# 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 will first develop and implement 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 will then be applied to the same species in the Indian Ocean at the CTBTO location at Diego Garcia.

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 Applied Research Laboratory at Penn State (ARL Penn State) are working collaboratively with the Centre for Research into Ecological and Environmental Modeling (CREEM) at the University of St. Andrews. The CREEM, St. Andrews team provides expertise in density estimation techniques from passive acoustic datasets, while collaborators at ARL Penn State 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 a current ONR YIP Award N000141110619 to Miksis-Olds (ARL PSU). 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 allows the distribution of animals to be estimated without requiring randomly placed multiple instruments. It is anticipated that bearings to a large number of calls can be estimated. We plan to use the bearing data, coupled with estimates of call source levels and sound propagation models in the study area, to estimate the distribution and density of calling whales in the monitored area. To do this, we will use the bearing, source level and transmission loss estimates to estimate the location of each call and range over which calls can be detected (together with estimates of uncertainty on these quantities). A detailed detector characterization will give probability of detection as a function of signal-to-noise ratio (SNR), and hence we can estimate probability of detection for each received call. Spatio-temporal variability in the efficiency of the automatic detector will also be considered. Call "abundance" at the location of each call can then be 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 will be smoothed in space with a Generalized Additive Model 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. Estimation of the range of acoustic detection is a function of signal source level, SNR of detection, and sound propagation. 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 will be 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., 2014), so a seasonal component will be included in the optimal acoustic coverage model. SNR detection thresholds will be established at each site for both a north and south array element. SNR detection threshold will be 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 will provide a distribution of regional source level estimates. This will be preferable to source level estimates taken from the literature. The proposed 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 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 will be a distribution on source level, and will include quantification of measurement error in bearing. Uncertainty in these inputs will be 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

A project kick-off meeting took place at the CREEM, University of St. Andrews September 12-13, 2014. PIs Miksis-Olds (ARL) and Thomas (CREEM), Post-doc Harris (CREEM), and graduate student Julia Vernon (ARL) participated. This meeting served to focus efforts on meeting the first year tasks of completing a pilot study, merging datasets, and determining the details for moving forward with analogous analyses for the CTBTO IMS and OBS datasets.

The team identified a 3-4 month time period over which to conduct the pilot study. The pilot study will be conducted over December 2007-February/March 2008 at Wake Island in the Equatorial Pacific Ocean. This time period provides complete overlap between the CTBTO IMS data and the OBS data. Fin whales have been identified as the target species for the pilot study. During the pilot study, the team will assess the performance of a match filter detector for comparison to manual detections. It was also determined that an analysis of the ambient noise times series needs to be conducted to identify the proportion of time high sound levels would prevent the detection of all fin whale vocalizations. Time periods when whales are not able to be detected should be eliminated from the ultimate animal density calculations to provide the most accurate estimate.

## RESULTS

Limited results are available at this point, as the project only started 3 months ago. Initial propagation modeling was completed for a northern and southern hydrophone at each CTBTO IMS location out to 1,000 km. The OASIS Peregrine parabolic equation (PE) model (in collaboration with Kevin Heaney, OASIS) was used to model propagation loss between a receiver in the sound channel and a source within the upper 300 m of the water column to be consistent with the depth of vocalizing baleen whales (Figure 1). It was determined that modeling out to 1,500 km may be required depending on the maximum source levels estimated to be produced by blue and fin whales.

Initial ambient sound level analyses have been completed for a single north and south hydrophone at each location from the start of data recording through 2012. Minute sound level averages were computed and will be the foundation of the analyses to exclude time periods when high ambient levels mask whale detections completely. Maximum sound levels in the Indian Ocean at Diego Garcia were periodically observed to exceed 120 dB re 1μ$Pa^2$/Hz. Maximum sound levels in the Equatorial Pacific at Wake Island were observed to exceed 130 dB re 1μ$Pa^2$/Hz periodically (Figure 2).

## 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.

## TRANSITIONS

To be determined as this project unfolds.

