SSC Pacific FY15 annual report on

PMRF Marine Mammal Monitoring

Cameron R. Martin[1], Stephen W. Martin[1], E. Elizabeth Henderson[2], Tyler A. Helble[2],
Roanne A. Manzano-Roth[2] and Brian M. Matsuyama[1]

[1] National Marine Mammal Foundation, San Diego, CA 92106

[2] Space and Naval Warfare Systems Center Pacific, San Diego, CA 92152

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C. R. Martin
S. W. Martin
E. E. Henderson
T. A. Helble
R. A. Manzano-Roth
B. M. Matsuyama

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Marine Mammal Foundation, 2240 Shelter Drive, Suite 200, San Diego, CA
SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, CA

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14. ABSTRACT

This report documents Space and Naval Warfare Systems Center Pacific (SSC Pacific) marine mammal monitoring efforts in FY15 for COMPACFLT at the Pacific Missile Range Facility (PMRF), Kauai, Hawaii, including during U.S. Navy mid-frequency active sonar (MFAS) training. Data products (both recorded hydrophone data and standard PMRF range products) were obtained and analyzed. Collaborative efforts with R. Baird and B. Southall were also performed involving estimating received levels for tagged animals that were exposed to MFAS during training activities.

Results of fully automated processing are presented for all data collections throughout the fiscal year in terms of the beaked whale foraging dives per hour and the number of baleen whale passive acoustic localizations on and near the range. These ‘quick look’ results directly provided unvalidated information regarding these species’ presence and occurrence throughout the PMRF range with qualitative relative abundance. While manual processes are currently required to validate the species detections and localizations, the automated quick look data are useful tools that help pinpoint data collections for further investigation (such as Bryde’s (Balaenoptera edeni) whale calls in the summer).

A case study is presented for estimating exposures to baleen whales from surface ship mid-frequency active sonar training conducted in February 2015. Estimated received levels varied from 156 to 167 dB re 1 µPa on two suspected fin whales and one minke whale. Cessation of calling was documented as a potential behavioral response with another potential change in the minke whale’s call intervals after an exposure.

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Two papers were published in the Journal of the Acoustical Society of America in 2015 and are included as appendices. The first article published January 2015, documented passive acoustic methods (PAM) for localizing humpback whales (Megaptera novaeanlgiae) on the range. The second article published May 2015, documented minke whales (Balaenoptera acutorostrata) responding to navy training with a reduced number of calling individuals in the area for three training events (February 2011, February 2012 and February 2013). Both publications were done in collaboration with the Office of Naval Research (ONR) and Living Marine Resources program (LMR) science and technology efforts.

Multiple draft papers are also in process and are included as appendices, all of which will be submitted for peer review publication. Two papers deal with Blainville's beaked whale (Mesoplodon densirostris) group foraging dives. One paper examined baseline dive activity over a three-year period (2011-2013), and one documented the reduction in Blainville's beaked whale dives in response to six U.S. Navy MFAS training events conducted over the same period. A third draft paper planned for peer review submission documented Bryde's whale encounters observed from analyses of PMRF recorded data.

15. SUBJECT TERMS

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Executive Summary

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Contents

Appendix A- Martin, S.W., Martin, C.R., Matsuyama, B.M. and Henderson, E.E. (2015). Minke whales (*Balaenoptera acutorostrata*) respond to navy training. J. Acoust. Soc. Am. 137(5), 2533-2541.

Appendix B – Helble, T. A., Ierley, G.R., D'Spain, G.L. and Martin, S.W. (2015). Automated acoustic localization and call association for vocalizing humpback whales on the Navy's Pacific Missile Range Facility. J. Acoust. Soc. Am. 137(11), 11-21.

Appendix C – Henderson, E.E., S.W. Martin, R.A. Manzano-Roth, B.M. Matsuyama. (2016). Occurrence and habitat use of foraging Blainville's beaked whales (*Mesoplodon densirostris*) on a US Navy range in Hawaii. Manuscript in preparation.

Appendix D – Manzano-Roth, R.A., E.E. Henderson, S.W. Martin, C.R. Martin, B.M. Matsuyama. (2016). Impacts of a U.S. Navy training event on beaked whales dives in Hawaiian waters. Manuscript in preparation.

Appendix E – Helble, T. A., S.W. Martin, G. R. Ierley and E.E. Henderson. (2016). Swim track kinematics and calling behavior attributed to Bryde's whales on the Navy's Pacific Missile Range Facility. Manuscript in preparation.

Acronyms

BARSTUR – Barking Sands Tactical Underwater Range

BSURE – Barking Sands Underwater Range Expansion

COMPACFLT – Commander Pacific Fleet

DCLDE – Detection, classification, localization and density estimation

DCLTDE – Detection, classification, localization, tracking and density estimation

FIREX – Amphibious Warfare Naval Surface Fire Support Training

FY – Fiscal year

GPL – Generalized Power Law detection process

ICI – Dual use as inter-click-interval and inter-call-interval

IRIG – Inter-Range Instrumentation Group time code format for transferring timing information

LMR – Living Marine Resources program

M3R – Marine Mammal Monitoring on Navy Ranges, a Naval Undersea Warfare Center program which consists of multiple computers in a system installed at U.S. Navy ranges for detecting and localizing marine mammals.

MATLAB – Mathworks copyrighted scientific software environment

MFAS – Mid-frequency active sonar (1-10 kHz) primarily from surface ship sonar

ONR – Office of Naval Research

PAM – Passive acoustic monitoring

PCIMAT – Personal Computer Interactive Multisensor Acoustic Training

PMRF – Pacific Missile Range Facility

SCC – Submarine Commanders Course training event

SSC Pacific– Space and Naval Warfare Systems Center Pacific

SUBEX – Anti-Submarine Warfare submarine tracking event

USWEX- Anti-Submarine Warfare surface tracking event

Introduction

In fiscal year (FY) 2015 the SSC Pacific Detection, Classification, Localization, Tracking, and Density Estimate (DCLTDE) Laboratory automatically processed data recorded on bottom mounted hydrophones at the Pacific Missile Range Facility (PMRF) to detect and localize several species of marine mammals and estimate received levels from mid-frequency active sonar (MFAS) transmissions. This ongoing passive acoustic monitoring (PAM) effort has been focused on addressing questions regarding the presence, occurrence, and abundance of marine mammals at PMRF, in addition to estimating their exposures from MFAS and possible subsequent behavioral responses. Acoustic data were recorded throughout the FY for baseline studies on a two-day-a-month sample basis and on an ‘as often as feasible’ sample basis for decimated data used for baleen whale species baseline studies. In addition, data was collected before, during and after the Submarine Commanders Course (SCC) training events held in February and August.

Automated processing has progressed over the past several years such that when hydrophone data arrive in San Diego, they are automatically processed for detecting and localizing marine mammal calls from fin whales (*Balaenoptera physalus*), sei whales (*Balaenoptera borealis*), Bryde’s whales (*Balaenoptera edeni*), minke whales (*Balaenoptera acutorostrata*), sperm whales (*Physeter macrocephalus*), Blainville’s beaked whales (*Mesoplodon densirostris*) and Cuvier’s beaked whales (*Ziphius cavirostris*). Beaked whale dive groups were automatically detected and localized to the nearest hydrophone locations while the other species were localized as individuals. In FY15, localizations were also tracked using MATLAB® (R2014a, The Mathworks Inc., Natick, MA, United States) kinematic processes tuned for each species’ call rates and swim speeds.

Descriptions of automated processing methods are briefly described herein with references to more detailed descriptions. Presence, occurrence, and relative abundance of species automatically processed are presented as a quick look for all FY15 acoustic data recordings available for analysis at the time of this report (October 1, 2014 - August 27, 2015), while more recent data was still at PMRF. Appendices of published peer reviewed papers as well as those in preparation are provided. The provided appendices document both minke whales and Blainville’s beaked whales responding to US Naval training at PMRF between 2011 and 2013. Responses were observed as a reduction of vocalizing whales (e.g. numbers of localized individual minke whales and beaked whale group foraging dive rates). These behavioral responses were observed in relatively large areas (3,780 km^2 for minke whales and approximately 1,500 km^2 for beaked whales) and a 3-year time period (three February SCCs for the minke whale analysis and six SCCs for the beaked whale analysis). A before, during, and after experimental paradigm was utilized. Data collected during training was further categorized as phase A and phase B with the latter being the only period in which MFAS from surface ships was utilized.

A test case analysis of MFAS exposures is provided (estimated received levels and potential behavioral responses) for two fin whales and one minke whale. All three whales were exposed to MFAS on February 15¯16, 2015 during an Anti-Submarine Warfare (ASW) surface tracking training event (termed USWEX) with what was believed to be the same minke whale being exposed again a day and a half later on February 17, 2015 at the onset of the surface ship MFAS component of the Submarine Commanders Course (SCC) training event (i.e. phase B). Estimated received levels ranged from 156 to 167 dB re 1 μPa with apparent behavioral responses of cessation of calling for four of the MFAS ship-whale encounters and one encounter with apparent cessation of calling to a non-MFAS transmitting ship's approach.

Data Collection

Standard PMRF range data products have been obtained from PMRF for biannually held SCC training events since February 2011. The PMRF standard data products have provided locations for all platforms from the start to finish of training events. Recorded acoustic data from subsets of PMRF's bottom mounted hydrophones were also collected to support analysis for marine mammal vocalizations.

Two types of acoustic recordings were obtained in FY15. The standard recordings (Table 1) were full bandwidth recordings at the 96 kHz native sample rate and captured the majority of the hydrophones' 50 kHz of bandwidth. Since late August 2012, 62 hydrophones were recorded at the full bandwidth rate a few days a month and also for multiple days associated with each SCC training event. Prior to August 2012, recordings at the full bandwidth rate were collected for 31 PMRF hydrophones with subsequent recordings collected for 62 PMRF hydrophones. Late in August of 2014 a new capability at the range allowed the recording of the 47 wideband hydrophones (the newest 41 Barking Sands Underwater Range Expansion [BSURE] replacement hydrophones and the 6 Barking Sands Tactical Underwater Range [BARSTUR] broadband hydrophones) at a reduced sample rate of 6 kHz, referred to as decimated data. The decimated data recordings allowed for long-term data collections to capture the presence of low-density species such as Bryde's whales.

Localizing and tracking whales provides a wealth of information for endangered and data deficient species *while they are calling* including: times of presence and areas utilized on the PMRF range; cue rates; call characteristics; habitat use; and kinematic swim patterns. By establishing a robust baseline for baleen whale behaviors observed via passive acoustics, it may be possible to identify behavioral responses (differences from baseline behaviors) beyond cessation of calling when whales are exposed to MFAS during training events. Collecting raw acoustic data has been pivotal in developing, testing, and improving new and existing automated algorithms that have processed thousands of hours of multi-channel data to date. Large data sets are required for developing robust baselines for whale species' densities, call metrics, behaviors and kinematic swim patterns. In addition, the recorded data allows future reprocessing with additional emergent marine mammal species DCLTDE algorithms.

A hard disk drive failure occurred with one disk (45 hours) of data from the August 2015 SCC data collection upon receipt in San Diego. However, monitoring notes exist for this time period and report the number of beaked whale dives and the absence of baleen species. This partially fills the data gap but since valid acoustic data is not available, this period cannot be reprocessed for additional species and detailed analysis regarding animal exposures and species validation cannot be performed. There are ongoing efforts investigating secure data recovery. An issue with the Inter-Range Instrumentation Group (IRIG) time code amplitudes varying has been detected in some FY15 data sets. Some automated DCL algorithms rely on valid IRIG time code to operate. Modification of the algorithms has remedied this issue for some of the data sets, and investigation of the cause of the amplitude variations will be conducted when personnel next visit PMRF.

Table 1. Approximate number of hours of multiple channel hydrophone data since data collections started in 2003.

Number of hydrophones recorded	Sample rate (kHz)	Hours of acoustic recordings				
		Feb 2002-Sep 2006	Mar 2007-Jan 2011	Jan 2011-Aug 2012	Aug 2012-Sep 2014	Oct 2014-Aug2015
24	44.1	722				
31	96		2915	2414		
62 (incl. all 41 BSURE replacements)	96				1952	1203
47 (decimated data)	6				676	4422

Automated Processing Algorithms

Automated DCL processing has evolved over time as new capabilities were added (e.g. new species included and new capabilities such as localizing and tracking whales), and multiple MATLAB and C++ algorithms have been utilized. MATLAB algorithms were typically used for processing recorded data only, while the C++ algorithms were utilized to process both recorded data and real-time data streams in the M3R system (Jarvis et al. 2014).

A custom C++ algorithm (UDPListen.exe) was used to detect all species except humpback whales (*Megaptera novaeangliae*) and has been included in the Department of Navy Application and Database Management System (DADMS) at SSC Pacific. The current version of the UDPListen.exe code (baseline 2 dated February 2015) includes sperm whale processing and updates to the detection algorithms for beaked whale foraging clicks. UDPListen.exe utilized the same front end processing for all species and was described in detail in Martin et al. 2015 (Appendix A). The front end processing utilized 16k sample length FFTs which provided improved signal to noise ratios compared to processing with shorter length FFTs such as in the M3R system (i.e. 2k sample FFT's). Different frequency bands were processed for various species calls (e.g. low frequency baleen calls were processed under 100 Hz and minke whale boing calls were processed from 1350 to 1440 Hz). Beaked and sperm whale detection processing was performed over the full 48 kHz bandwidth and required specific ratios of in-band energy (24-48 kHz for beaked whales and 3-10 kHz for sperm whales) to out-of-band energy (5-24 kHz for beaked whales and 20-48 kHz for sperm whales). Decimated data was sampled at 1/16th the full band rate with 1k FFT's for the same spectral bin resolution. Detection processing also required marine mammal vocalizations to have signal duration thresholds (e.g. the first stage of minke whale boing detection requires the call to be at least 0.8 seconds duration).

Classification processing was also performed within UPDListen.exe for minke and beaked whales. Minke whale boings were classified by reprocessing the detections to generate sub-hertz spectra for extracting features for classification (Martin et al. 2015; Appendix A). Beaked whale foraging echolocation clicks were classified by reprocessing for high temporal resolution and requiring up-sweep frequency modulation fitting with literature for Blainville's and Cuvier's beaked whales (Johnson et al. 2006; Zimmer et al. 2005). Beaked whale ICIs were also utilized for species classification.

A separate C++ model based localization algorithm (C3D.exe described in Martin et al. 2015; Appendix A) was implemented in 2013. This algorithm localized baleen calls and sperm whale clicks by utilizing automatic detector start times across multiple hydrophones (with a minimum of four, and up to dozens of hydrophone detections included in individual localizations). This method was chosen over the more computationally intensive process of cross correlating multiple hydrophone pairs. C3D.exe also provided an ability for detections and localizations to be replayed over time for situational understanding (including ship positions and tagged animal positions) and has been employed in real-time at PMRF in the M3R system, as well as on recorded data at the SSC Pacific DCLTDE Laboratory.

In addition to performing DCL for marine mammal vocalizations, the UDPlisten.exe and C3D.exe algorithms also included capabilities to detect and localize active sonar transmissions in the mid-frequency band (1 to 10 kHz). This allowed for precise information on the locations and times of MFAS transmissions for use in estimating received levels on marine mammals and behavioral response analyses.

MATLAB algorithms employed include: 1) Generalized Power Law (GPL) detection (Helble et al. 2012) and model-based localization using cross correlation for determining relative arrival times and 2) tracking of localizations using automatically generated localization reports. The MATLAB GPL detection algorithm was initially incorporated for detecting and localizing humpback whales using sequences of song units (Helble et al. 2015; Appendix B). This localization method allowed some capability for depth determination (Ireley et al. in prep). These algorithms were also utilized for other species (e.g. Bryde's whales, Helble et al. 2016 in prep; Appendix E). The MATLAB tracking algorithms organized localizations into separate tracks of individuals utilizing species-specific call intervals and call rates. Track-before-classification processing was done for low frequency baleen whales (i.e. tracks were established before species determination). These tracks can also be used to statistically characterize features of the calls' (e.g. frequencies, intervals and durations) and potentially relate kinematic variables with different behavioral states.

FY15 automatic processing results for presence, occurrence and relative abundance

Immediately after receiving acoustic data recordings and creating backups for data integrity, automated processing was performed to establish basic presence on range information for species with currently implemented automated algorithms (i.e. a 'quick look' analysis). The quick look analysis provided unvalidated relative species abundance as the number of automatically localized calls per hour (Figures 1-3) and automatically grouped beaked whale group foraging dives per hour (Figure 4).

Metrics were plotted on a semi-log scale and values below 0.01 were plotted as 0.01. Spurious localizations that were spatially and temporally isolated may result in values over 0.01 in quick look analyses. Metrics were also normalized by the duration of a dataset to obtain the number of localizations or dives per hour. It is important to consider the effect of dataset duration (width of gray regions in Figures 1-4) when interpreting the normalized metric in order to understand the raw number of localizations or dives that occurred.

Notice that with the addition of the decimated data collections (Figures 1-3) 56% of the total time between October 2014 and August 2015 was captured in recordings. Full bandwidth collections accounted for 15% of the same total time period, with more collections in the months of training compared to full bandwidth baseline collections (e.g. two days a month). Full bandwidth data collected for 62 hydrophones provided 45 hours of data for a 2TB disk drive while decimated data provided over 30 days of data for the same 2TB of storage. The decimated data was important for obtaining baseline information on baleen species for comparison to observations made during training events. Baseline information for baleen whales was related to metrics such as: how often localized individuals were on the range and the kinematics of how they moved (swim patterns, speeds, dive depths, etc.), in conjunction with details of the calls they made when localized (e.g. call intervals, durations of single calls and sequences of calling, frequencies, and bandwidths). Data collection periods without data points were for datasets with IRIG time issues (discussed previously) and further effort is required to process them.

