Variance for the bearing-only method was estimated using a bootstrap procedure, where the distributions of source level, noise level, the detector characterization and spatial models were allowed to vary, to capture uncertainty in these components of the method. Results of 100 iterations of the bootstrap returned unrealistic density results in some iterations, many orders of magnitude above the point estimate, suggesting model extrapolation in some iterations, returning extreme values. This requires further investigation.

The lower density estimated by distance sampling is expected in this case. Calls close to the OBS instrument also have negative coherency values, so will also be excluded by the use of the coherency selection criterion. The probability of detection in distance sampling does not account for these calls, whereas the detection probability used in the bearing-only method does account for these calls.

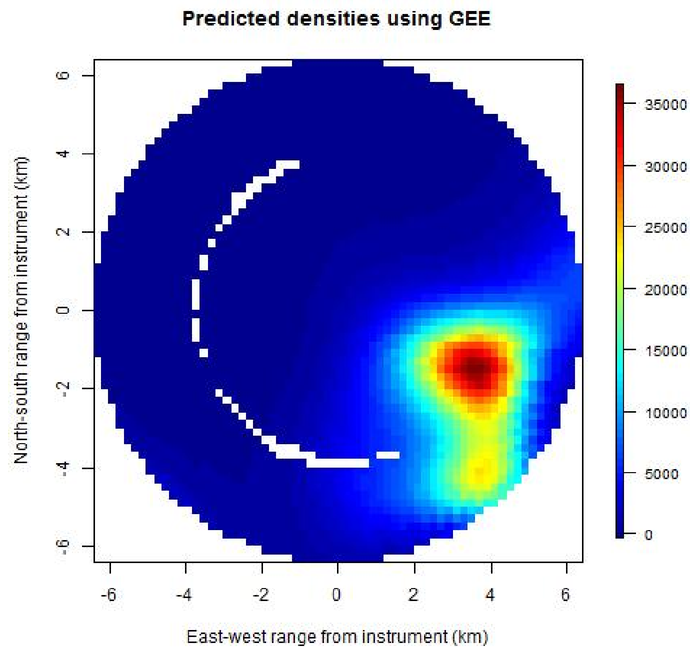

Figure 2. Estimated spatial distribution of fin whale call density from OBS19 (calls per km^2).

Objective 3: Developing Multipliers - Fin Whale Source Level

The source level distribution from the pilot study (averaged on the dB scale) had a mean of 177.7 dB re 1 μPa^2 (standard deviation: 3.30, n = 79) using the Peregrine transmission loss model and 177.6 dB re 1 μPa^2 (standard deviation: 3.03) using spherical spreading to predict propagation loss. Further, estimated source level decreased significantly as a function of range when using the Peregrine model (linear regression coefficient = -2.20, p-value < 0.001, n = 76 due to the removal of three outlying data points using Cook's distance measures). Estimated source levels assuming spherical spreading also decreased slightly with range, though not significantly (linear regression coefficient = -0.62, p-value = 0.27, n = 76) (Fig. 3). Given that the means and standard deviations of the two source level distributions in the pilot were almost identical, the source level estimates using the more complex, bathymetry-dependent Peregrine model were used for all simulations and pilot data analyses.