## 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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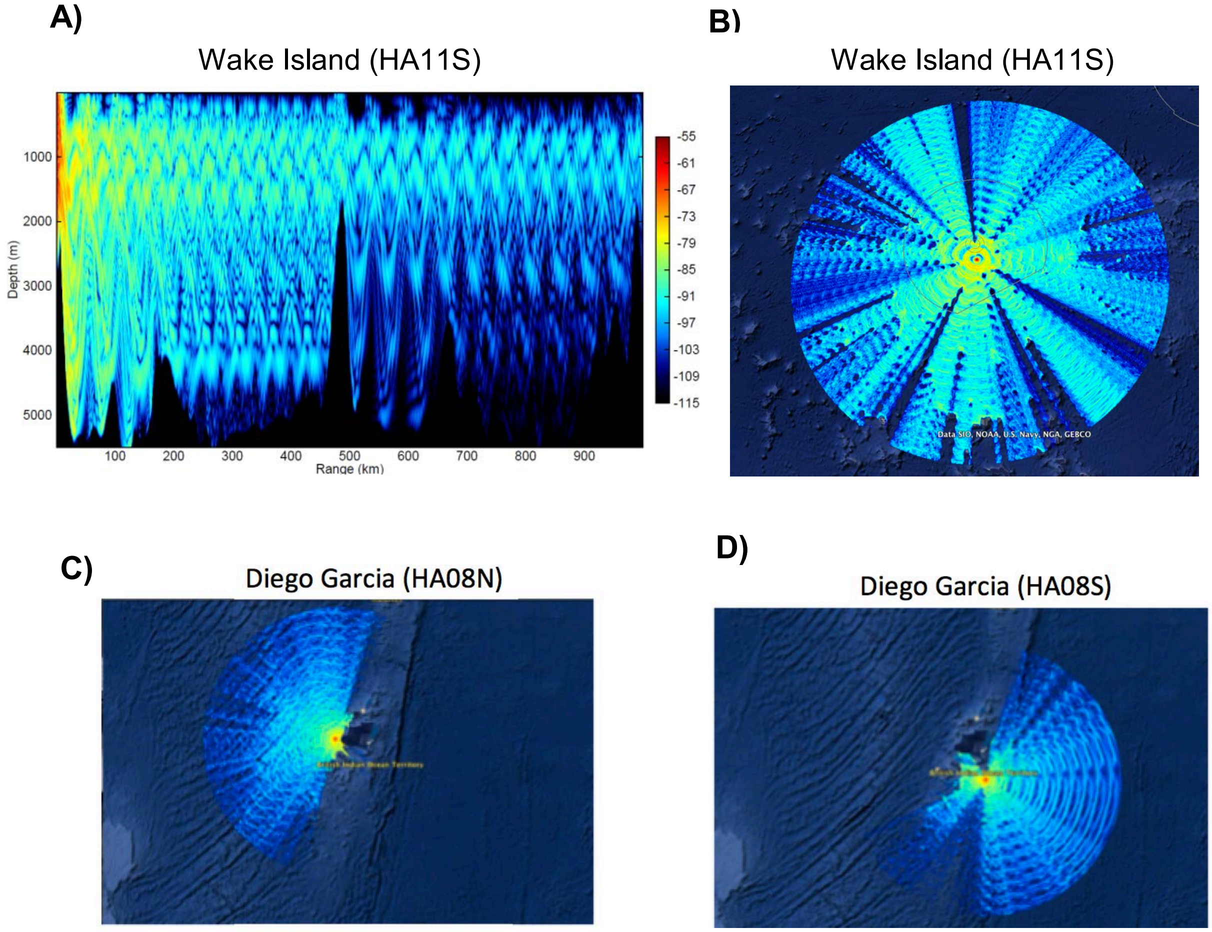