Figures 1-4 were a result of fully automated processing and were not validated or fully characterized to ensure automatic results did not include false positives (incorrect species classifications). Notice that the vertical scale is a log scale with 10^0 indicating an average of one localization per hour, which seems low. However if the data collection was a decimated collection lasting 10 days, this relates to 240 localizations, which if concentrated temporally and spatially would likely indicate whale presence, but if not could be false positives.

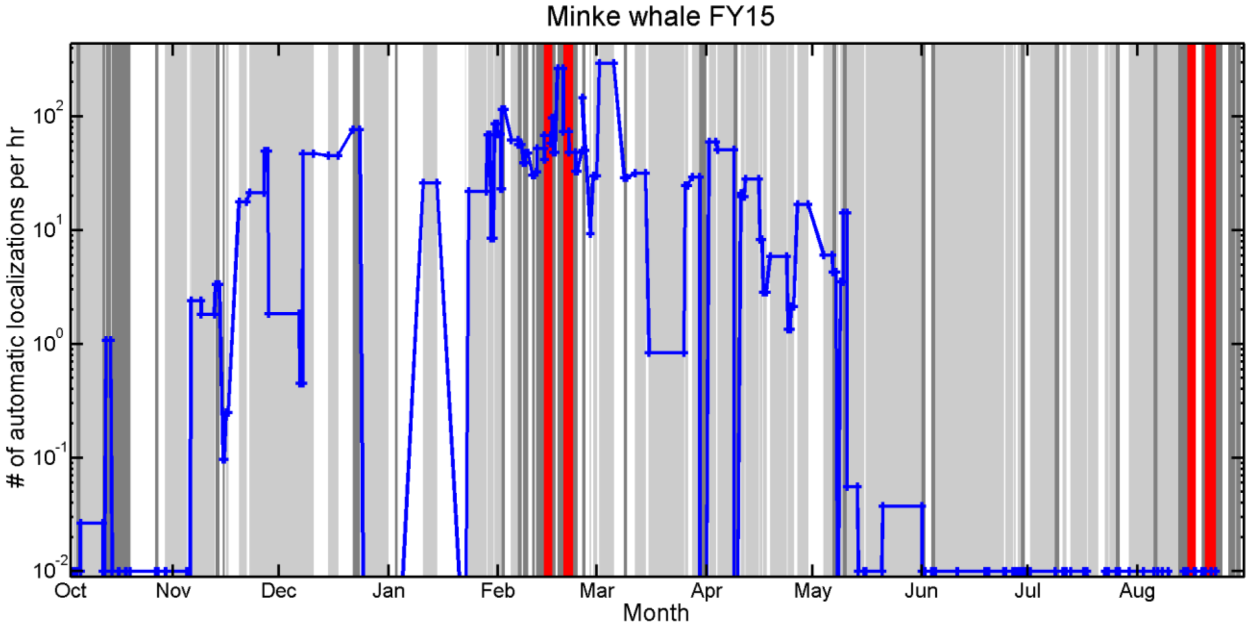

Figure 1. Number of automatically localized minke whale boing calls per hour. Gray shaded regions indicate availability of full bandwidth data (dark gray) or decimated data (light gray). White indicates periods of time when no data was collected. Red shaded regions were during phase A and B of the February and August SCCs when only full bandwidth data was collected. As automatically detected calls attributed to minke whales are also automatically classified, automatically processed minke whale results have few localized false positives.

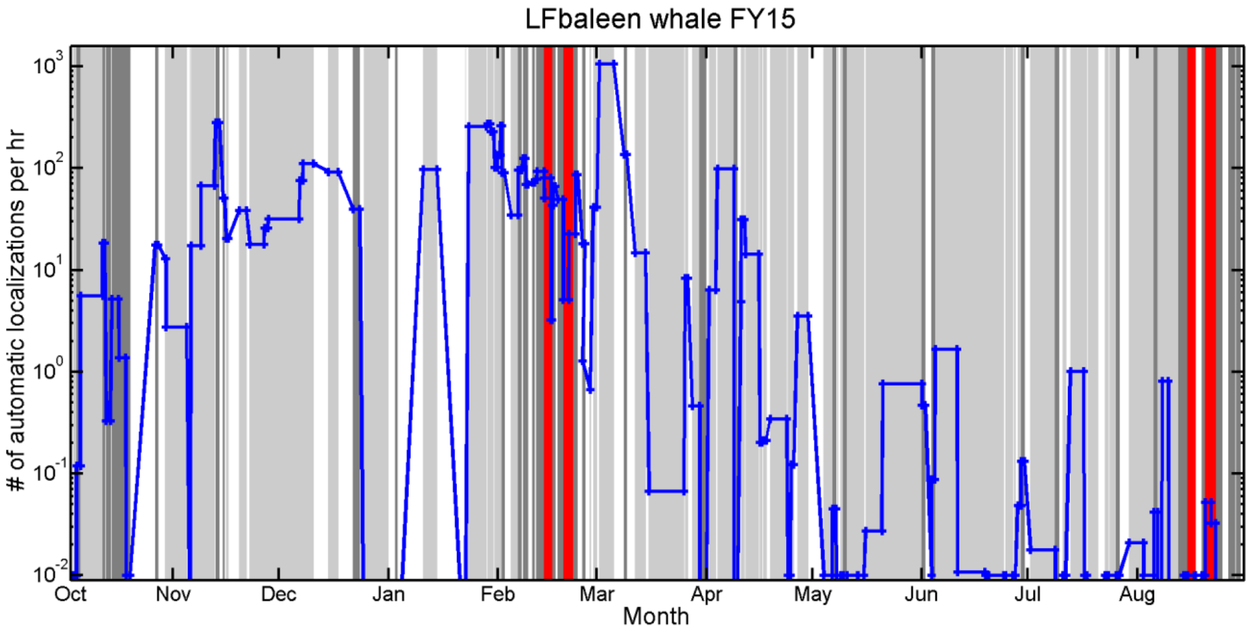

Figure 2. Number of automatically localized low-frequency baleen whale calls per hour. Gray shaded regions indicate availability of full bandwidth data (dark gray) or decimated data (light gray). White indicates periods of time when no data was collected. Red shaded regions were during phase A and B of the February and August SCCs when only full bandwidth data was collected. Low-frequency baleen peaks outside of the expected seasonal presence could indicate localizations from low-frequency baleen species such as Bryde's whales, which are present year round. These are unvalidated automatic results and require validation to associate localizations with a low-frequency baleen species.

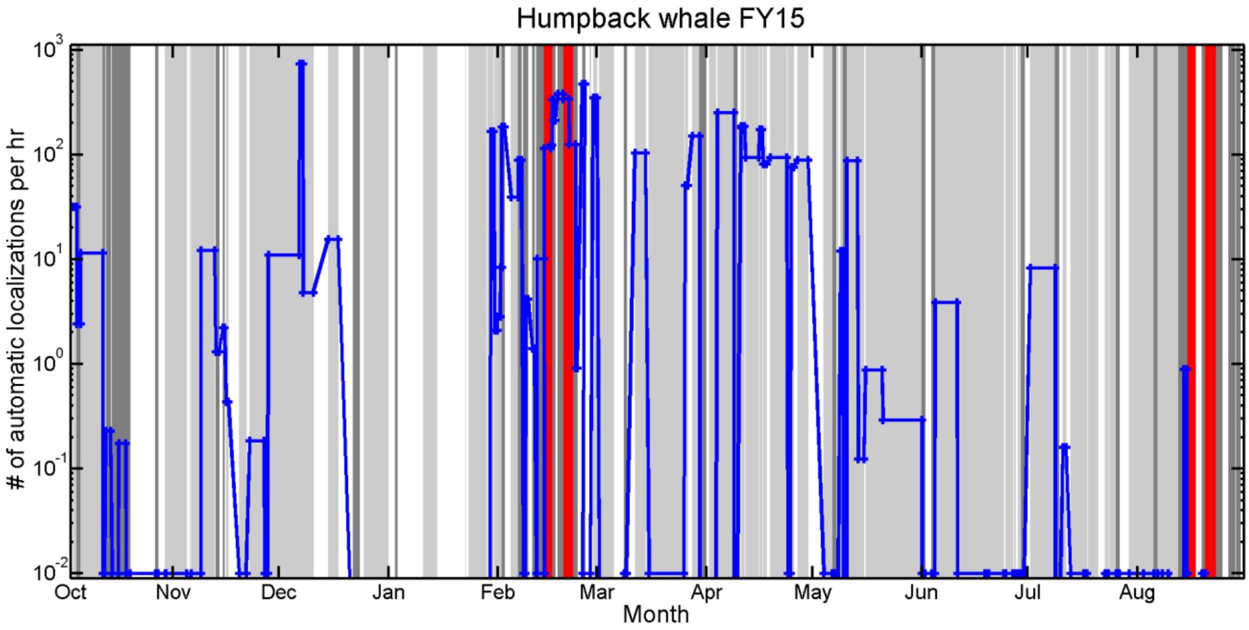

Figure 3. Number of automatically localized suspected humpback whale calls per hour. Gray shaded regions indicate availability of full bandwidth data (dark gray) or decimated data (light gray). White

indicates periods of time when no data was collected. Red shaded regions were during phase A and B of the February and August SCCs when only full bandwidth data was collected. Peaks outside of the expected seasonal presence could indicate localizations that are not humpback whales. These are unvalidated automatic results and require validation to ensure they are humpback localizations.

Tracking of localizations is being implemented for automatically localized baleen whales. Current semi-automated kinematic tracking allows counting individuals which are calling, and these processes are being refined to enable density and abundance estimation. For this baleen whale analysis the metric utilized to estimate basic presence on range was the number of localizations per hour since it significantly reduced false positives compared to automatic call detections. Species that emitted calls at more rapid rates had higher numbers of localizations for a single individual per unit time. For example, humpback whales produce song units every few seconds (Figure 3) and had more localizations per hour than minke whales (Figure 1). For data collected during the February 2015 SCC (175 hours) humpback whales had an average of two times more localizations than minke whales, although there was an average of five times more individual minke whales tracked than individual humpback whales tracked. Thus, one should not compare the number of localizations across species without considering the species' call rates.

Notice that presence and abundance of migratory species (humpback, minke, and some low frequency baleen whales) shown in Figures 1-3, corresponds to expected seasonal migratory trends. Some humpback data points that occurred out of season (e.g. detections in October-November and July-August) could be from other sources of sound in the humpback whale vocalization band and additional manual validation effort is required to ensure they are humpback localizations. The additional manual verification effort has been performed when reporting on specific details (such as the estimated exposure analysis described later, and reports provided in the appendices). As an example, the quick look plot for humpback whales (Figure 3) has a peak in late June and into July for a long term recording. Preliminary investigation shows 1403 localizations temporally and spatially clustered indicating an actual track, with additional effort required to determine if it was a humpback whale or some other source. Some peaks for low-frequency baleen localizations that have occurred out of the expected seasonal trend for migratory baleen whales have corresponded to the presence of Bryde's whales, which are present year round (Martin and Matsuyama 2014, Helble et al. 2016 in prep; Appendix E). Automatically processed sperm whale detections and localizations results were not included herein as this capability is still being refined.

The low frequency (i.e. under 100 Hz) baleen whale detection and localization process can detect multiple species' calls (e.g. fin, sei, Bryde's whales and potentially blue whale calls), but confusion exists in terms of automatically assigning calls to specific species. Rankin and Barlow (2007) documented calls from sei whales just north of Maui, with the majority of calls consisting of 39 Hz to 21 Hz down swept calls with 1.3 second durations. The species identification was made by an experienced team of observers and was confirmed with biopsy samples. These types of calls had previously been thought to be attributed only to fin whales. Two other sei whale calls were also documented by Rankin and Barlow (2007), both sweeping down from 100 Hz to 44 Hz with 1 second durations which are also similar to other *Balaenoptera* species calls. When 20 Hz pulses were present in that data, the calls were assigned to fin whales. As to date these calls have not been attributed to any other species.

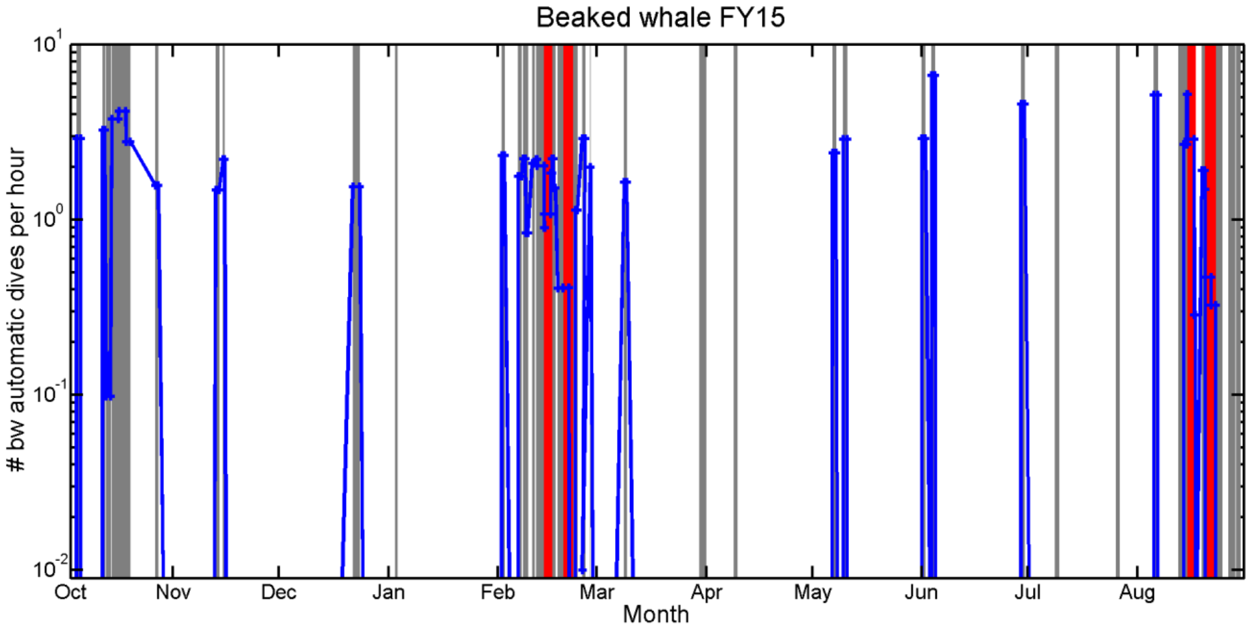

Figure 4. Number of automatically grouped beaked whale group foraging dives per hour. Gray shaded regions indicate availability of full bandwidth data (dark gray). Decimated data collections are not shown due to insufficient bandwidth for processing beaked whale clicks. White indicates periods of time when no data was collected. Red shaded regions were during phase A and B of the February and August SCCs when only full bandwidth data was collected. The false positive rate for automatically grouped beaked whale foraging dives has been shown to be a variable rate and was 3 to 42% of the total number of groups in 2013.

The beaked whale foraging click detector (Figure 4) includes appreciable and variable false positives from other echolocating odontocetes. Results to date for manually validated beaked whale foraging dives have shown a variable rate of false positives; for example, in 2013 the rate of false positives varied from 3 to 42% of the total number of groups. The probability of detecting beaked whale clicks primarily depends on the click's signal-to-noise (SNR) ratio. The requirement for detecting a beaked whale group foraging dive was to set a high detection SNR to primarily detect clicks when an animal is scanning towards a bottom hydrophone. This is justified as a group of three beaked whales in a 20 minute dive vocal period can produce over 10,000 foraging clicks at three clicks per second. Characterization of the beaked whale foraging click detector has been done (Manzano-Roth et al. 2016 in prep; Appendix D) indicating that for a beaked whale click with a SNR over 25 dB the probability of detecting clicks was 0.39.

Manual validation of automatically detected and grouped beaked whale foraging group dives was performed during follow-on detailed analyses to ensure that false positives were removed (such as done in Appendices C and D).

MFAS exposures, estimated received levels, and PAM determined behavioral responses

Estimation of received levels on marine mammals at PMRF during U.S. Navy training was done utilizing acoustic propagation modeling in combination with ship and animal relative geometries and the timing of MFAS transmissions. In order to determine when MFAS activity occurred, MFAS block times were created from range products and PAM localized MFAS transmissions. MFAS block times define when individual platforms begin and cease transmitting. When gaps with no MFAS activity occurred over several minutes a new MFAS block was started. For estimating individual received levels on animals the precise times of single MFAS transmissions were utilized.

There are multiple advantages and disadvantages to both BRS-type studies and marine mammal monitoring during actual training events. BRS studies do control more variables and have acoustic capable tags on animals prior to exposures, allowing direct measurements of received levels as well as animal x, y, and z movements while the tag is attached. However, there are potential concerns in several areas: the act of tagging and focal following animals with small boats may alter their behavioral states; high costs are involved with the activity; a relatively small number of exposures are obtained; and simulated sonars from nearby vessels are often used, or if actual sonars are used they are not employed in a tactical manner. Monitoring of actual U.S. Navy training events has two major disadvantages. No information is obtained when animals are not calling, and there is a lack of experimental control. However, monitoring of actual U.S. Navy training events has multiple advantages: it is non-invasive to animals; it can be done for a relatively low cost; extensive baseline observations are possible; large numbers of exposures can be monitored; and actual U.S. Navy sonars are employed in a tactical manner. In addition, monitoring U.S. Navy hydrophone assets on ranges covers very large areas compared with many BRS studies (e.g. Martin et. al. 2015; Appendix A showed calling minke whales reduced densities in an area of 3,780 sq. km). Combining PAM monitoring of U.S. Navy training results with BRS study results could improve the understanding of behavioral responses of marine mammals to MFAS exposures.