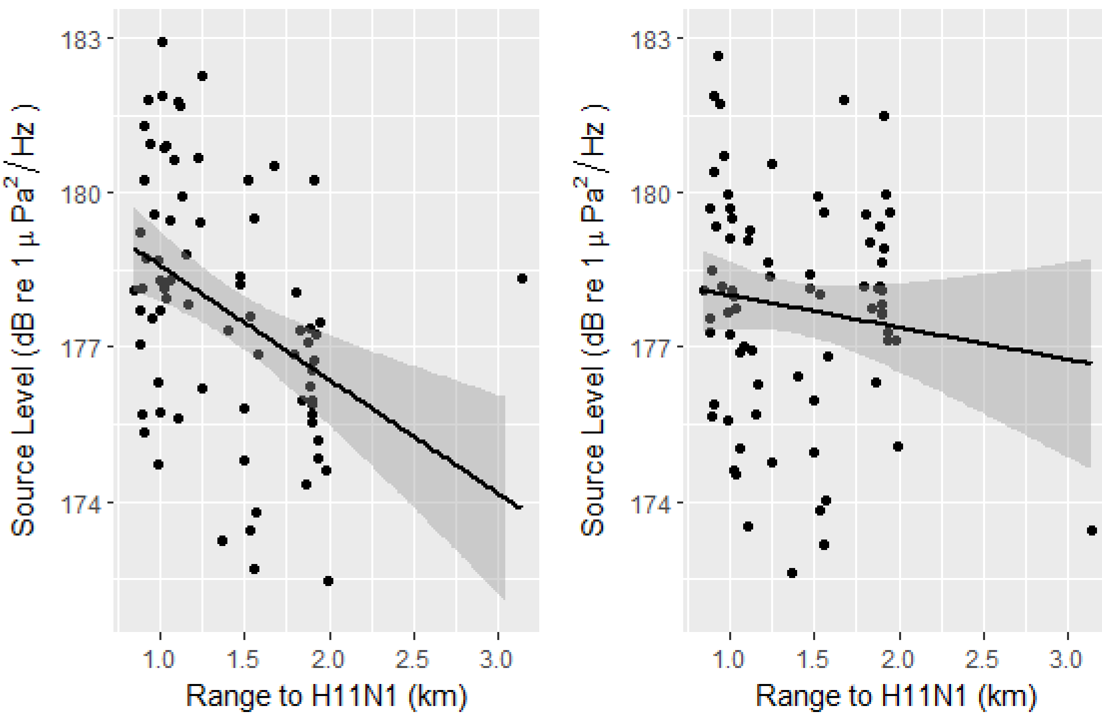

Figure 3. Source levels estimated from 79 calls using transmission loss derived from (left) the Peregrine model and (right) assuming spherical spreading. Both plots show a fitted linear regression model (black line), with associated 95% confidence intervals shaded in gray.

The intensity averaged estimated source level of fin whale calls from the entire Wake Island dataset (2007-2013) was 189.5 dB re 1 μPa^2. Source levels from the population of fin whales in the North Atlantic measured from the OBS data had a linearly averaged mean of 189 dB re μPa^2. These values compare extremely well with estimated fin whale source levels reported for populations in the Northeast Pacific Ocean (189.5 re 1 μPa^2 in Weirathmueller et al., 2013) and Southern Ocean (189.4 re 1 μPa^2 in Sirovic et al., 2007).

Unlike the 79 fin whale calls analysed in the pilot study that showed a decrease in estimated source level with range, the 20,722 estimated fin whale source levels assessed in the full dataset (2007-2013) showed a slight increase with range (Figure 4). When detections with estimated source levels were examined as a function of detection bearing, no clear pattern was observed (Figure 5). However, analysis of the estimated source level as a function of bearing using a Generalized Additive Model (using a cyclical smooth to acknowledge that 0 and 359 degrees are very similar values) did indicate that some bearings consistently returned lower source levels than others (Figure 6). This could be due to 1) ocean physics relating to the impact of sound propagation characteristics along certain bearings, 2) the behaviour of fin whales vocalizing more loudly at certain bearings, or 3) other mechanisms not yet identified. Further, there were significant differences in estimated source level between years.