***Figure 1. A) Receiver modeling TL output from the Peregrine PE model at CTBTO location at H11 S1 in the Pacific Ocean at Wake Island during the winter season (20 Hz, 1000 km range). TL is shown as a function of depth and range at 280$^o$ bearing. B) TL receiver output from the Peregrine PE model as a function of range around HA11 S1 at Wake Island. C) TL receiver output from the Peregrine PE model as a function of range around HA08 N1 and (D)HA08 S2 in the Indian Ocean at Diego Garcia.***

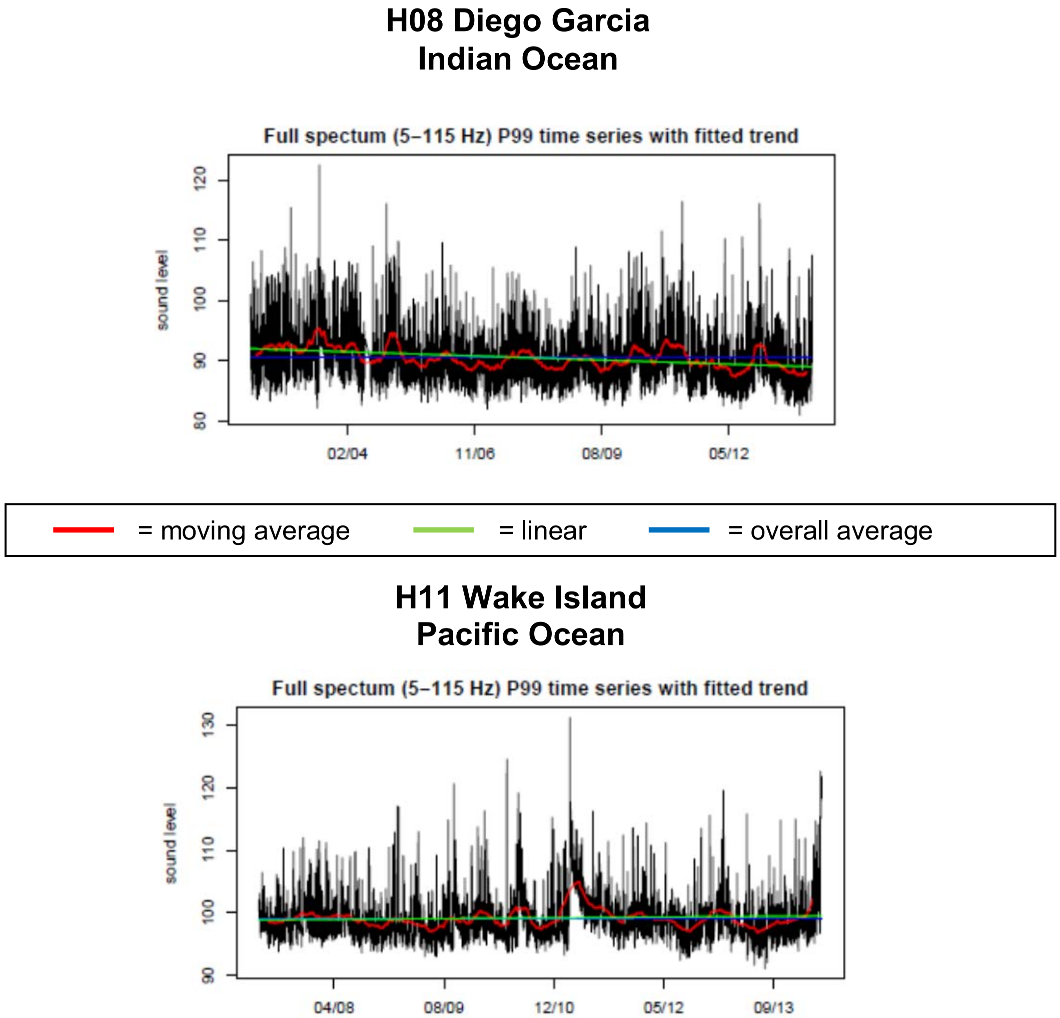


***Figure 2. Time series of daily 99% sound levels (P99) over the duration of the CTBTO IMS datasets at Diego Garcia (H08) and Wake Island (H11).***