Previous reports have documented some estimated received levels of marine mammals during U.S. Navy training events that were detected by various modalities including: shipboard observers, PAM detections, aerial sightings (e.g. Martin and Kok 2011), and satellite tagged animals (Baird et al. 2014). Estimation of received levels for marine mammals detected using these methods was made possible by utilizing state of the art passive acoustic DCL algorithms. However, these efforts still required significant manual interactions, such as determining which localizations were from which individuals, species identification using passive acoustic data, and propagation modeling using the U.S. Navy's Personal Computer Interactive Multisensor Analysis Training (PCIMAT), which required significant operator interaction for inputting data and logging results. Efforts in FY15 included transitioning to use of a parabolic equation acoustic propagation model (Peregrine) developed by Ocean Acoustical Services and Instrumentation System Incorporated. Peregrine was utilized to improve the process for reporting estimated exposures, with better defined estimates (e.g. mean values with standard deviations over both depth uncertainty and range uncertainty). Various propagation models (e.g. PCIMAT, Peregrine, and the sonar equation) agreed fairly well for shorter distances (under several km), however they often diverged from each other at longer distances (over 10 km) due to the complexities of actual vs. modeled sound velocity profiles, and surface and bottom interactions.

Additional semi-automated methods are now available which help reduce the manual effort involved in the estimation of received levels and determination of potential behavioral responses. Specifically, recent ONR- and LMR-sponsored efforts in the DCLTDE Laboratory have resulted in two different methods for tracking individuals based upon model-based localizations. In addition, batch mode propagation modeling methods used with the Peregrine parabolic equation propagation model, along with the sonar equation which incorporates spherical and cylindrical spreading loss and absorption effects. However, even with the addition of the newer methods the process to analyze and present results for individual ship – animal encounters and estimate received levels requires significant manual effort (e.g. ensuring no land mass shadowing between the source and the receiver, ensuring no calls were missed, validating calls in localizations, attempting to verify species based upon the acoustic parameters of localized calls, and determining ship-animal encounter geometries).

The test cases presented in this report were conducted to work out methods and identify modifications to the automated processes that will reduce manual interactions, thus enabling the estimation of large numbers of ship-animal exposures and potential behavioral responses (or lack thereof). The sonar equation was utilized for estimating received levels throughout this report unless otherwise noted. With more automated processes one could determine cumulative sound exposure levels on animals from the various sources involved, rather than reporting instances of maximum estimated received sound pressure levels. In addition to the distance between the MFAS ship and whale being documented, the angle off the bow of the MFAS transmitting ship relative to the whale was documented as an additional covariate to consider in ship-animal encounters. Unpublished observations during prior U.S. Navy training has shown a minke whale ceased calling when a surface ship was moving towards it but not transmitting MFAS (S. Martin, personal observation). For security concerns the angle off the bow is presented in terms of 90 degree sectors centered on the bow, port and starboard beams, and the stern of the MFAS ship (i.e. bow sector is +/- 45 ° from the bow, beam sectors are +/- 45 to +/-135 ° and the stern sector is +/- 135 to 180 °). Proposals have been submitted to ONR and LMR for 1) developing methods to determine robust baseline kinematic tracks for baleen whales for comparison to exposure data to estimate responses, and 2) developing tools for automating the steps that require the most manual interactions when performing exposure analyses.

The February 2015 Submarine Commanders Course training event and related data collections (e.g. before, during and after) included other training activities (Table 2). Data collected from the before period had an ASW submarine tracking training event (termed SUBEX) occur on February 5, 2015 (GMT) for which neither acoustic data or range products were obtained (all times mentioned henceforth are in GMT). The weekend data collection had an Amphibious Warfare Naval Surface Fire Support training event occur (termed FIREX) on February 15, 2015 and an ASW surface tracking event occur (termed USWEX) on February 15 and 16, 2015. The FIREX involved both inert and high explosive rounds and used an area of the ocean to represent land. Acoustic data is currently only available for the FIREX and USWEX. The USWEX involved surface ship MFAS activity and an analysis of three whales (two fin whales and one minke whale) exposed to MFAS was conducted. Behavioral responses were determined to have occurred and were documented. The onset of phase B SCC also includes analysis of a minke whale exposed to MFAS and behavioral responses.

Table 2. Chronology of the events and data collection efforts associated with the February 2015 SCC training event.

	Acoustic data	Range products	Start day/time (GMT)	End day/time (GMT)
Before	Y*	N	4 / 17:55	5 / 16:25
SUBEX	N	N	5 / 17:30	6 / 02:30
Before	Y*	N	6 / 02:36	12 / 02:00
SCC Phase A	Y	Y	12 / 02:23	14 / 08:00
Weekend	Y*	N	14 / 08:13	15 / 06:00
FIREX	Y	N	15 / 17:40	15 / 21:00
USWEX	Y	N	15 / 22:32	17 / 10:06
SCC Phase B	Y	Y	17 / 10:11	19 / 14:12
After	Y*	N	20 / 01:07	21 / 11:42
			22 / 20:43	24 / 16:30

*acoustic recording data gaps exist for various reasons (e.g. range replaying data in preparation for training, power outage, and time code signal issues).

Fin and minke whale exposures, est. received levels and responses: February 15-16, 2015

MFAS activity occurred during the ASW surface tracking training (USWEX) for 2 hours and 10 minutes between 22:32 February 15, 2015 and 00:42 February 16, 2015. The MFAS activity was a single MFAS block as the transmissions occurred throughout the 2 hour and 10 minute period. Over this period there were three whales automatically localized, two were from low frequency baleen whale call detections and one was from minke whale boing call detections. The two low-frequency baleen whale localizations were presumed to be fin whales since these tracks contain 20 Hz pulses with ICIs of approximately 28 seconds, which fits well with published information on fin whales (Watkins et al. 1987).

Figure 5 illustrates the encounter of the MFAS surface ship with the three whales. The gray areas in Figure 5 indicate the approximate locations of the MFAS transmissions, with three star symbols indicating approximate ship locations for estimated MFAS exposures to the three separate whales. The first exposure, with an estimated received level of 156 dB re 1 μPa, occurred near the start of MFAS transmissions at 22:32 February 15, 2015 on a presumed fin whale (indicated as whale 1) located 14 km off the port beam sector of the ship. Whale 1, which had been calling for the previous 60 minutes, indicated by the orange line track, went silent after the first MFAS transmission. This is considered a potential behavioral response to MFAS resulting in a cessation of calling, and more information regarding fin whale baseline calling behavior needs to be determined to establish certainty.

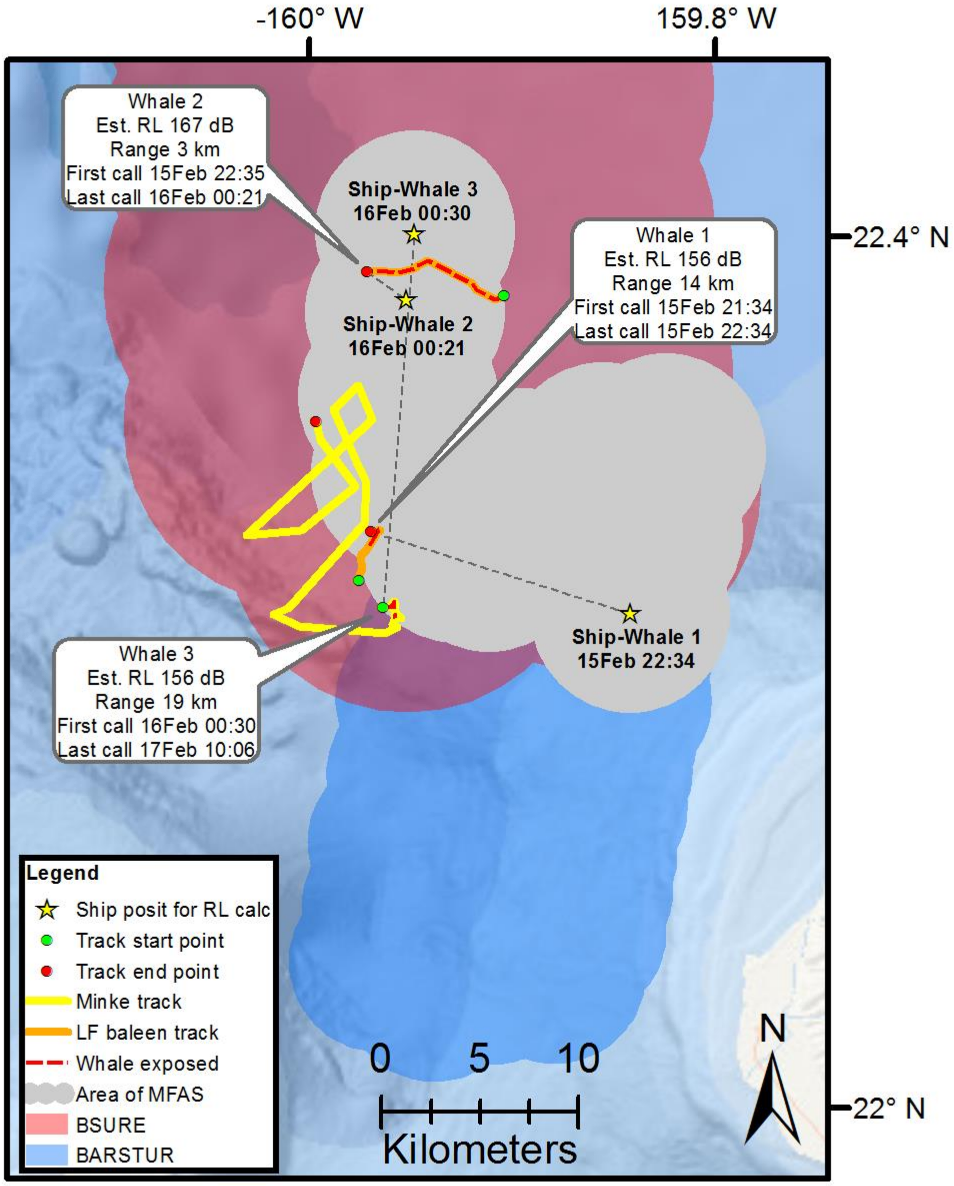

Figure 5. Situational map display showing areas of MFAS, tracks attributed to two fin whales and one minke whale, approximate ship locations for three estimated exposures and PMRF hydrophone range areas. The red highlighted area indicates the location of the BSURE range and the blue highlighted area indicates the location of the BARSTUR range. The light gray area indicates the areas of surface ship MFAS activity during the USWEX. Tracked whales' first and last call times are listed along with estimated received levels which correspond to MFAS locations indicated by the star symbols. The red dashed line within an animal track indicates when an animal was exposed to MFAS. The gray dashed lines associate ship and whale positions at the time of an MFAS exposure for which received levels were estimated.

The second estimated received level was performed near the end of the MFAS activity for the presumed second fin whale termed whale 2. Whale 2 was localized initially at 22:35 February

15, 2015, just three minutes after MFAS began and a minute after whale 1 ceased calling. Whale 2 was undoubtedly not the same animal as whale 1 since movement of an individual over 13 km in one minute is unrealistic. Whale 2 was located 17.9 km off the port beam sector of the transmitting MFAS ship at the time of its first localized call. Whale 2 continued to vocalize, and was localized travelling west of its initial position while the MFAS ship continued transmitting and getting closer to the whale for the next 1 hour and 46 minutes. Whale 2 was therefore exposed to MFAS from the surface ship the entire time it was localized. The closest point of approach of the ship to whale 2 was analyzed to represent the maximum estimated received level on whale 2. The star symbol in Figure 5 labeled 'Ship-Whale 2 16 Feb 00:21' indicates the ship's approximate location for the estimated maximum received level on whale 2 of 167 dB re 1 µPa while located 3 km off the port beam sector of the ship.

Near the end of the MFAS activity on February 16, 2015, a minke whale (whale 3) was localized approximately 18 km off the stern sector of the MFAS ship with an estimated received level of 156 dB re 1 µPa. This received level is likely biased high as it does not account for shadowing of whale 3 as it was located nearly directly off the stern. Whale 3 continued vocalizing while receiving lower exposures from the MFAS ship as it continued heading to the north, until the end of the MFAS block at 00:42 on 16 February 2015.

These ship-whale encounters document two presumed fin whales' apparent behavioral response by ceasing to vocalize due to SCC training with MFAS. This response is typical of fin whales since irregular gaps in calling for 20-120 minutes has often corresponded with the onset of loud sounds such as the start-up of propeller cavitation and sonar, and also the close approach of ships and other whales (Watkins 1986, Watkins et al. 1987). It is reasonable to suggest that whale 1 ceased calling due to the onset of MFAS with an estimated received level of 156 dB re 1 µPa. However, whale 2 began calling after the onset of MFAS and continued to vocalize until the combination of increasing received levels (max 167 dB re 1 µPa) and an approaching ship resulted in a cessation of calling. The cumulative exposures for these two situations prior to the cessation of vocalizations are quite different and illustrate the contextual importance of the onset of MFAS and ship orientation. In contrast, the minke whale (whale 3) continued to vocalize after the onset of MFAS and while exposed to MFAS with an estimated received level of 156 dB re 1 µPa from a ship increasing its distance from the animal.

Whale 3 actually continued vocalizing over the next 33+ hours with no MFAS activities occurring until the onset of the SCC phase B activities. At 10:06 on 17 February 2015 a recording disk change occurred. The approximate track of this minke whale (whale 3) over this entire 33+ hour period is indicated in Figure 5, with the animal meandering on the south-west portion of the BSURE range. The track for whale 3 was automatically generated using a custom MATLAB program from automated localizations which satisfied certain tracking parameters such as: the distance traveled between calls was reasonable for the species; 8 or more hydrophones were used in each localization solution; a maximum least squared error of 0.1 was required for valid localizations; at least 10 elements (calls) were required in a track; and a maximum time of 2400 seconds was allowed between calls in a track otherwise a new track would be established. The tracking program showed this minke whale emitted 293 calls and stayed within an area between 22.2° to 22.34 ° latitude and -159.95° to -160.05° longitude. The automatically determined call interval over this day and a half period was ICI mean of 411.1 seconds (± 187.3 seconds) with a range of 182.8 to 2131.3 seconds.

February 17, 2015 SCC phase B onset minke whale estimated exposures

Figure 6 provides information similar to Figure 5 for data between 10:11 to 14:17 on February 17, 2015, although on a larger scale showing the entire PMRF range complex. The onset of MFAS training in SCC phase B occurred at 12:01 on 17 February and is of special interest for observing potential behavioral responses of calling whales to MFAS activity. Several minke whale tracks are shown during this time period, both on the range and to the west of the range. At least two minke whales located to the west of the range were emitting calls at a rapid rate, with ICIs on the order of 0.5 minutes. The gray area in Figure 6 illustrates the areas of MFAS activity from participating MFAS surface ships (more than one involved) for the first two MFAS block times of 12:01 to 12:50 and 13:50 to 14:17. Two exposures are shown on what is believed to be the same minke whale as whale 3 in Figure 5. This minke whale (whale 3) was used for estimation of received levels given it was located closest to the MFAS ships at the onset of phase B of the SCC training.

The first exposure shown in Figure 6 is for whale 3's last call at 12:11 on February 17, 2015 before going quiet, which was 10 minutes after the first surface ship's MFAS transmission in phase B of the SCC training event. The star symbol labeled "Ship-Exposure 1" indicates the ship's approximate location for the estimated received level of 167 dB re 1 μPa for whale 3 located 3 km off the bow sector of the ship. Whale 3 exhibited a cessation of calling under similar circumstances as the first presumed fin whale (whale 1), in which they both ceased calling almost immediately after the onset of MFAS activity. It appears the same animal (whale 3) resumed calling at 12:58 when no MFAS activity was occurring and was located 3.9 km to the NW of its last location at 12:11. While it is not certain this second group of calls was from the same minke whale (whale 3), it is a reasonable assumption given that the average swim speed over the 47 minutes would need to be 5 km/h, which is a reasonable swim speed for a minke whale. The direction was away from the location of the MFAS ship and the Dominant Signal Component (Martin et al. 2014) observed on the bottom hydrophones was similar to those from whale 3 (1397 Hz +/- 2 Hz). Presumed whale 3 ceased calling a second time just prior to when the surface ships began the second block of MFAS activity. The second received level (labeled "Exposure 2" in Figure 6) was estimated to be 160 dB re 1 μPa for presumed whale 3 located 11 km off the starboard beam sector of the ship (i.e. +45° to + 135° from the bow).