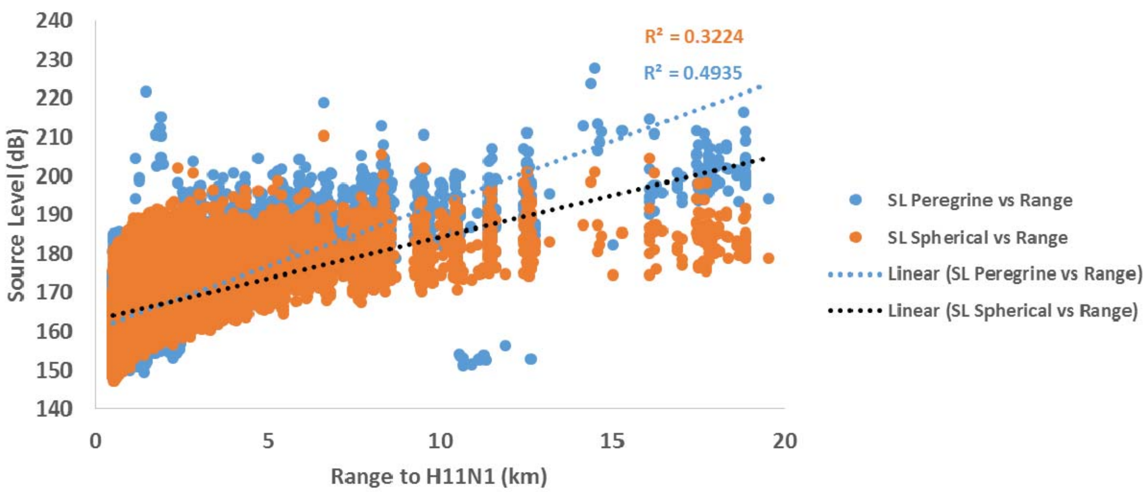

Figure 4. Fin whale source levels as a function of range for estimated source levels using the Peregrine Parabolic Equation model for transmission loss (blue) and spherical spreading (orange) (n=20,722).

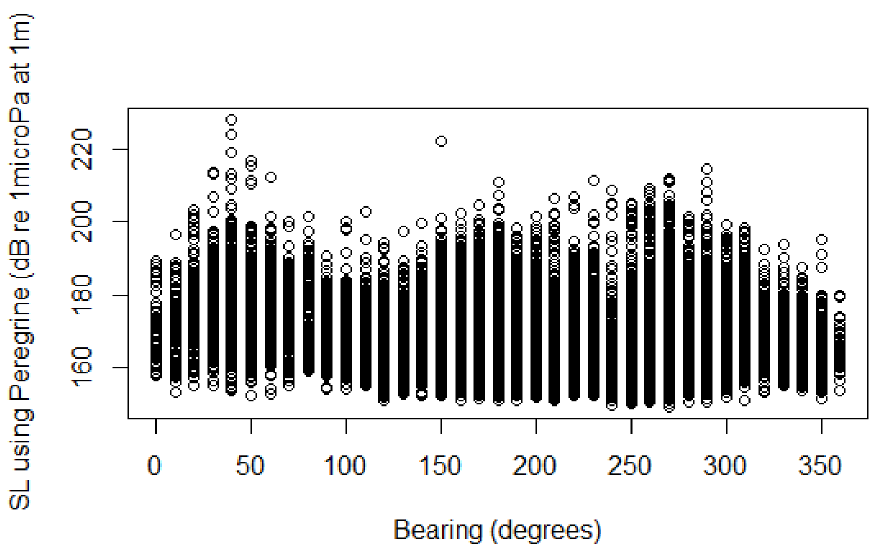

Figure 5. Estimated fin whale source levels using the Peregrine Parabolic Equation model for transmission loss from Wake Island as a function of bearing (n=20,722).

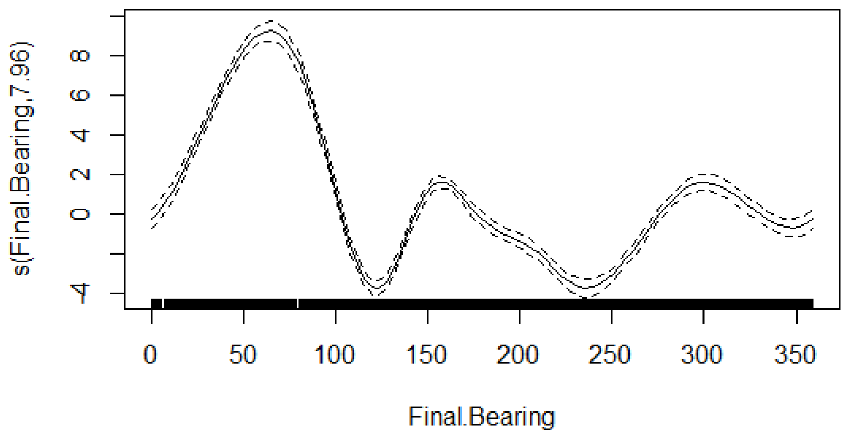

Figure 6. The modelled relationship between estimated fin whale source levels using the Peregrine Parabolic Equation model for transmission loss from Wake Island and bearing, using a Generalized Additive Model Estimated (n=20,722).

Objective 4: Density and spatial distribution of whales at Wake Island in the Pacific Ocean

The whole Wake Island time series (first reported on in FY17) was rerun using the adjusted method to determine the monitored area, described above. Further, based on the OBS comparison, the thresholds used to define a loud call in quiet noise were found to be too conservative so were redefined by taking the 99th and 1st percentile from the source and noise level distributions and identifying locations where the chance of detecting such a call fell below 0.25%. The results are presented in Fig 7. The reduced densities compared to the preliminary results reported in FY17 are as a result of the increase in the estimated monitored area. Confidence intervals (95%) around the estimates are also given in Fig 7. The interval for Yr 10/11 is smaller than the other intervals because the variance associated with the detection probability was omitted from these results, due to computational issues. However, in general, the bootstrap procedure for variance estimation of the detection probability did not produce the same extreme results as seen in the OBS comparison.

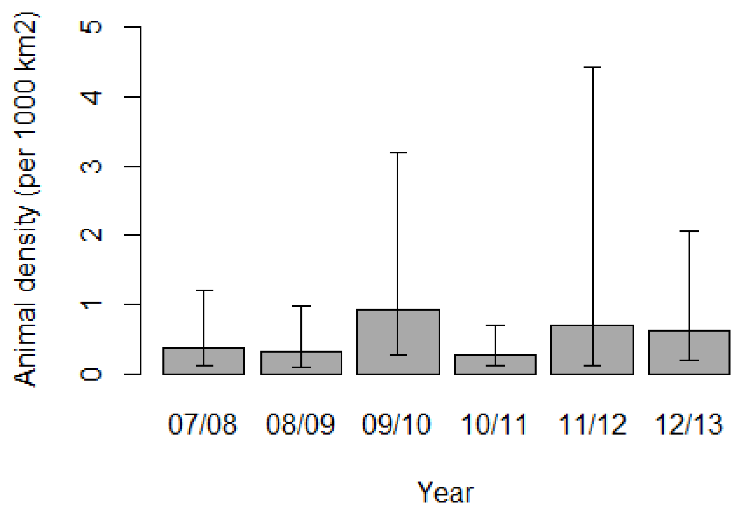

Figure 7. Estimated densities (animals/1000 km^2) for the whole Wake Island time series.

Objective 5: Seasonal distribution of whales at Diego Garcia in the Indian Ocean

The annual pattern of fin whales acoustically detected at Diego Garcia did not indicate a strict July-Nov migration period (Figure 8). These results indicate year round acoustic presence of fin whales at this location. Also of significant note is that 2011-2012 appears to be an anomalous period in that fewer fin whales were detected around Diego Garcia during this time period. Acoustic detections remained low through the first half of 2013 before returning to more typical detection levels in July 2013.

Sri Lankan pygmy blue whale vocal presence, as detected from peaks in the weekly averaged PSDs, was seasonal (Figure 9). The week of peak calling activity was variable within a year across the decade and likely related to oceanographic variability driving whale distribution (Branch et al. 2007; Stafford et al. 2011). Vocal activity was detected nearly year round at this location. Peak periods of vocal activity averaged over the decade occurred during Weeks 21 and 22 corresponding to the months of May-June in the austral fall.

Annual rate of decrease of both units was estimated from the regression analysis using the average peak frequencies in Weeks 21 and 22 from 2002-2012 to reflect the measured shift during the peak in vocal activity. The QQ plot (not included here) suggested an adequate model fit and all model assumptions were met. The peak frequency of both units of the Sri Lankan pygmy blue whale call significantly decreased across years ($F_{1,36} = 395.69$, $p < 0.001$). Unit 3 tonal calls peak frequencies measured in Weeks 21 and 22decreased from 106.5 Hz to 100.7 Hz over a decade corresponding to a 0.54 Hz/year rate of decrease (Figure 10). This is an approximate 13% decrease from 1984 when the peak frequency was reported at 115.5 Hz (McDonald et al. 2009), and a 5.4% decrease over the past decade. Over the same time period, the frequency content of the ~ 60 Hz Unit 2 FM upsweeps measured in Weeks 21 and 22 did not change as dramatically. The regression model predicted a 0.18 Hz/year rate of decrease corresponding to only an approximate 3.1% decrease over the past decade. The interaction term between year and unit was selected in the model ($F_{1,36} = 92.66$, $p < 0.001$), indicating that the rates of frequency change across years differed significantly between the two units.