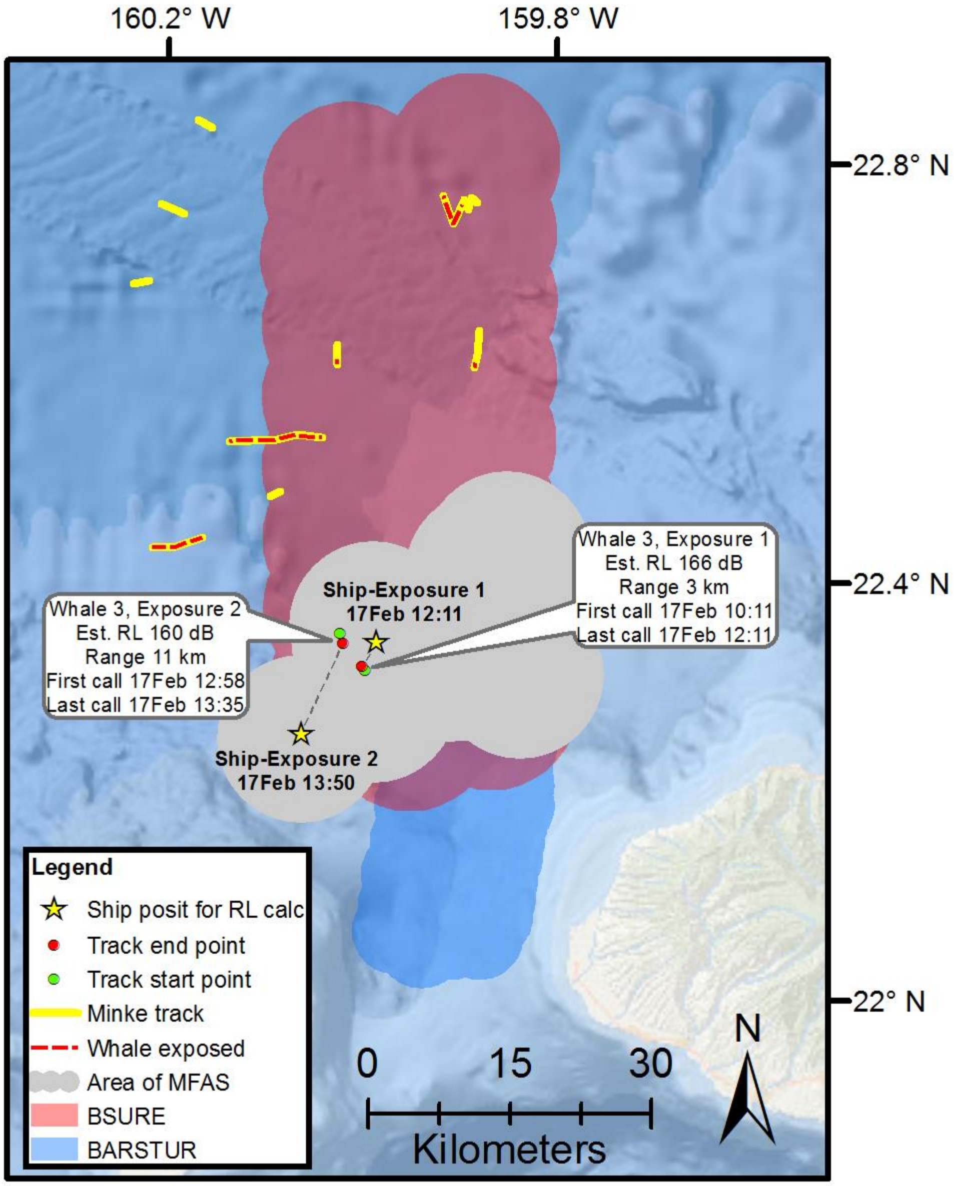

Figure 6. Locations for a minke whale between 10:10 to 14:17 on February 17, 2015. The red highlighted area indicates the location of the BSURE range and the blue highlighted area indicates the location of the BARSTUR range. The light gray area indicates the areas of surface ship MFAS activity over this period for the onset of the SCC phase B activity occurring at 12:01. Tracks of multiple minke whales are plotted in yellow. Two estimated received levels are shown for a minke whale, along with the approximate ship locations at the time of the exposures indicated by the two star symbols. The red dashed line within animal tracks indicates when animals were exposed to MFAS. The gray dashed lines associate ship and whale positions at the time of an MFAS exposure for which received levels were estimated.

This ship-whale encounter is complex in that multiple MFAS ships are involved and appears the same minke whale (whale 3) not only ceased calling but resumed 47 minutes later and ceased a second time after calling for 37 minutes. It is presumed that this encounter involved the same minke whale since there were small spatio-temporal differences between the two exposure tracks and similar dominant spectral components (defined in Martin et al. 2015; Appendix A) of the localized calls. Although minke whale boing behavior specifically regarding time between calling bouts is not well documented, it is not rare to observe similar pauses as described during calling bouts for PAM tracked minke whales at PMRF (personal observation S. Martin and C. Martin). Figure 7 provides detailed time series plots of this ship-animal encounter to better convey the timing involved between 10:10 (recording media changed) and 14:17 (end of MFAS block 2) on February 17, 2015. Figure 7 subplot 1 provides the automated (and manually verified) minke whale boing call intervals for whale 3 over this period. Each symbol indicates the time a call was emitted on the x-axis with the y-axis indicating the call interval to the next call in the sequence on a log scale. Between 10:11 and 12:11 the minke whale emitted 16 calls (mean ICI=467.5 s +/- 175 s, range =281 - 904 s) which compared favorably with the 293 earlier calls from whale 3 (mean ICI=411.1 s +/- 187.3 s).

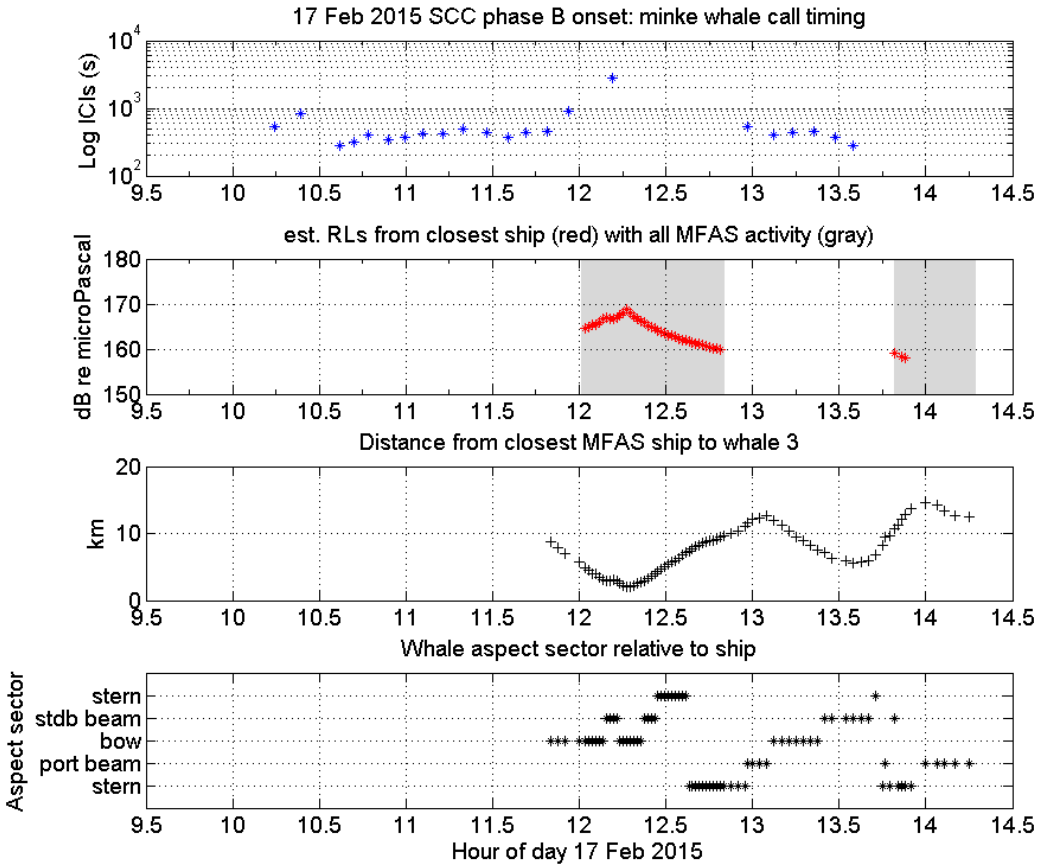

Figure 7. Details of the minke whale encounters with MFAS ship(s) at the onset of phase B training from 10:10 to 14:17 GMT on February 17, 2015. Figure 7 consists of 4 subplots, from top to bottom: 1) minke whale (whale 3) call timing, 2) estimated received levels from the closest MFAS ship and the first two MFAS blocks from all ships shown in gray, 3) the distance between the closest ship and whale 3, and 4) the relative aspect of whale 3 to the closest ship.

The onset of MFAS activity for the onset of phase B of the SCC occurred at 12:01 as shown in Figure 7, which is the first MFAS activity on the range since 00:42 on February 16 (over 35 hours of no MFAS activity). The MFAS activity started at 12:01 on February 17 and occurred after whale 3's 15th call and before its 16th call. The ICI between these two calls was 904 seconds, which is about two standard deviations from the mean and could indicate an additional behavioral response to the calling pattern of the whale. However, a large number of ship-whale encounters need to be analyzed to determine if there is a statistical correlation of ICIs increasing when exposed to MFAS. Analysis for larger numbers of ship-animal encounters is planned and will be reported in subsequent reports.

Figure 7 subplots 3 and 4 provide distance and relative aspect of the whale to the ship's bow; ship positions were not available until the beginning of the phase B training event at approximately 11:50. Figure 7 subplot 3 illustrates the ship heading towards the whale (indicated by the bow sector aspect) with the distance (Figure 7 subplot 2) decreasing from 9 km to approximately 3 km at 12:11, the time of whale 3's last call for 47 minutes. Estimated received levels are shown in Figure 7 subplot 2 for each closest ship position from the onset of the MFAS activity at 12:01 to 12:11 utilizing the whale's positions nearest in time. The estimated received levels increased from 163 dB to 166 dB re 1 µPa over this time period. Estimated received levels between 12:11 and the whale's next call localization at approximately 12:58 were calculated assuming the whale traveled silently from the two locations, which were 3.9 km apart and at a constant velocity of 5 km/h over 47 minutes. The closest ship to whale 3 transmitted MFAS over the full duration of the first MFAS block times.

Figure 7 shows presumed whale 3 commence calling again just several minutes after the MFAS activity ceased (i.e. after the end of the first MFAS block period). The closest ship continued getting farther from whale 3 until 13:05 when it was over 10 km away and changed course and began heading closer to whale 3. Whale 3 was observed to only emit six calls from 12:58 to 13:35 as the closest ship got within approximately 5 km of the whale without MFAS activity occurring during the time. Given that MFAS activity did not began again until 13:50, this encounter without MFAS could have elicited a cessation of calling behavioral response from the closest ship approaching within about 5 km of the whale. Some estimated received levels for the closest MFAS ship to whale 3's last known location are shown from 13:50 to 13:57, with the highest estimated received levels under 160 dB re 1 µPa for distances over 10 km.

Summary of Ship-Whale Encounters, MFAS Exposures

Table 3 summarizes the ship-whale encounters described above. All estimated receive levels were based upon the sonar equation, with the exception of the Peregrine levels provided in Table 3. The Peregrine propagation model provided a mean and standard deviation for animal depths between 10 and 30 m with a range uncertainty of +/- 300 m. This analysis serves as a test case for investigating different types of analyses that are possible during U.S. Navy MFAS training events. Given the manual effort currently required in performing this type of analysis, the test case serves to identify areas where additional automation can significantly reduce the amount of manual effort. The test case also serves to document the types of results possible for evaluating the most appropriate types of analysis desired. This analysis could be vastly expanded to include all animals that are localized over the full duration of the SCC training event (phase B lasts on the order of 2.5 days). In addition, for instances where one whale is exposed to multiple MFAS transmitting ships, a cumulative sound exposure level-type metric could be utilized and include MFAS exposures from all ships, however providing details for multiple ships has information security related issues for unclassified venues.

Table 3. Summary of ship-whale encounters described 15-17 February 2015. Estimated received levels are only calculated when a calling whale is in the presence of MFAS activity. Distances are determined as a transmitting or non-transmitting ship's closest point of approach to a whale, or the distance to a whale's last localized position before ceasing to vocalize. Exposure durations are the difference between the time of an animal's first and last localizations that coincide with MFAS activity.

Date Time (GMT)	Training Event	Whale species	Sonar eqn. est. RL (dB re 1µPa)	Peregrine mean RL (dB re 1µPa)	Peregrine st. dev. (dB re 1µPa)	Distance to closest ship (km)	Exposure duration while calling(min)	Behavioral response
15 Feb 22:34	USWEX	fin (whale 1)	156	161	0.1	14	1	Cessation of calling at onset of MFAS activity
16 Feb 00:21	USWEX	fin (whale 2)	167	171	0.7	3	106	Cessation of calling after MFAS prolonged exposures and close approach of transmitting ship
16 Feb 00:30	USWEX	minke (whale 3)	156	158	0.1	18	12	None observed
17 Feb 12:11	SCC phase B MFAS block 1	minke (whale 3)	166	168	0.5	3	57	Cessation of calling at onset of MFAS activity (SCC phase B). Tracked for preceeding 33 h w/o MFAS.
17 Feb 13:35	SCC phase B	minke (whale 3)	NA	NA	NA	5	NA	Second cessation of calling as non-transmitting ship approaches (see Figure 7)
17 Feb 13:50	SCC phase B MFAS block 2	minke (whale 3)	160	162	0.02	11	7	Estimated RL using last known position at 13:35

Species Updates

Minke Whales

Documentation of minke whales responding to three U.S. Navy SCC training events (February 2011, 2012 and 2013) was reported in Martin et al. 2014 and later published in the Journal of the Acoustical Society of America in May 2015 (Martin et al. 2015; Appendix A). That analysis utilized manual efforts to define individual minke whales by satisfying multiple requirements (e.g. at least 4 successive localized boings within specific spatio-temporal and frequency parameters requirements) and documented a statistically reduced number of calling minke whales during the surface ship MFAS portion of the SCC training events (i.e. phase B). The number of localized individual minke whales was presented as a minimum density estimate on an hourly basis for an area of 3,780 km^2. As the number of hours for each before, during and after period (with one exception) were over 30, the confidence intervals in the estimates were surprising low. The average minimum density estimates were compared within each year (e.g., 2011 before to 2011 phase B) and across years (e.g. 2011 before to 2012 before) using a Mann-Whitney/Wilcoxon rank sum statistical test. The inter-annual tests showed all values were statistically different, indicating that the densities varied across years. Overall, the average minimum density of minke whales decreased significantly during phase B when compared to all other periods intra-annually. While densities for phase A were less when compared to the before period, it is not certain if reduced calling could be attributed to the presence of phase A activities, or if it is due to the natural variation in behavioral trends. For further details regarding minke whale tracking and density estimates refer to Martin et al. 2015; Appendix A.

Automated tracking processes initially developed under the ONR Advanced DCL project with Oregon State University (D. Mellinger and J. Klay), San Diego State University (M. Roch), Naval Undersea Warfare Center (D. Moretti), and SSC Pacific (S. Martin) utilized localization outputs and arranged them into individual tracks based upon spatio-temporal parameters, similar to what was done manually in Martin et al. 2015. Currently, the automated tracking code is still being integrated into the monitoring analysis and should make similar analyses as done in Martin et al. 2015 far less time consuming for the February 2014, 2015, and future February SCC events. The process can also be extended to other localized species' analyses.

Humpback Whales

Automated PAM technical processing efforts funded by ONR and LMR were applied to SSC Pacific analyses in support of the COMPACFLT monitoring effort. These processes (GPL detection, model-based localization, and tracking) are being utilized to process recorded PMRF hydrophone data to localize humpback whales on the BSURE range (Helble et al. 2015; Appendix B). Successive localizations within required spatio-temporal characteristics are processed to create tracks. By fitting smoothed trajectories to a track, swim kinematics can be derived to define calling behavior and estimate the variability of cue rates due to differing behavioral states. Depth information is also being extracted by PAM processing (Ireley et al. 2015 in prep) and appears reasonable for species such as humpback whales with song unit call intervals on the order of a few seconds. Efforts are underway to document acoustically-determined humpback baseline occurrence and habitat use patterns on the PMRF offshore range area where U.S. Navy training events occur. These results will serve as a baseline for comparison against tracks localized during training in order to document potential behavioral impacts.

Preliminary results from analysis performed on baseline data recorded between September and June 2011-2014 (87 days of data) indicate that humpback whales were only detected from December to June (42 days of data), and predominantly in February and March. For the 42 days of data a total of 81 individual humpback whale tracks were obtained (Table 4) with a range of one to nine tracks a day. Kinematic analysis of tracks was done to derive metrics for potentially defining basic behavioral states. Metrics included indices of directivity (least distance over cumulative distance), deviation (difference between bearings from one position to the next), cumulative over least distance traveled, and track duration. The resulting track behaviors included Travel, Drift Dive, and Mill, as well as tracks that combine multiple behaviors (Combo) or are too short to assign a behavioral state (Short). In addition to the above-mentioned metrics, these behaviors differed in speed and depth distributions, although not significantly (Table 5). For example, Mill tracks had the deepest maximum depths, with some as deep as 300 m, while Drift Dive tracks had the shallowest mean dive depths (Figure 8). Travel tracks covered the longest distances and occurred over the longest durations, while Drift Dive and Mill tracks tended to be slower and shorter than both Travel and Combo tracks. The mean, median, and overall bearings of each track were also estimated. These data were presented at the 21st Biennial Conference on the Biology of Marine Mammals in December, 2015 (Henderson et al. 2015), and will be submitted for publication in a peer-reviewed journal in early 2016.

Table 4. Total humpback whale tracks identified at PMRF per year, with the number of hours of recording effort per year.

Year	Track Count	Effort (Hrs)
2011	25	543
2012	22	691
2013	13	427
2014	21	428
Total	81	2090

Table 5. Metrics of humpback whale tracks by behavioral state, including the F-score and p-value from ANOVAs, with significant results in bold.

Behavior	Mean Directivity (km/km)	Mean Straight Distance (km)	Mean Cumulative Distance (km)	Mean Duration (h)	Mean DevInd (deg)	Mean Speed (km/h)	Mean Depth (m)	Max Depth (m)
Travel	0.98±0	17.5±9.8	17.7±9.8	5.2±6.7	2.4±2.1	5.7±1.8	28.4±8	95.0±30.7
Drift Dive	0.8±0.1	7.3±6.8	10.5±8.2	3.7±3.6	42.2±26.6	3.5±3.8	30.1±9.1	94.7±35.7
Mill	0.3±0.2	4.2±6.9	8.1±7.1	3.1±2	79.5±36.9	3.1±4.8	32.1±15	165.8±145
Short	0.8±0.2	1.4±1.3	1.8±1.2	0.4±0.5	58.9±51.9	7.4±7.7	28.9±8	105.8±56.7
Combo	0.9±0.1	12.8±11.9	14.0±12.3	4.9±5.9	24.2±24	5.1±3.8	30.8±7.7	97.4±34.7
F-score	34.14	9.38	7.53	2.56	9.76	2.04	0.17	1.43
P-value	<0.0001	<0.0001	<0.0001	0.045	<0.0001	0.098	0.95	0.24

Preliminary results indicated that travel tracks shifted their predominant headings over the course of the spring breeding season, with tracks heading mostly south in December and January as humpbacks are presumably arriving in Hawaiian waters from their winter feeding grounds, then shift to the southwest during February and March, and finally shift east-southeast in April and May. Other preliminary results suggest that the median bearings of Drift Dive tracks may follow prevailing oceanographic currents. This needs to be explored further, but may indicate that the whales are truly drifting with the currents while singing, then repositioning themselves to drift again. Social sounds have been recorded during interactions of humpback whales and joining of competitive pods (e.g. Darling and Bérubé 2001; Darling et al. 2006; Zoidis et al. 2007), and many of these sounds are included as units in a song. Therefore, the Short tracks should be explored in more detail to determine if these are actual song bouts or in fact represent bursts of social sounds which could indicate an interaction between whales.

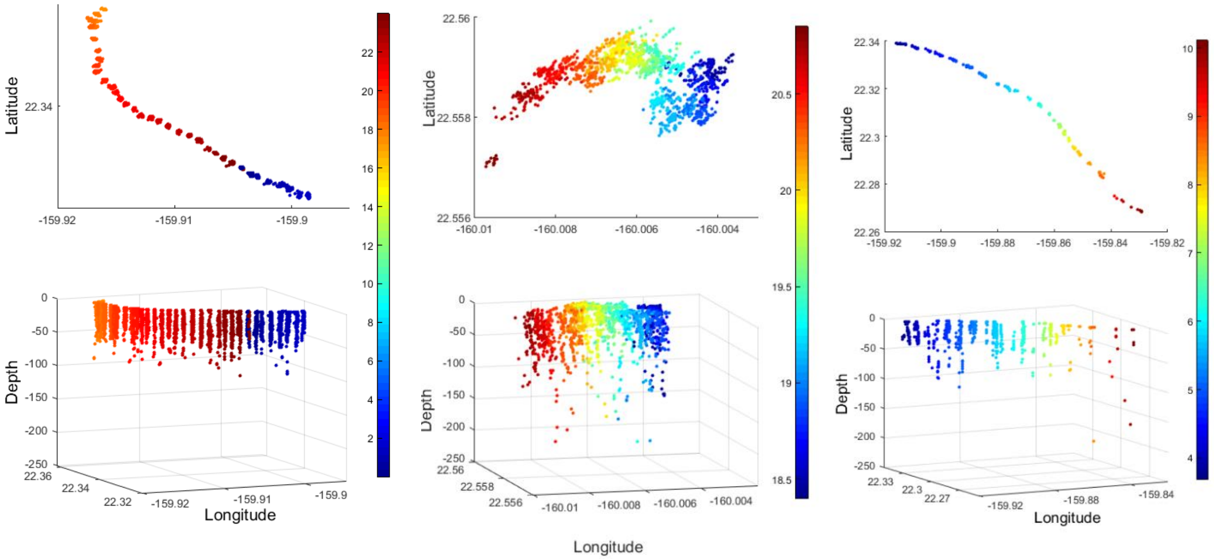

Figure 8. Representative humpback whale tracks for (left) Drift Dives, (middle) Mill, and (right) Travel behaviors. Bird’s-eye views of the tracks are given in the top plots, while the 3-dimensional tracks including depth are given in the bottom plots.

Low Frequency Baleen Whales (Fin, Sei, Bryde’s and Potentially Blue Whales)

With the installation of the BSURE range replacement hydrophones at the end of calendar year 2010, a new capability to process marine mammal calls less than 100 Hz became available. Multiple species of baleen whales that may be present in the area produce a variety of calls under 100 Hz including blue, fin, sei, Bryde’s, humpback and minke whales. A “low frequency baleen whale” call detector was developed from other research efforts (ONR and the DoD Test Resource Management Center’s Test and Evaluation S&T program’s Advanced Instrumentation Systems Technology effort). This detector is being utilized to detect signals under 100 Hz with durations over 0.25 s and either down swept characteristics or constant frequencies.

As previously described, fin whale calls (termed “20 Hz” calls) are somewhat unique (McDonald et al. 1995) and when detected and localized at PMRF have been attributed to fin whales. However, other calls detected which sweep down in frequency in this range could come from multiple species (e.g. fin, sei, blue, Bryde’s whales). Therefore, when tracks for low frequency baleen whales that only contain down swept signals are discovered in this range, they currently are not being automatically attributed to a single species. However, this preliminary step helps locate these calls in the recordings, which can then be examined manually to determine the correct species when possible. As more information on the calls of low frequency baleen whales in Hawaiian waters become available, automatic species identification may be possible.

The low frequency down-sweep call detector has also detected calls attributed to Bryde's whales, which are described more as a broadband burst pulse with amplitude modulation components. These were first observed at PMRF in August 2013 in real time as a track that moved from east to west across the range in a fairly straight line (Martin and Matsuyama 2014). August is outside the typical season when other baleen whales frequent the area (as seen in Figures 1-3); however, Bryde's whales appear to be present year round as they are the only species of baleen whale with a year-round tropical and sub-tropical distribution (e.g. Smultea et al. 2010). Additional calls and subsequent localizations attributed to Bryde's whales have previously been informally reported in earlier yearly reports. This year, the MATLAB GPL detector and call correlation model-based localization processes were tuned to the calls attributed to Bryde's whales. Both methods were used to process recorded data in order to compare methods and potentially obtain depth information for the species, given the relatively sparse information for Bryde's whales in Hawaiian waters. The report on Bryde's whale encounters (Helble et al. 2016 in prep; Appendix E) will be submitted to a peer-reviewed journal in early 2016.

Beaked Whales

Automated PAM processing has been utilized to detect beaked whale frequency modulated foraging clicks. A MATLAB routine was utilized to automatically sort foraging click detections into beaked whale group foraging dives based on spatial and temporal patterns. Figure 4 provides the fully automated results for the beaked whale group foraging dives per hour for all FY15 full bandwidth recorded data available. However, these fully automated results were not validated and could contain significant differences when compared to validated results. These differences consist of the inclusion of false positive detections (mostly resulting from other cetacean clicks and occasionally from other noise sources), combining all beaked whale species' dives together, and incorrect automatic aggregations of clicks, all of which are corrected during the manual validation process. For peer reviewed publications, manual validation of both beaked whale automated detections and group foraging dives are performed to ensure the false positive rate is either zero or very close to zero so as to not artificially inflate the presence of beaked whales at the PMRF range.

Automatic detections are predominantly attributed to Blainville's beaked whales since they are the dominant beaked whale species detected with PAM at PMRF. However, clicks attributed to Cuvier's beaked whales have been detected, as have Cross Seamount types of FM foraging clicks (McDonald et al. 2009). Conceptually the number of beaked whale group foraging dives can be converted to an abundance of beaked whales by utilizing the average number of individuals in a group (2.6 to 3.6 whales; Baird et al. 2006), combined with an average number of foraging dives a single group made in a day (0.43/hour; Baird et al. 2006). The distribution of Blainville's beaked whales is non-uniform across the range with apparent preferred habitat in the 800 to 2000 m water depth areas where slopes are the steepest. Using only this area of preferred habitat (approximately 400 km^2) where hydrophones are spaced within 4 km of each other, detection of a group on the range could be assumed to be close to 100%. The density of Blainville's beaked whales in calendar year 2013 was estimated to be 11.7 whales/440 km^2 (± 0.26) (Henderson et al. 2016 in prep; Appendix C).

Baseline analyses have been performed (including the above-mentioned manual validation process) for all available baseline acoustic recordings from 2011 to 2013 (Henderson et al. 2016 in prep; Appendix C). The number of Blainville's beaked whale foraging dives varied significantly across data collections and could interfere with before, during and after interpretations of responses attributed to MFAS transmissions. As mentioned, Blainville's beaked whale foraging dives differ spatially across the range, with more dives detected in water depths between 1 and 3 km with slopes greater than 20%. However, Blainville's beaked whale dives occur across the range throughout the year, and although there were broad variations in dive counts both intra-and inter-annually, no clear seasonal pattern emerged (Figures 9 and 10). There was however a slight diel pattern to the dives, with a small decrease in dives during crepuscular periods. This long term baseline analysis of full bandwidth data provides the ability to determine trends in habitat use and foraging dive behavior on large spatial (>1500 km^2) and temporal (3 years) scales. This baseline analysis is integral to understanding if behavioral responses to sonar are actually occurring, or if differences in behavior during MFAS activity are not actually significantly different from the natural variance in behavioral trends.

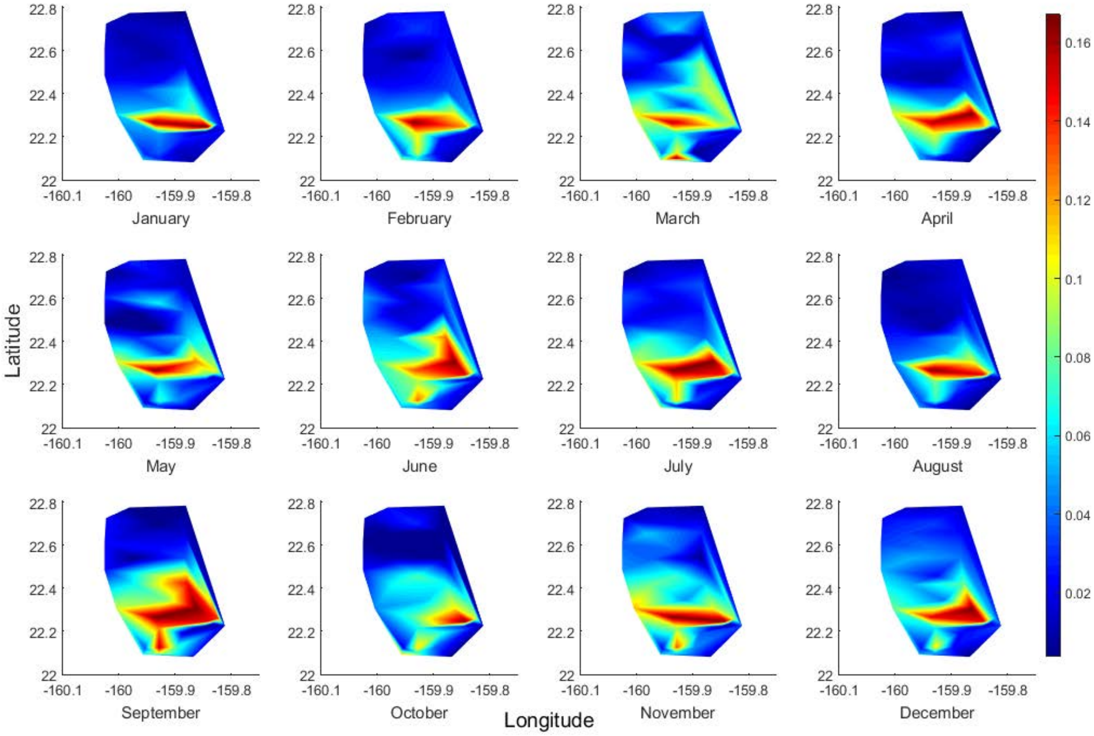

Figure 9. Map of Blainville's beaked whale dive locations across the range for each month, combined across all years and normalized by the monthly recording effort.

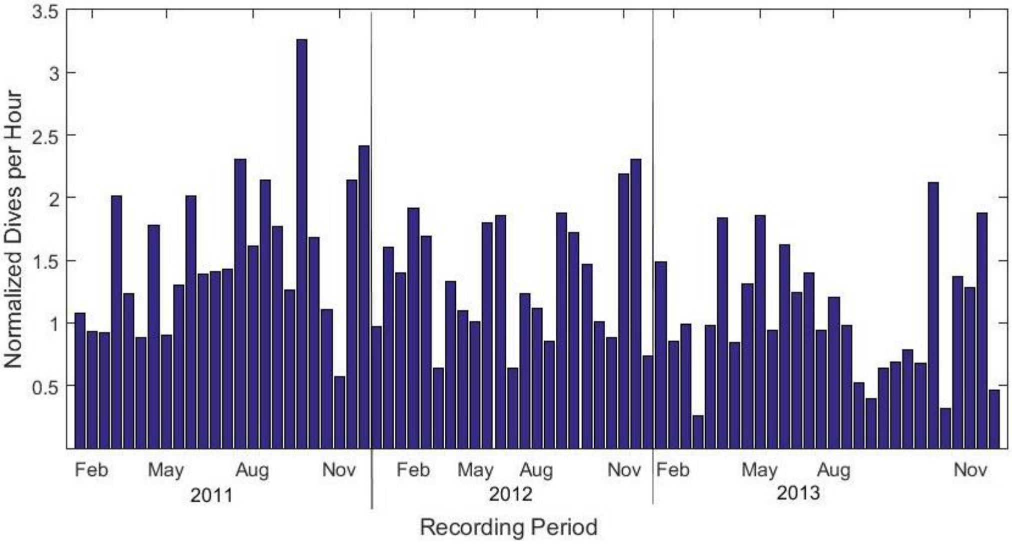

Figure 10. The number of Blainville's beaked whale dives per recording period on 31 hydrophones, normalized by the recording effort per period.

An analysis of Blainville's beaked whale group foraging dives was previously conducted for before, during and after data for the February 2012 SCC (Manzano-Roth et al. 2013). Current analysis expanded on this and now has been performed on a total of six SCC training events from 2011 through 2013 (February and August each year) (Manzano-Roth et al. 2016 in prep; Appendix D). Automatic beaked whale detections and dives were manually validated for all periods of time as described above. The periods of time during SCC training were broken down to phase A and phase B, with phase B being the only period involving surface ship MFAS training, keeping terms consistent with previous analyses (Table 6). Blainville's beaked whale dives for each period of time were pooled across all six SCCs and compared between periods with a chi-square goodness of fit test. The number of dives concurrent with MFAS during phase B was significantly lower than the number of dives occurring without MFAS activity during phase B. Within phase B more dives were detected on hydrophones on the edges of the range ($p=0.0053$) suggesting that beaked whales may be moving away or off the range during MFAS activity (Figure 11). Beaked whales on U.S. Navy ranges in the Bahamas (Moretti et al. 2010, McCarthy et al. 2011, Tyack et al. 2011) and off the coast of Southern California (DeRuiter et al. 2013) have responded similarly to both simulated and real MFAS activity.

Table 6. Blainville's beaked whale dive detection data from the before, phase A, phase B (with MFAS), between, and after phases over all six training events for the original 31 hydrophones.

Training Event	Period	Duration (h)	Dive Count	Dives per h	Sonar Duration (h)	# dives with sonar
Feb-11	Before	89.65	87	0.97		
	Phase A	43.96	21	0.48		
	Phase B	69.61	36	0.52	21.38	12
	After	77.25	72	0.93		
Aug-11	Before	71	140	1.97		
	Phase A	78.92	214	2.71		
	Phase B	64.08	42	0.66	22.52	15
	After	48	85	1.77		
Feb-12	Before	94.84	166	1.75		
	Phase A	54.6	67	1.2		
	Phase B	62.62	30	0.48	16.5	8
	After	90.5	59	0.65		
Aug-12	Before	92.29	107	1.25		
	Phase A	50.35	36	0.71		
	Phase B	64.49	21	0.33	12.87	2
	After	55.33	47	0.89		
Feb-13	Before	28.6	37	1.29		
	Phase A	52.42	23	0.44		
	Between	71.89	56	0.78		
	Phase B	62.58	14	0.36	25.09	12
	After	22.32	6	0.27		
Aug-13	Before	19.78	25	1.26		
	Phase A	54.91	43	0.78		
	Between	72.2	63	0.87		
	Phase B	44.53	15	0.42	23.78	6
	After	112.17	64	0.57		

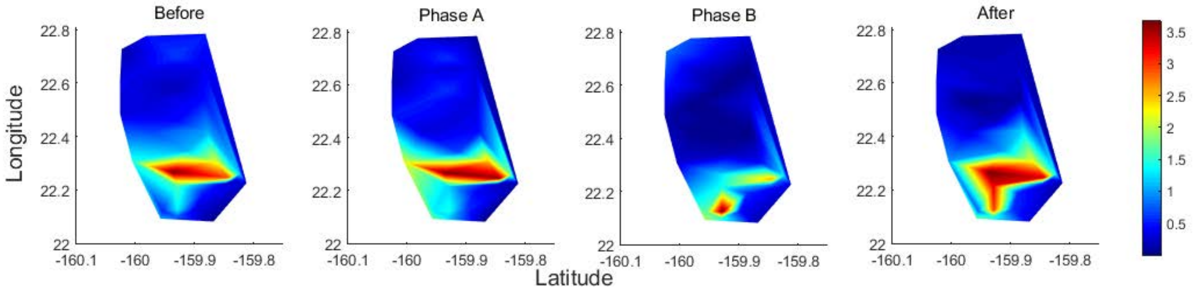

Figure 11: Maps of the distribution of Blainville's beaked whale dives (normalized as the number of dives per hydrophone per hours of effort) across the range for all training event periods combined (before, phase A, phase B, and after) for 2011-2013, showing an overall reduction in dives and a shift in distribution of dives to the southern and edge phones during phases A and B.