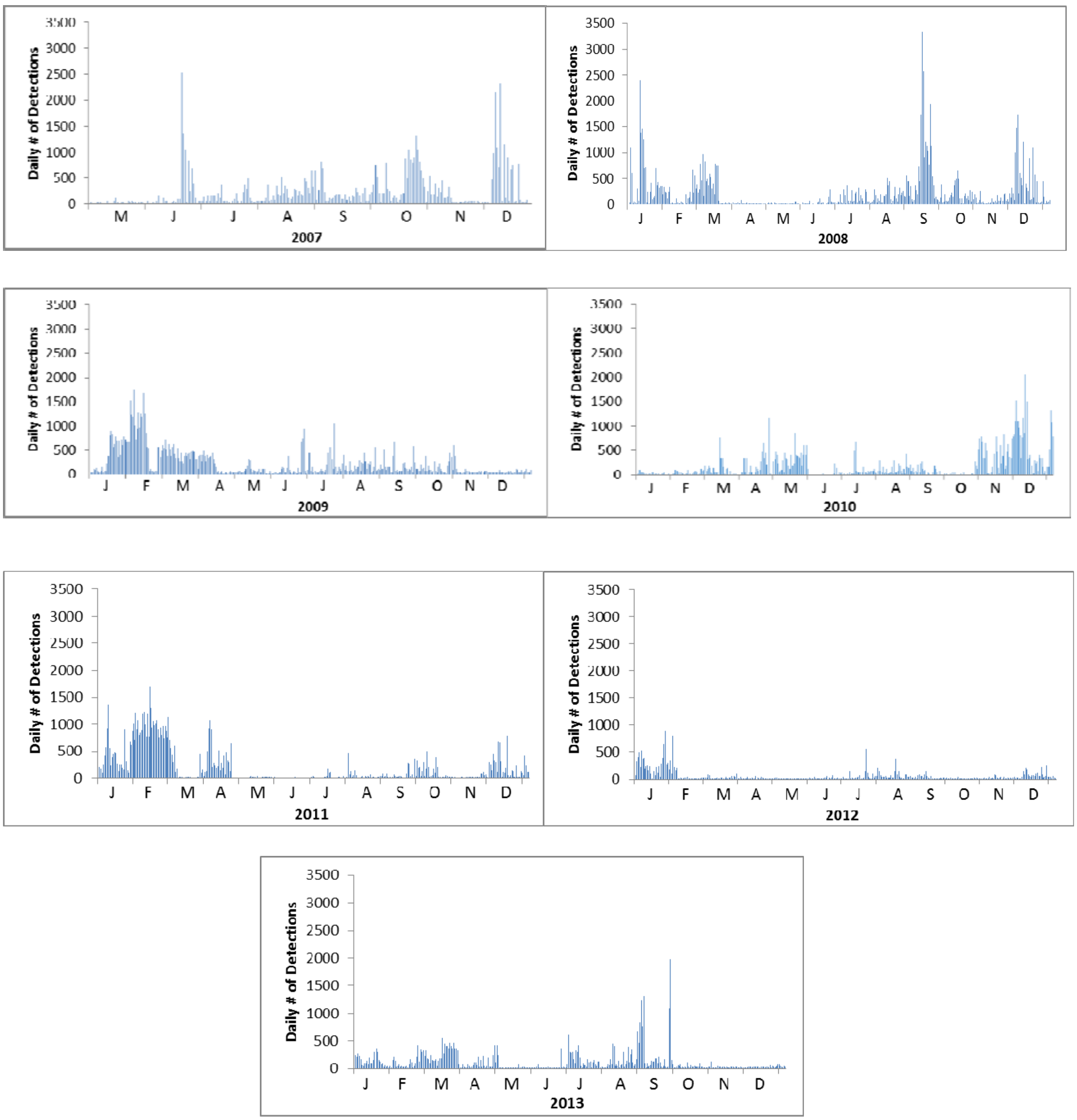

Figure 8. Annual distribution of detected fin whale calls at Diego Garcia from 2007-2013.