Collaborative Efforts

Previous collaborative effort with R. Baird, D. Webster, and B. Southall were performed on satellite tagged data from 2011 to 2013 (Baird et al. 2014). The previous work documented apparent indifference of bottlenose (*Tursiops truncatus*) and rough-toothed dolphins (*Steno bredanensis*) movements relative to MFAS, and movement of short-finned pilot whales (*Globicephala macrorhynchus*) from long distances towards increasing levels of MFAS activity. This type of analysis was deemed to be a powerful approach for observing large-scale movement patterns of species exposed to MFAS. Additional effort began mid-FY15 to analyze satellite tagged odontocete data from later 2013 through February 2015. The effort was still ongoing at the end of FY15 and will be reported at a later date.

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Minke whales (*Balaenoptera acutorostrata*) respond to navy training

Stephen W. Martin[a)] and Cameron R. Martin
National Marine Mammal Foundation, 2430 Shelter Island Drive, Suite 200, San Diego, California 92106, USA

Brian M. Matsuyama and E. Elizabeth Henderson
SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, California 92152-5001, USA

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Minke whales (*Balaenoptera acutorostrata*) were acoustically detected and localized via their boing calls using 766 h of recorded data from 24 hydrophones at the U.S. Navy's Pacific Missile Range Facility located off Kauai, Hawaii. Data were collected before, during, and after naval undersea warfare training events, which occurred in February over three consecutive years (2011–2013). Data collection in the during periods were further categorized as phase A and phase B with the latter being the only period with naval surface ship activities (e.g., frigate and destroyer maneuvers including the use of mid-frequency active sonar). Minimum minke whale densities were estimated for all data periods based upon the numbers of whales acoustically localized within the 3780 km^2 study area. The 2011 minimum densities in the study area were: 3.64 whales [confidence interval (CI) 3.31–4.01] before the training activity, 2.81 whales (CI 2.31–3.42) for phase A, 0.69 whales (CI 0.27–1.8) for phase B and 4.44 whales (CI 4.04–4.88) after. The minimum densities for the phase B periods were highly statistically significantly lower ($p < 0.001$) from all other periods within each year, suggesting a clear response to the phase B training. The phase A period results were mixed when compared to other non-training periods. *© 2015 Acoustical Society of America*.

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I. INTRODUCTION

There have been concerted efforts to understand the role of active sonar in the stranding of marine mammals since the multi-species stranding event in the Bahamas in 2000.[1] Much of the focus has been on beaked whale species as this stranding event resulted in seven dead animals, six of which were beaked whales. This stranding was also unusual in that two minke whales (*Balaenoptera acutorostrata*) stranded. One of the stranded minke whales spent over 24 h on the beach and was physically removed to deep water by a boat. The second stranded minke stayed in a shallow enclosed harbor for 2 days before being escorted to deep water by a boat. Neither minke whale was examined while in shallow water or on the beach, and they were not reported to re-strand.

Various reports have shown behavioral responses (e.g., cessation of foraging clicks and changes in dive ascent rates) of beaked whales to mid-frequency active sonar (MFAS) activity at the U.S. Navy's three test ranges: the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, the Southern California Offshore Range (SCORE) off California, and the Pacific Missile Range Facility (PMRF) in Hawaii.[2–4] MFAS is defined as active sonar containing frequencies from 1 to 10 kHz. The Behavioral Response Study (BRS) conducted off southern California has also reported that some of the blue whales (*Balaenoptera musculus*) studied responded to simulated naval MFAS by a cessation of deep feeding, increased swimming speeds, and directed travel away from the sound source.[5] It is noteworthy that some of the blue whales did not exhibit any observable response despite exposures at moderately high levels of simulated MFAS (up to 165 dB re 1 μPa). Fin whales (*Balaenoptera physalus*) have also shown changes in acoustic signal parameters resulting from shipping noise and seismic air gun activity.[6]

There have been suggestions that some reported effects could partially be due to ship activity rather than solely from MFAS or air guns. Richardson *et al.*[7] documented disturbance reactions of baleen whales to multiple disturbance sources including ships and boats. Watkins[8] reported on four baleen whale species [minke, fin, right (*Eubalaena*), and humpback (*Megaptera novaeangliae*)], reactions to boats in Cape Cod waters with a general finding that avoidance was especially strong when boats directly approach whales and that whales go silent when disturbed. Richardson[9] observed that when boats (e.g., seismic vessels, drill ships, and dredging vessels) approached within 1–4 km of bowhead whales (*Balaena mysticetus*), the whale's surface/dive cycles became shorter and the whales swam away rapidly. Moore and Clarke[10] reviewed potential short-term impacts of multiple sources of human activity including commercial shipping on gray whales (*Eschrichtius robustus*) in the northeast Pacific where whales usually responded to specific levels of continuous broadband noise by altering course to avoid the

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[a)] Electronic mail: steve.martin@nmmpfoundation.org sources. A study of minke whales on a feeding ground off Iceland found a possible decrease in foraging behavior in the presence of whale watching craft.[11] Minke whales in Hawaii are believed to be there for breeding purposes, so sensitivity to boats may be different from that on feeding grounds.

Minke whales are a difficult species to sight due to their relatively small size, low visibility blow, and short surfacing intervals, which is compounded in Hawaiian waters in the winter/spring months due to generally higher sea states. A boing sound had been seasonally acoustically detected off Hawaii[12] since the 1960s and was suspected to be produced by a whale species,[13] but was only recently determined to be a minke whale vocalization.[14] Given the seasonal and spatial overlap of minke whale boing calls with humpback whale songs, it is suspected that only sexually active males make boing calls for breeding purposes, similar to the humpback whale.[15] The minke whale boing call has been previously automatically detected[16] and localized[17] using recorded acoustic data from PMRF. Model-based localization methods have also been applied to U.S. Navy range hydrophone data for sperm whale (*Physeter macrocephalus*) clicks[18,19] and more recently for humpback whales.[20] A model-based localization method was utilized in this study to investigate minke whale boing calling behavior for all available recorded data during the month of February over three consecutive years (2011–2013).

Utilizing recorded acoustic data from the PMRF underwater range hydrophones, individual minke whales were automatically detected and localized based upon their boing calls. This study included times of naval training activities involving multiple vessels (various sized surface ships and undersea vessels) and aircraft (both fixed and rotary wing) that were participating in, and supporting, the training activity. The number of individual boing calling minke whales in the study area was quantified on hourly intervals, grouped as being from times before, during and after the naval training events. The average number of boing calling minke whales in 1 h observation intervals provided minimum estimated densities of minke whales in the study area for the periods of time for which recorded data were available.

II. METHODS

A. Study area

The study area of 3780 km^2 was 54 km in the east-west direction and 70 km in the north-south direction, which represented the area where minke whales could be reliably localized. The study area was approximately centered on the area where U.S. Navy training occurs offshore the island of Kauai, HI, but had been extended to the east and west of the hydrophones by approximately 20 km. The study area was not extended significantly to the north beyond the hydrophone range due to localization accuracy concerns or to the south due primarily to different bathymetry characteristics. The majority of the study area (approximately 98%) had water depths greater than 2 km and relatively slowly varying depth contours. Approximately 45% of the study area was over 4 km depth, 41% was 3–4 km, 12% was 1–3 km depth and less than 2% of the area was less than 1 km in depth (the southeast corner of the study area). Figure 1 provides a map of the study area with approximate locations of the 24 hydrophones utilized in the analysis.

B. Training activities

The same types of anti-submarine warfare training events, Submarine Commanders Course (SCC) operations, occurred during the month of February in 2011, 2012, and 2013. The Hawaii-Southern California Training and Testing Activities Final Environmental Impact Statement/Overseas Environmental Impact Statement[21] (EIS/OEIS) provides additional information for the SCC training events that were done to train prospective submarine commanders in rigorous and realistic scenarios. The SCC training events are advanced, integrated anti-submarine warfare (ASW), multidimensional training events conducted in coordinated at-sea operations in rigorous and realistic scenarios. The SCCs incorporated ASW tracking exercise and ASW torpedo exercise, which are further broken down by platforms involved (submarine, surface ships, helicopter, and maritime patrol aircraft). Tracking exercises became torpedo exercises when a lightweight or heavyweight exercise torpedo was launched. Training was categorized into two phases for this study, phases A and B. The phase A period represented submarine crews searching, tracking, and detecting other submarines almost exclusively without active sonar used as active sonar use would reveal the tracking submarine's presence to the target submarine. Phase B training incorporated the other platforms (surface ships, helicopters, and maritime patrol aircraft) in the ASW training. Other periods of time of available data were before and after the training with an additional weekend period only in 2013 between phases A and B (termed between). Training may have involved activities

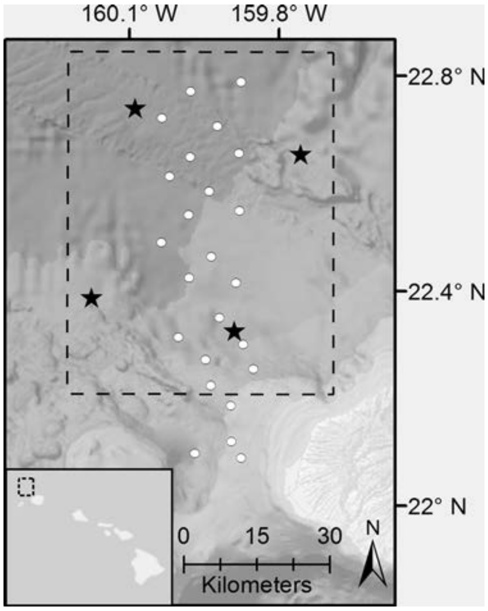

FIG. 1. Map view of the region with the 3780 km^2 study area located off the Na Pali coast of Kauai, HI, indicated with dashed lines. Approximate locations of the 24 range hydrophones utilized in the analysis are indicated by the white circles. Stars indicate localizations of four minke whales (each containing from 7 to 11 separate localizations) for the 1 h period ending at 12:00 GMT on 11 February 2012.

from other countries; in those cases, the ships were treated as similar to U.S. Navy ships (e.g., frigate, destroyer, cruiser, and submarine). Given the complexity of the training event, no effort was made in this study to evaluate individual ship-animal encounters; rather this study was conducted over a relatively large scale area to investigate the effect of the training as a whole on the boing calling behavior of minke whales.

The EIS/OEIS lists various acoustic sources with potential impact concerns including mid-frequency sonars and countermeasures, high frequency sonars, torpedo sonars, and vessel and aircraft noises. MFAS has been identified as the Navy's primary tool for detecting and identifying submarines in the EIS/OEIS. Mid-frequency sonars involved in the training included: hull mounted sonars (e.g., surface ships' AN/SQS-53C and AN/SQS-56 and submarines' AN/BQQ-10), helicopter dipping sonars, and sonobuoys. Mid-frequency acoustic countermeasures listed for SCC training includes mid-frequency towed active acoustic countermeasures (e.g., AN/SLQ-25) and mid-frequency expendable active acoustic countermeasures (e.g., MK 3). A high-frequency potential source listed includes hull-mounted submarine sonars (e.g., AN/BQQ-10). Torpedo sonars listed in the EIS/OEIS include lightweight torpedoes (e.g., MK 46, MK54) and heavyweight torpedoes (e.g., MK 48).[21]

Range support activity (smaller surface craft and rotary-wing aircraft for recovery of exercise torpedoes) occurred in both phases of the training. The phase B training period had more potential contribution to impacts on minke whale behavior compared to the phase A training due to more platforms being involved (multiple surface ships, ASW rotary-wing and fixed-wing aircraft) as well as being the only phase with MFAS from surface ships. The majority of activity from fixed-wing aircraft was during phase B, although some activity also occurred during phase A. The hours of surface ship MFAS operations in phase B were logged and represented as relative overall levels (highest, nominal, and lowest), and a comparison was made of the amount of phase B time that consisted of two surface ship MFAS sources operating at the same time. The MFAS sources typically operate with duty cycles well under 10%.

C. Automated acoustic detection, classification, and localization

The minke whale boing consists of an initial transient component followed by a long call (mean duration of 2.6 s) with both frequency and amplitude modulation.[14] The call is complex, with multiple spectral components from around 100 Hz to over 10 kHz (Fig. 2 in Ref. 17). For bottom mounted hydrophones located in deep (>1 km) water such as at PMRF, the last detectable component of the minke boing at distances over 30 km is typically detected in the 1350–1440 Hz band.[16,17] The peak frequency in this band, termed the dominant spectral component (DSC), has been shown to be a feature to help isolate individuals in some situations.[17] Boing sounds had previously been documented to typically have intervals of 5–6 min[13] as well as a much faster average rate of 28 s between calls.[14]

Thirty-one bottom-mounted range hydrophones were recorded; of those, 24 had suitable bandwidth for detection of minke boing calls. Eighteen of the 24 hydrophones had a frequency response range of approximately 50 Hz to 48 kHz and were located in relatively flat bathymetry in water depths from 2400 to 4800 m. The remaining six hydrophones (the six most southern shown in Fig. 1) had different response characteristics (approximately 100 Hz to 48 kHz) and were located in shallower water (650–1750 m) in areas of steeper bathymetry. The study area was focused in the deeper waters, and the southernmost four hydrophones were outside the study area. In late August of 2012 an additional 31 hydrophones were added; 23 of these had response frequencies from approximately 50 Hz to 48 kHz and were located within the study area, bringing the total number of hydrophones recorded suitable for minke whale boing analysis to 47. For compatibility with the earlier years, this study utilized the same 24 hydrophones for the February 2013 data. However, an additional analysis was conducted for February 2013 to compare the localizations from the 47 hydrophones with the subset of 24 hydrophones which were recorded in the prior years.

An improvement to the boing detector previously utlized[16,17] was made to better detect the onset of the call; this improved the accuracy of the automatic detection start time and in turn improved the localization accuracy. Automatic minke boing detections were required to exceed the background noise level estimate in the detection band for at least 0.8 s. Previous localizations of boing-vocalizing minke whales were performed using two-dimensional hyperbolic methods and times of arrival with four hydrophones were required in the solution.[17] While the previous localization method worked well for animals located within the hydrophone array, model-based localization was added to improve localization farther from the hydrophone array.

The model-based localization utilized is similar to other methods previously reported.[18–20] Model-based methods compare measured time differences of arrival (TDOA) across multiple hydrophones with arrival times based upon modeled TDOAs from potential source locations. Measured TDOAs have typically been based upon cross correlation of signals received from spatially separated hydrophones. Here the measured arrival times were based upon the automatic detection start times. The time difference of arrival between two hydrophones, i and j ($TDOA_{ij}$ or ΔT_{ij}) is defined as $T_i - T_j$ where T_i is the measured presumed first detected arrival of a single call and T_j is the measured arrival of the call at the jth hydrophone. The weighted least squares (LS) between measured ($\Delta T_{ij,measured}$) and modeled ($\Delta T_{ij,modeled}$) TDOAs as defined by Eq. (1) were minimized utilizing a spatial grid search method where i represents the hydrophone with the first detected arrival of a single call and j represents hydrophones with subsequent arrivals of the call to the maximum of N hydrophones

$$LS = \sqrt{\sum_{j=2}^{N} W_{Tj,modeled} \frac{\left(\Delta T_{ij,measured} - \Delta T_{ij,modeled}\right)^2}{N}}. \quad (1)$$

The weighting function $W_{Tj,modeled}$ weighs the contributions to the *LS* according to their order in the time of arrival with the later arrivals weighted less than earlier arrivals and normalized such that $\sum_{j=2}^{N} W_{Tj,modeled} = N$. Using these results, a new search grid was established with reduced spacing centered at the cell location possessing the lowest *LS* value. This process was repeated for a maximum of 16 iterations with subsequent iterations resulting in finer grid resolutions provided that the *LS* thresholds were achieved. If the final candidate location met threshold criteria, the localization was kept; otherwise, the localization was discarded, and a new set of detection times was loaded into the algorithm. Animal depth was assumed to be at or near the surface, and the actual hydrophone depths were utilized with an assumption of iso-velocity water, computed as the average over the historical sound velocity profile for the area and time.

The threshold criteria for an accepted localization involved multiple requirements. The first stage of the localization process computed a tentative solution that required the DSC frequencies of the first four detections to be within 5 Hz of one another to reduce the search space down from all possible detections. This was justified, as a single call would ideally be detected with the same frequency as received on different hydrophones; however, for various reasons (e.g., propagation effects and complexities of the amplitude modulated constant frequency portion of the boing call), the precise frequency can vary a small amount. Measured TDOAs from other hydrophones were later included into the localization solution using a smaller initial start grid centered at the four TDOA locations. *LS* grid iterations continued, and the threshold criteria were again applied. Known singularities exist when the *LS* minimization process encounters local minima; however, these can be reduced by further requiring a minimum threshold requirement on the number of hydrophones used in the final localization. When processing the 24 recorded hydrophones, it was not unusual to have over a dozen hydrophones included in the localization solution for a single boing call.

Potential localization solutions also required that the weighted *LS* could not exceed 0.25 s, and individual TDOA differences from measured to modeled did not exceed 0.25 s. These parameters are configured by the user and affect localization performance with these settings providing localization solutions with maximum accuracy errors on the order of ±375 m. These settings resulted in providing more call localizations from an individual for improved call interval analysis. By tightening both of these two timing parameters to 0.075 s, the localization precision increased to a maximum on the order of 150 m; however, fewer calls are localized.

While no data existed to ground-truth the minke whale localization coordinates, the localization process had also been applied to MFAS pulses from surface ships that compared favorably with global positioning system data for the ships (typical differences under 50 m). In addition, the minke whale boing localizations described here had also been compared with other model based acoustic localization techniques for the minke whale boing call[20] with differences typically under 200 m.

Four spatially collocated and frequency coherent call localizations were utilized as a threshold for declaring the presence of an individual minke whale. The four calls must have occurred within the span of an hour and be within a few hundred meters of one another. The DSC frequency deviation of the four calls also had to be within 5 Hz of one another. Spurious localizations were often characterized as isolated in space from true localizations. Spatial/temporal review of automatic localizations helped visualize individual animal movements over time. A temporal window of 1 h was utilized to review the minke boing localizations and estimate the number of individual minke whales present in the study area. At the end of a 1 h period, the number of localized individuals in the preceding hour was logged.

The analyst would determine the number of localizations in the previous hour using features such as the time and distance between localizations, DSC frequency of calls, number of hydrophones in each solution, and the least squares of the localization solution. Figure 1 shows the result of this processing for the period 1100 to 1200 GMT on 11 February 2012 where four individual minke whales were represented by the four star symbols. Each star symbol represents multiple separate localization solutions over this 1 h period (the north-west and south-east animals had 10 localizations each while the south-west individual had 7 localizations and the north-east animal had 11). The repeated localization times for each animal represented by the star symbol fit the 5–6 min typical boing call interval[13] for minke whales.

D. Density estimation

Ward *et al.*[22] estimated densities of localized sperm whales using two major assumptions: (a) that all periods of whale presence were identified and (b) all individuals vocalizing within the study area were included. Sub-sampling of the data was done to count whales with *k* sample periods over the available data period with the estimated average density of sperm whales given as shown in Eq. (2), where *n* is the number of individuals counted over the *k* 10 min sample periods, *A* is the study area (in km^2), p_p is the proportion of the total time monitored (in min) and $\hat{p}_v$. is the estimated proportion of time an individual whale vocalizes at least once in the 10 min sample intervals[22]

$$\hat{D} = \frac{n\,p_p}{A\,k\,\hat{p}_v}. \qquad (2)$$

The mean number of whales detected over the *k* sample periods is represented by *n*/*k*. Here our mean number of whales localized in all available data was equivalent to *n*/*k*. Given that all available data were utilized for the measured numbers of whales in each 1 h of data, p_p was equal to 1.0.

An estimation of minke whale density not only requires $\hat{p}_v$ in the denominator of Eq. (2) to reflect the proportion of time an individual vocalizes but also the ratio of calling animals to all animals in cases such as minke whale boing calls (i.e., the proportion of males to females and juveniles in this area). Given there were no current estimates for these two parameters, they were both set to their maximum value of

1.0 to represent a minimum average density of minke whales based on the mean of the observed numbers of boing calling minke whales present for the duration of the period of interest. For this study, we also assumed that all vocalizing individuals in the study area were counted (probability of correctly localizing calling individuals = 1.0) and that the probability of a false positive was zero (declaring an individual present when actually not = 0). With these assumptions, the estimated minimum average density of minke whales for our study area (A) and time periods reduces to

$$\hat{D}_{min} = \frac{\hat{n}}{A}, \tag{3}$$

where $\hat{n}$ is the mean number of localized whales counted in the study area A. Here we use 1 h intervals for measurement of animal counts.

The assumption of correctly counting all calling individuals with no false positives was not unrealistic given the methods utilized and the 1 h observation intervals. The typical minke whale boing rate is a call produced every 5–6 min; however, when two calling animals are in close proximity, the call rate increases to calls produced approximately every 0.5 min.[13,14] One minke whale producing boing calls at the typical rate would result in the production of 10–12 boings in a 1 h observation interval if continuously calling. This increases the probability of localizing whales as it provides multiple opportunities for the localization of a whale given that only four localizations in the same area are required for confirmation. Also the probability of four incorrect localizations occurring in the 1 h observation interval that met all of the stated criteria (i.e., all within a few hundred meters of one another, DSC frequencies being within 5 Hz of each other, and call intervals matching known minke boing call rates) was extremely low. Observation intervals shorter than 1 h resulted in less than perfect localizations with potential false localizations, and intervals over a couple of hours resulted in duplicate counting of individual animals that stopped and resume calling within the sampling period. The accuracies of the whale localizations have not been verified with techniques such as visual sightings or global positioning system capable tags on the animals and were assumed to decrease with increasing distances from the hydrophones. Overall localization accuracy was believed to vary from a few dozen meters within the hydrophone array to a few hundred meters towards the outer boundaries of the study area.

Given the preceding assumptions, the variance of the density estimate is equal to a function of $\hat{n}$ and the coefficient of variation determined as the standard error (i.e., standard deviation of n divided by the square root of the number of samples) divided by the estimate ($\hat{n}$).[23] The 95% confidence intervals of the density were estimated assuming a lognormal distribution for the density estimate and a normal approximation to the distribution of log(density).

The average noise levels in the detection band utilized for automated minke boing detection (approximately 1350–1440 Hz) is also of interest to ensure that the reduction of detections are not due to an increased noise level from training activity (e.g., surface ship noises and MFAS transmissions masking the calls). Data indicated that any increased noise level in this band was small compared to the signal to noise ratios for boing calls detected on the PMRF range.

III. RESULTS

Throughout the month of February over the 3-yr study period (2011–2013), 766 h of recorded acoustic data from 24 bottom-mounted hydrophones were collected. All available data were utilized in the analysis with the breakdown of hours by year as 255 h in 2011, 298 h in 2012, and 213 h in 2013. Some of these data were not collected immediately adjacent in time to the training activities (e.g., one before period in 2012 and the only available after period data for 2013).

Table I summarizes the number of hours of available data for each period of time (i.e., before, phase A, between, phase B, and after) along with the mean minke whale minimum density estimates ($\hat{D}_{min}$) for the periods in the study area size of 3780 km^2 and the 95% CI of the minimum density estimates. In all three years, the densities during the phase A and B periods were depressed relative to the before periods. Although the estimated densities were different from year to year, the trends of densities within years being depressed during periods of training compared to the before periods holds. The 2013 phase B CIs are large due to the mean estimate being small (0.06 whales in the 3780 km^2 study area). The 2011 after period has the highest estimated density for all periods.

While the precise number of participants is sensitive information, in general, the numbers of training participants (e.g., vessels and aircraft) in the phase As were fairly

TABLE I. Estimated minimum densities of minke whales in the 3780 km^2 study area offshore of Kauai, HI, $\hat{D}_{min}$ with 95% confidence intervals in parentheses and number of hours of effort, N, for each period of time by year for the month of February.

		Before	Phase A	Between	Phase B	After
Feb 2011	N (h)	65	42	–	70	78
	$\hat{D}_{min}$	3.64	2.81	–	0.69	4.44
	(CI)	(3.31–4.01)	(2.31–3.42)		(0.27–1.8)	(4.04–4.88)
Feb 2012	N (h)	94	51	–	64	89
	$\hat{D}_{min}$	2.77	2.04	–	0.70	2.08
	(CI)	(2.41–3.18)	(1.65–2.52)		(0.28–1.76)	(1.73–2.5)
Feb 2013	N (h)	5	52	67	67	22
	$\hat{D}_{min}$	–	1.21	1.58	0.06	1.409
	(CI)		(0.84–1.75)	(1.14–2.19)	(0.001–4.63)	(0.93–2.12)

consistent, while the numbers of phase B participants was highest in 2011 and lowest in 2012. The phase B participants' contributions of MFAS activity was the least for 2012 and the most for 2013. The percentage of time when hull-mounted sonar (e.g., AN/SQS-53C) was operational in phase B was approximately 20% in 2011, 20% in 2012, and 29% in 2013. The percentage of time when hull-mounted (e.g., AN/SQS-56) was operational in phase B was approximately 32% in 2011, 4% in 2012, and 33% in 2013. The percentage of time when two sonars were active concurrently in phase B was approximately 13% in 2011, 0.4% in 2012, and 25% in 2013.

Figure 2 provides time sequence plots of the number of localized boing calling minke whales in 1 h observation intervals (*n*) in the study area for all available recorded data with the different periods of time indicated for each year. Figure 2 shows the high variability for the numbers of animals localized in the 1 h periods. The number of localized minke whales present decreased over the years for the data analyzed with a maximum of nine individuals localized in one observation period in the 2011 after data. The number of localized minke whales during phase B periods decreased relative to all other periods within the same year with the unique situation of no minke whales localized for 63 h following the start of phase B in 2013 (although in general the number of localized whales in 2013 were lower compared to the prior years).

To gain insight into the distributions of the number of acoustically localized minke whales present in 1 h observation intervals, histograms were generated for all periods of time (Fig. 3). These histograms show the numbers of acoustically localized minke whales (*n*) (minimum of 0 and maximum of 9) that were present in the 1 h observation intervals with the number of total hours available (*N*) shown in the upper right of each histogram. The 2013 phase B data had low numbers of detected minke whales; 62 of the available 67 h (93%) had no localizations. In 2013, phase A, between, and after had only one minke whale localized in the study area for the majority of the available hours. In 2011, there was a peak of four minke whales present for 28 of the available 65 h (43%) for the before period compared to the before period for 2012 with a peak of two whales for 34 of the available 94 h (36%). A comparison of the before period data with the phase A and B periods within years shows trends of reduced numbers of whales in phase A, with the phase B numbers reduced even further.

The number of localized minke whales in 1 h observation intervals was tested for normality using the Shipiro–Wilks normality test. The before periods for 2011 and 2012 data tested highly significant as non-normal ($p < 0.001$). The Mann–Whitney/Wilcoxon rank-sum test was therefore selected, given its ability to deal with non-normal distributions as well as the significant number of ties in the ranking process, to test if the means of any two distributions are the same.

The Mann–Whitney tests indicated that for the comparisons within periods *across* years (e.g., before to before, phase A to phase A, etc.), only the comparison of 2011 phase B and 2012 phase B had the same means ($p = 0.77$); all other comparisons across years were significantly different (p values ranged from 0.044 to less than 0.001). The before periods represent the best estimate at baseline data; however, the before periods had different means ($p < 0.05$) across all paired year comparisons (i.e., 2011 to 2012, 2011 to 2013, and 2012 to 2013). The small sample size of the before data for 2013 (5 h) should be considered when interpreting the data. The fact that before periods over different years had different means suggests that the densities of calling animals

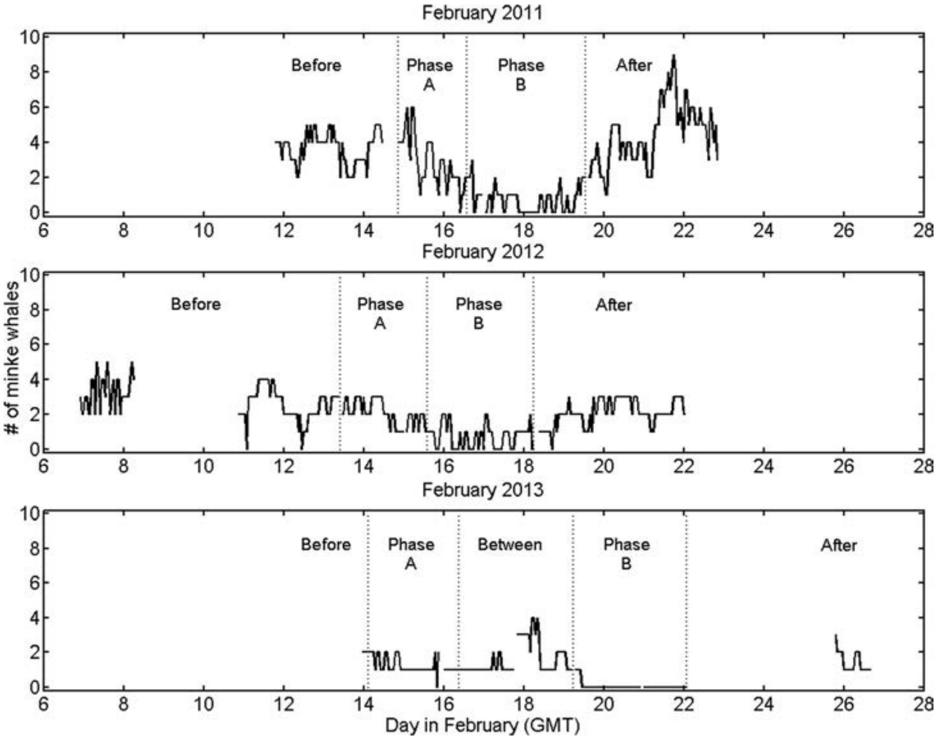

FIG. 2. Number of minke whales acoustically localized in the study area in 1 h periods for February 2011 (top), 2012 (middle), and 2013 (lower). Labels on each figure represent the periods of time associated with navy training activity (before, phase A, between, phase B, and after). Blank periods indicate periods that recorded data was not available.

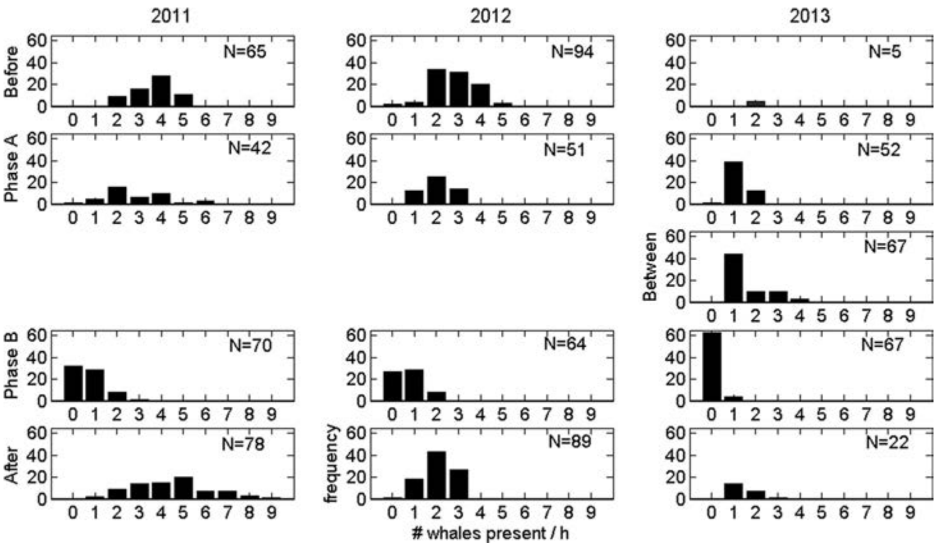

FIG. 3. Histograms of the numbers of individual minke whales localized (horz axis min 0 to max 9) in 1 h observation intervals by year (columns) and periods of time relative to training (before, phase A, between, phase B, after). Plots have the same scale for ease of comparing the distributions of localizations with the number of hours (*N*) inset in upper right of each histogram. Before periods represent a nominal baseline for 2011 (65 h) and 2012 (94 h). The 2013 before period had limited data available. Phase B distributions show clear shifts to the left indicating fewer numbers of minke whales localized in 1 h observation intervals.

in our baseline was different from year to year, and therefore interannual differences may factor into the differences observed across all sampling periods.

The Mann–Whitney tests of the 10 paired combinations involving phase B data *within* years (i.e., three paired tests in 2011, three paired tests in 2012, and four paired tests in 2013 due to the additional between period) indicate that the means of the phase B data are all highly significantly lower ($p < 0.001$). Phase B was the only period of time with activity from naval surface ships participating in the training (i.e., maneuvering and periods of MFAS transmissions as opposed to range support craft present in both the A and B periods). Phase B was also the only period when the mean number of animals in the study area was less than one per hour. This suggests that the phase B training activity impacted the number of localized minke whales, resulting in fewer calls as compared to the other time periods.

The Mann–Whitney paired tests involving phase A *within* years had mixed results compared with other periods of time (e.g., phase A to before, phase A to after). Phase A to before periods *within* each year had statistically significant different means ($p < 0.05$) as did the 2011 phase A to after period ($p < 0.001$). However, the 2012 and 2013 phase A to after periods both tested as not different ($p = 0.709$ and $p = 0.18$, respectively). Thus impacts of phase A training on minke calling behavior was not as clear as the phase B impacts and requires further study of more baseline data. Finally, the 2013 between period tested as different when compared to the after period ($p = 0.766$) but not different when compared to the before period ($p = 0.05$ but recall only 5 h of before data for this year).

The results from the localizations in 2013 that utilized the 47 available hydrophones were similar to results using only the subset of 24 hydrophones for compatibility with 2011 and 2012 comparisons. As expected there were a few more localized animals at longer distances from the hydrophones in a few of the hour periods. The Mann–Whitney test comparing the 47 to 24 hydrophone localizations across periods had means that were not significantly different across all but one of the periods (the after period $p = 0.0106$), when the larger number of hydrophones resulted in a higher mean number of animals per 1 h periods (1.95 compared to 1.41).

IV. DISCUSSION

The use of estimated densities for calling minke whales based upon localizations of individuals to investigate density and potential responses to navy training activities is a new application of the science of acoustic detection, classification, and localization. This method is favored as much of the analyses, including localizations, were automated, and it is not unreasonable to perform the analysis for all available data rather than sub-sampling the available data. The numbers of acoustically localized minke whales producing boing calls were shown to have highly statistically significantly reduced means for the phase B training activities, which included surface ship training with MFAS, when compared with all other available periods of data (before, phase A, between, and after) within years.