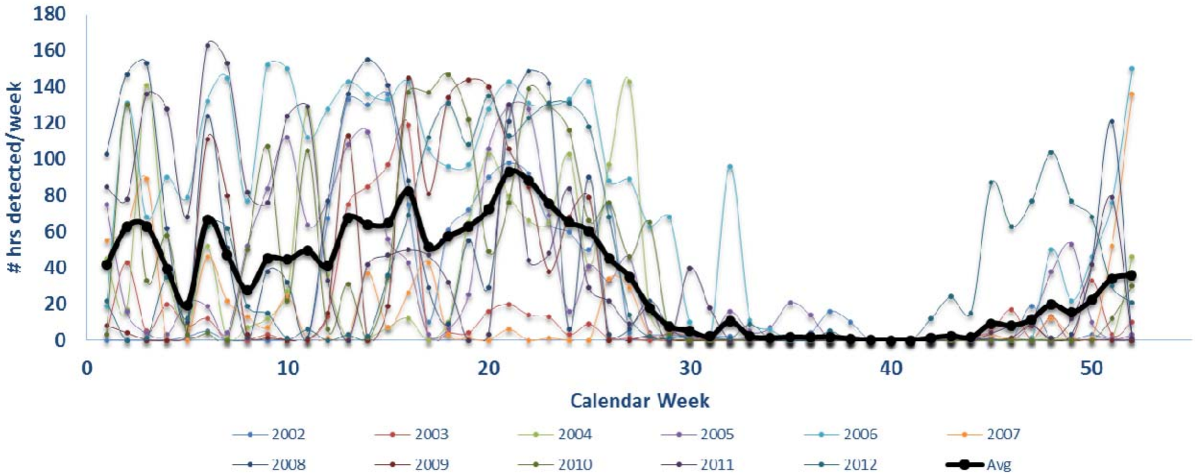

Figure 9. Annual time series and decade average of hourly vocal presence detected per week. Average decadal vocal activity peaked during Weeks 21-22, and data from these two weeks were used in further power spectral density trend analyses.

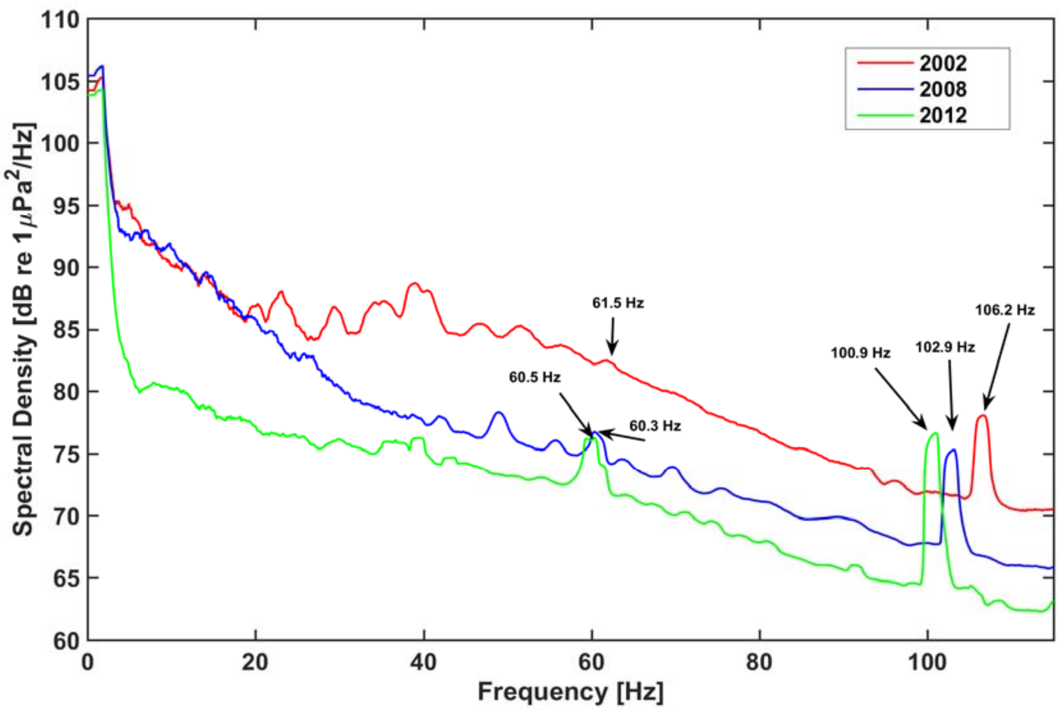

Figure 10. Power spectral density of ambient ocean sound averaged over Week 22 (28 May – 3 June) in 2002, 2008, and 2012. The indicated peaks reflect the tonal peak of Sri Lankan blue whale calls.

IMPACT/APPLICATIONS

Acoustic monitoring for the presence of marine life is an ongoing Navy need in meeting regulatory requirements, and offers a low cost alternative to visual surveys. The density estimation method developed here for the targeted low frequency vocalizations of blue and fin whales will be directly applicable to other species and frequency ranges using sparse arrays of fixed or remotely deployed PAM systems. Outputs will be of direct relevance to Navy risk assessment models.

Results from this fin whale year's work indicate that estimated source levels of the fin whale 20 Hz call is almost identical across three ocean basins for the four popualtions reporting estimated source levels: 1) this study in the Equatorial Pacific Ocean, 2) this study in the Northeast Atlantic, 3) Weirathmueller et al., (2013) in the Northeast Pacific Ocean, and 4) Sirovic et al., (2007) in the Southern Ocean. This provides growing evidence that for this species, the source level of the 20 Hz call can be correctly extrapolated across time and space in future density estimation applications.

TRANSITIONS

With the success of the pilot study and application of the developed methods to the full fin whale data set at Wake Island, the transition of the developed density estimation methods to the U.S. Navy Marine Species Monitoring Program would be appropriate for application to marine mammal species with stable, stereotyped calls.

RELATED PROJECTS

The propagation modeling included in this study in collaboration with Kevin Heaney (OASIS) is directly related to ONR Ocean Acoustics Award N00014-14-C-0172 to Kevin Heaney titled "Deep Water Acoustics".

The current project is also directly related to and follows on to ONR Award N000141110619 to Jennifer Miksis-Olds titled "Ocean Basin Impact of Ambient Noise on Marine Mammal Detectability, Distribution, and Acoustic Communication". Patterns and trends of ocean sound observed that study will be directly applicable to the estimation of signal detection range in this study.

The density estimation method development builds on the work of Danielle Harris (PhD work funded by UK DSTL; Cheap DECAF project funded by ONR N00014-11-1-0615) and Len Thomas (DECAF project, funded by NOAA and JIP through NOPP).

Result from tagging studies under ONR Award N00014-14-1-0414 "Behavioral context of blue and fin whale calling for density estimation" to Ana Širović will better inform the species specific multipliers for converting number of vocal detections into number of animals by providing information on source level and call rates.

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PEER REVIEWED PAPERS

Harris, D, Miksis-Olds, JL, Thomas, L, Vernon, J (2018). Fin whale density and distribution estimation using acoustic bearings derived from sparse arrays. *The Journal of the Acoustical Society of America.* 143, 5, 2980-2993.

Warren, VE, Marques, TA, Harris, D, Thomas, L, Tyack, PL, Aguilar de Soto, N, Hickmott, LS, Johnson, MP (2017). Spatio-temporal variation in click production rates of beaked whales: implications for passive acoustic density estimation. *The Journal of the Acoustical Society of America.* 141, 3, 1962-1974.

Vernon, J (2017). Fin whale distribution in the Indian and Equatorial Pacific Oceans in support of passive acoustic density estimation. M.S. Thesis. The Pennsylvania State University.

PRESENTATIONS

Over the course of this project, several presentations have been given (reported in previous annual reports and listed again below). In FY18, two further presentations were given about the project.

Harris, D, Miksis-Olds, JL, Thomas, L, Vernon, J (2017). Large Scale Density estimation of blue and fin whales: combined whale distribution and density estimates using bearing data. 22nd Biennial Conference of the Society for Marine Mammalogy. Halifax, Nova Scotia, 23-27 October 2017.

Širović, A, McDonald, M, Balcazar-Cabrera, NE, Buchan, S, Cerchio, S, Clark, C, Davis, G, Findlay, F, Gagnon, G, Kyo, N, Leroy, E, Miksis-Olds, J, Miller, B, Oleson, E, Pangerc, T, Rogers, TL, Samaran, F, Simard, Y, Stafford, KM, Stevenson, D, Sugioka, H, Thomisch, K, Tripovich, JS, Truong, G, Van Opzeeland, I, Van Parijs, S, Yoshida, R. Brownell Jr, RL (2017). Blue whale songs wordwide: an update. 22nd Biennial Conference of the Society for Marine Mammalogy. Halifax, Nova Scotia, 23-27 October 2017.

Vernon, J (2017). Fin whale distribution in the Indian and Equatorial Pacific Oceans in support of passive acoustic density estimation. M.S. Thesis. The Pennsylvania State University.

Miksis-Olds, JL (2016). Source level of fin whale calls from the Equatorial Pacific Ocean. Journal of the Acoustical Society of America 140: 3019.

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Harris, D, Miksis-Olds, JL, Thomas, L, Vernon, J (2016). Large Scale Density estimation of blue and fin whales: combined whale distribution and density estimates using bearing data. International Statistical Ecology Conference. Seattle, WA, June 28-July 1, 2016.

Harris, D. (2016) Eavesdropping on the ocean: using passive acoustic monitoring technologies to estimate marine mammal population sizes. Seminar given at Oregon State University, Washington State University and University of Washington.

Vernon, JA, Miksis-Olds, JL (2016). Seasonal variability in distribution of fin whales around Wake Island. 171st Meeting of the Acoustical Society of America, Salt Lake City, UT. May 23 -27, 2016. *The Journal of the Acoustical Society of America* 139.4: 2061.

Vernon, JA, Miksis-Olds, JL, Harris, D (2015). Analysis of bearings of vocalizing marine mammals in relation to passive acoustic density estimation. 170th Meeting of the Acoustical Society of America. Jacksonville, FL, November 2-6. *The Journal of the Acoustical Society of America* 138.3: 1792.

Harris, D, Thomas, L, Miksis-Olds, JL, Vernon, JA (2015). Large scale density estimation of blue and fin whales: combined distribution and density estimates using bearing data. 7th International Workshop on Detection, Classification and Localization of Marine Mammals Using Passive Acoustics. La Jolla, California. July 13-26.

Miksis-Olds, JL (2015). Keynote: Unraveling soundscapes – Learning to be good ocean listeners. Underwater Acoustics Conference & Exhibition 2015. Crete, Greece. June 21-26.

Vernon, JA (2015). Automatic detection and bearing calculation of vocalizing marine mammals in relation to passive acoustic density estimation. Imagining the Future of Ocean Science Symposium. Center for Marine Science & Technology, Penn State. 14 July, 2015.

Harris, D, Thomas, L, Miksis-Olds, JL, Vernon, JA (2015). Large scale density estimation of blue and fin whales: combined distribution and density estimates using bearing data. 7th International Workshop on Detection, Classification and Localization of Marine Mammals Using Passive Acoustics. La Jolla, California. July 13-26.

Vernon, JA (2015). Automatic detection and bearing calculation of vocalizing marine mammals in relation to passive acoustic density estimation. Imagining the Future of Ocean Science Symposium. Center for Marine Science & Technology, Penn State. 14 July, 2015.

Vernon, JA, Miksis-Olds, JL, Harris, D (2015). Analysis of bearings of vocalizing marine mammals in relation to passive acoustic density estimation. 170th Meeting of the Acoustical Society of America. Jacksonville, FL, November 2-6.

HONORS/AWARDS/PRIZES

No further honors or awards occurred in FY18, but we list a previously reported award from FY17.

Jasmin Buteau (UNH undergraduate) received the first place award in Biology at the 2017 Interdisciplinary Sciences and Engineering Symposium during the Undergraduate Research Conference (URC) at UNH. Her presentation was titled “Characterizing an Unknown Blue Whale (*Balaenoptera musculus*) Population in the South Atlantic Ocean Through Acoustic Analysis of Song”.