While the mean numbers of calling minke whales in phase A were consistently less compared to the before periods, the after periods did not consistently increase relative to phase A periods. In addition, the 2013 between data were higher than the phase A data but also higher than the after data. Given that only 5 h of before data were available in 2013, and the inconsistencies in phase A comparisons with other periods, it is not certain if the phase A activities reduced the minke whale calling behavior. Reduced calling could be associated with the phase A activities, or it could be a result of not having sufficient baseline data available to fully represent the variations for minke whale calling behavior. Phase A activities included range support activities that were also present in phase B (e.g., exercise torpedo recovery surface craft and rotary-wing aircraft). The presence of both aircraft and boats have been shown to negatively affect baleen whales.[9–11]

The February 2013 phase B data were distinctive in that there were no localized minke whales for the majority of phase B; however, 2013 also had the lowest number of localized minke whales present compared to the other years. Preliminary analysis of the Feb 2014 and 2015 data indicates increased numbers of animals compared to 2013; this would not support a hypothesis of a continued downward trend, which might be inferred based upon the 2011–2013 data. This underscores the need for additional data and analysis to understand the complexities of minke whale boing calling behavior.

Acoustic density estimation for an odontocete species such as Blainvilles beaked whales (*Mesoplodon densirostris*) or sperm whales are based upon foraging echolocation clicks, which all but the youngest of the species must produce to survive. Baleen whale calls are often gender specific (e.g., humpback whale song, blue whale AB calls,[24] and minke whale boing calls) and dependent upon behavioral states. While the measured numbers of localized minke whales varied from year to year, it is not certain if the densities are varying or if the variation is the result of different behavioral states with different calling behaviors. Minke boing calling behavior is also density dependent because when two animals are relatively close to one another, call rates increase by a factor of over 10.[13] This was occasionally observed in the PMRF data with one of the animals typically ceasing to call following an increased call rate encounter with another calling whale. This behavior has also been observed in humpback whales with singers joining or being joined by other males.[25,26] However, in contrast to the behavior observed in calling minke whales, the singers typically join with non-singing males rather than with another singing male. Thus the proportion of time, on average, that a boing calling minke whale actually vocalizes is complex and potentially difficult and expensive to obtain (e.g., successfully attaching medium-term acoustic tags on multiple animals with several day attachment durations). Studies of humpback whale singer-to-overall population ratios have also been shown to vary from year to year, but currently no similar data exist for minke whales wintering in Hawaiian waters. These factors were unknown at the time of this study and will likely remain unknown for not only minke whales but many baleen whale species for the near-term future. Reporting these results as a minimum density estimates was done to highlight these limitations and yet still provide some data on density estimates.

Future efforts are planned to automatically track localized individuals to reduce the amount of manual effort in performing this type of analysis in the future and to potentially perform snapshot-type acoustic density estimation. Additional efforts are also planned to quantify the encounters between minke whales and surface ships (e.g., examine separation distances, ship speeds, and angle off the bow of the whale from the ships) during training as well as estimating receive levels on whales when MFAS is present. Minke whales have been shown to respond to disturbances such as ships and aircraft activities, reduced calling behavior should not solely be attributed to sonar activity. Previous unpublished observations have identified situations where minke whales ceased calling as a surface ship approached with and without transmission of MFAS as well as situations where a whale has continued calling as an MFAS transmitting ship is moving away (S. Martin, personal observation). Quantifying these encounters in a more detailed study may help understand the effects of each type of disturbance on minke whales. This has implications for controlled exposure studies such as the southern California BRS[3,5] and the 3S study.[27]

The use of standard statistical tests to compare the number of localized boing calling minke whales violated some of the test's assumptions. While the Mann–Whitney test is nonparametric and robust to matches in rankings, it does make assumptions that the data are independent and the variances similar. The independence assumption is of concern; if a minke whale is present in the study area at hour N, it is often also present and counted in subsequent hours (e.g., $N+1$, $N+2,\ldots$) for several hours or more in many cases. This could be handled by only counting the onset of boing bouts from an individual or by employing methods for dealing with the dependence of the observations (such as utilizing the autocorrelation of the observations). This is an area appropriate for future research. In spite of this concern, the number of localized minke whales were measured for all available data, and the means and distributions of the phase B periods were obviously lower compared to all other periods.

V. CONCLUSIONS

The use of widely spaced, bottom-mounted hydrophone arrays to detect, classify, and localize marine mammals and assess behavioral responses to navy training activity is a powerful tool and is being pursued for other whale species (e.g., humpback, fin, sei, Bryde's, and sperm whales) using available PMRF data. The large number of hydrophones on U.S. Navy ranges provides unique opportunities to not only detect, classify, and provide presence information but to also localize individual whales in the area. This conceptually simplifies density estimation for vocalizing whales to a census type measurement, which can be considered a lower bound of whale density as it is only counting whales which are calling during the study periods. Such analyses are not typically possible with towed hydrophones or a handful of seafloor autonomous data recorders. In addition, the cost of obtaining range hydrophone data is low given the large quantity of existing data and relatively low cost to record additional data in the future. This favors use of the U.S. Navy range hydrophones for monitoring marine mammals on (and near) the U.S. Navy range rather than conducting separate types of acoustic data collections requiring deployment of autonomous recorders or towing of hydrophones from ships.

In addition to providing minimum density estimates for minke whales, this analysis also documented a behavioral response of calling whales related to U.S. Navy training. Previous studies of tagged beaked whales provided evidence that beaked whales depart an area during MFAS activity and later return.[2,28] No similar data currently exist for minke whales at PMRF (e.g., tagged animals), therefore it is not known if minke whales leave the area or simply cease calling.

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Automated acoustic localization and call association for vocalizing humpback whales on the Navy's Pacific Missile Range Facility

Tyler A. Helble[a)]
SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, California 92152-5001

Glenn R. Ierley and Gerald L. D'Spain
Scripps Institution of Oceanography, University of California at San Diego, La Jolla, California 92093-0701

Stephen W. Martin
SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, California 92152-5001

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Time difference of arrival (TDOA) methods for acoustically localizing multiple marine mammals have been applied to recorded data from the Navy's Pacific Missile Range Facility in order to localize and track humpback whales. Modifications to established methods were necessary in order to simultaneously track multiple animals on the range faster than real-time and in a fully automated way, while minimizing the number of incorrect localizations. The resulting algorithms were run with no human intervention at computational speeds faster than the data recording speed on over forty days of acoustic recordings from the range, spanning multiple years. Spatial localizations based on correlating sequences of units originating from within the range produce estimates having a standard deviation typically 10 m or less (due primarily to TDOA measurement errors), and a bias of 20 m or less (due primarily to sound speed mismatch). An automated method for associating units to individual whales is presented, enabling automated humpback song analyses to be performed. [http://dx.doi.org/10.1121/1.4904505]

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I. INTRODUCTION

Automated localization of marine mammals on the Navy's Pacific Missile Range Facility (PMRF) is important for animal density estimation and behavior studies. Because of the vast amount of stored acoustic data, these automated methods must run faster than real-time in application. Methods for localizing marine mammals using the time of arrival (TOA) or time difference of arrival (TDOA) of incoming transient signals produced by the marine mammals are well established.[1–7] Various implementations of these methods with species-specific considerations are used for localizing certain species of whales on U.S. Navy instrumented training ranges.[8–12] Humpback whales have been problematic to localize using the traditional TOA method, which requires that vocalizations from a given animal be uniquely matched across hydrophones in the array. Humpback songs consist of a sequence of discrete sound elements, called units, that are separated by silence.[13] Units are typically detected from humpbacks every few seconds on the range hydrophones. Arrival times for a given unit at the hydrophones may differ by up to 10 s across the array. Units from an individual are often repeated in a phrase, moreover different individuals may make similar units. Unique association of units across hydrophones is thus challenging. A TDOA method is hence more appropriate and here implemented by correlating *sequences* of units between pairs of hydrophones. This method is facilitated with use of the generalized power-law (GPL) detector[14] and enhanced with a spectral "templating" procedure to characterize individual units by extracting a fundamental for each unit and setting the remainder of the unit spectrogram to zero. Cross-correlations of sequences of these unit templates allow localization of multiple animals concurrently with an incorrect localization rate of 2% or less. The techniques used are broadly similar to those described in the multiple animal TDOA method in Sec. III A by Nosal.[7] However modifications were made to eliminate both the need for post-processing (thus allowing for real-time localization) and the assumption that animals vocalize frequently enough to produce traceable track lines (a track is defined as a sequence of localizations that can be attributed to one animal). These modifications assume that the number of vocalizing animals in the monitored areas is moderate to low: the algorithms can localize three marine mammals simultaneously in any subarray, with the ability to localize additional marine mammals at the expense of a reduced number of localizations per individual. The algorithms described are capable of operating in real-time on 14 hydrophones. When processing recorded data the algorithms operate on the 14 hydrophones at a rate approximately five times faster than real-time.

In addition to describing the localization methods suitable for real-time processing, a post-processing technique is also described in which information from the localization process is used to assign each unit in the spectrogram to

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[a)] Author to whom correspondence should be addressed. Electronic mail: tyler.helble@navy.mil individual whales. This added processing step is necessary for call association because the sequences of units originally used for localization may contain units from several whales. Call association can be particularly advantageous to those interested in the biological significance of song and social sound vocalizations in relation to conspecific interactions. Manual annotation of humpback song and social sounds is a laborious and difficult process and therefore automating the majority of the process is beneficial.

The objective of this paper is to describe a robust TDOA localization technique and related call association process focusing on humpback whale vocalizations. While not discussed, the methods are generally applicable to other vocalizing whale species for wide baseline array configurations if the incoming signals can be concurrently detected on four or more hydrophones. Section II A describes the methods used for vocalization detection and feature extraction, Sec. II B describes the cross-correlation techniques used to calculate the TDOAs, and Sec. II C describes the model-based approach used to convert TDOAs into position fixes. Section II D discusses the uncertainties and limitations of the localization process, and includes an optimization analysis for selecting parameters used to minimize localization errors. Section III A details the localization results for two humpback whales transiting through the PMRF range, and the associated uncertainties in the position fixes. Section III B describes the call association process for the same two whales. The final section summarizes the conclusions from this work.

II. METHODS

The PRMF range is located off the west coast of the island of Kauai in the Hawaiian Islands. Thirty-one time-synchronized hydrophones from the PMRF underwater range have been recorded on a sample basis of approximately two days a month over the past several years, with additional days of recordings associated with U.S. Navy mid-frequency sonar training events. Hydrophone data was initially sampled at 96 kHz and later down sampled to 10 kHz. Of these 31 hydrophones, 14 offshore hydrophones were selected for localization purposes, ranging in depth from 3150 to 4700 m, and covering a rectangular-shaped grid approximately 11 km to the east/west and 52 km to the north/south. The 14 hydrophones were subdivided into four subarrays (A, B, C, D), each containing five hydrophones as shown in Fig. 1. The TDOAs are computed between the center hydrophone of each subarray and the nearest four corner hydrophones. The maximum allowable time delay between the center hydrophone and each adjacent hydrophone in the subarray is limited to the direct path propagation time between them. The subarray configuration was chosen such that a direct path solution on four hydrophone pairs always exists across the monitored area for the noise conditions present on the PMRF range. Additional hydrophones were not included to reduce computational burden. The process for obtaining whale locations can be subdivided into three steps: detection and feature extraction, cross-correlation of those features to obtain TDOAs, and TDOA-based localization.

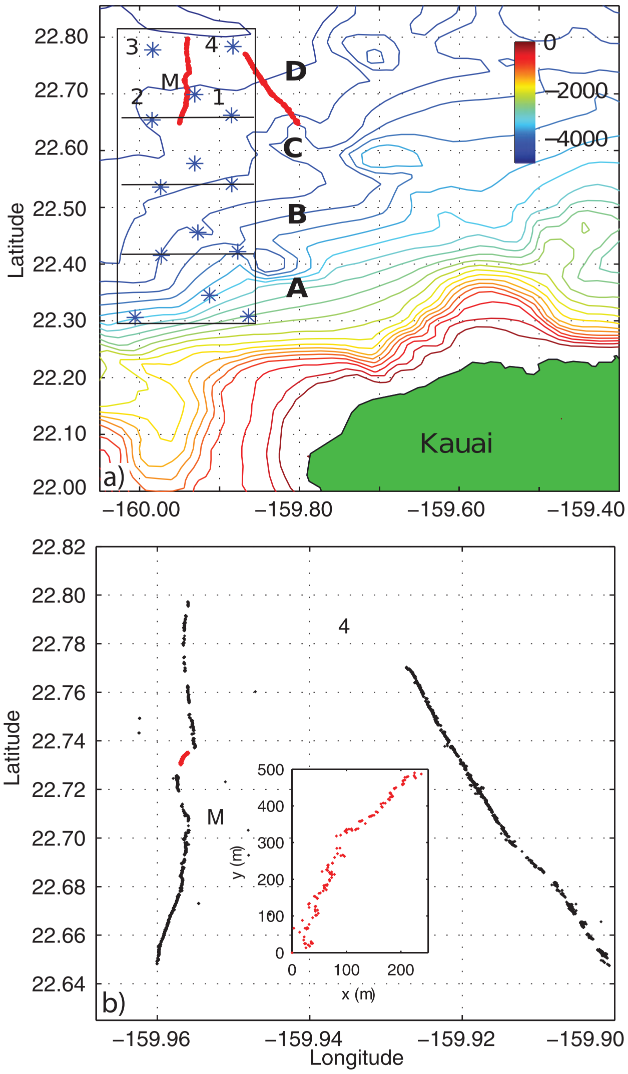

FIG. 1. Approximate positions of PMRF hydrophones illustrating subarrays A–D. The center hydrophone is marked on subarray D (M) and the four adjacent hydrophones (marked 1–4). Position fixes are shown for two humpback whales transiting through subarray D on March 11, 2013 (a), also shown in expanded form (b). The inset shows a detailed portion of the western track (highlighted in red), revealing tightly clustered localization fixes.

A. Detection and feature extraction

Detection of humpback song units is accomplished using the generalized power-law detector (GPL).[14] The GPL detector is based on the summation of band-limited spectral content. Unlike the energy detector, the GPL algorithm uses a higher power of the Fourier amplitude, which is appropriate when—as for humpback whales—the signal occupies a limited, but unknown, subset of the total search frequencies over which a signal may occur. The GPL detector outperforms energy detectors for humpback song units and has proven effective in accurately determining the start and end times of humpbacks units in acoustic records under widely varying ocean noise conditions and signal-to-noise (SNR) ratios.[14–16]

In the detection stage, a 60 s spectrogram is band-limited to the 150 to 1000 Hz frequency range and whitened based on an empirical estimate of the noise level at each frequency, μ_k, as defined in Eqs. (10), (11) in Helble *et al.*[14]

The Fourier amplitude at each frequency is then normalized by μ_k; a process equivalent to removing the noise that is time-stationary over the duration of the spectrogram.

Once a unit is detected, a templating procedure is used to determine the relevant spectral features of the unit. The full spectrogram is 60 s in length while the segment identified as a unit is only 1 to 2 s. The whitened Fourier amplitude of that short segment is reshaped as a single column vector and its noise level, μ_0, now across *both* frequency and time, is determined using the same algorithm [Eqs. (10), (11) in Helble *et al.*[14]]. All elements of the single column vector are then normalized by μ_0.

Elements exceeding $5\mu_0$ above the referenced noise level, μ_0, are set to one, and all the remainder are set to zero. The $5\mu_0$ cutoff value was chosen based on Monte Carlo simulations discussed later in Sec. II D. After restoring the single column vector to its original matrix dimensions, the binary reduction defines a series of "islands." The main spectral content of the unit is identified as the single island of largest area and remaining islands associated with the unit are discarded. The largest island is used as a mask which is then applied to the original whitened unit spectrogram leaving a single contour, normally the fundamental. The mask can be applied to other powers of the Fourier amplitude as needed in optimization. Single contours are preferred over multiple contours because they prove more robust during the cross-correlation process; the ability to accurately template the harmonics of the unit is variable among the hydrophones due to propagation effects and varying SNR. Figure 2(a) shows the original spectrogram for the center hydrophone on subarray D and the resulting unit templates for the center hydrophone and the four adjacent hydrophones. The unit templates are combined to create a sequence of units used for the cross-correlation process, discussed in the following subsection.

B. Cross correlation and TDOA

The generalized TDOA method described in Sec. III A by Nosal[7] operates under the assumption that TDOAs have been established between receiver pairs. However, the TDOA on one receiver pair does not need to be associated with the TDOA of another receiver pair and no effort is made to separate false TDOAs (such as incorrect pairings from multipath or incorrect pairing of calls from different animals). In order to vastly reduce ambiguities in localization without requiring a post-processing step, the method discussed here is more restrictive: the center hydrophone of each subarray acts as the "master" and therefore units detected on the center hydrophone must also be detected on each of the four adjacent hydrophones in order to produce a valid localization. Additionally, sequences of humpback vocalization units, rather than single units, are used in the cross-correlation process in order to minimize peaks in the TDOA that arise from incorrect call associations. These more restrictive parameters can be used because the density of the hydrophones is sufficiently high and the water depths sufficiently deep that direct path transmission to each of the five hydrophones is possible in the monitored area. The sequence of humpback units (rather than single units) can be used in the cross-correlation with minimum degradation in the number of resulting localizations because singing humpbacks produce units every few seconds when they are vocally active, and so whale positions change minimally over the duration of a sequence.[13,17]

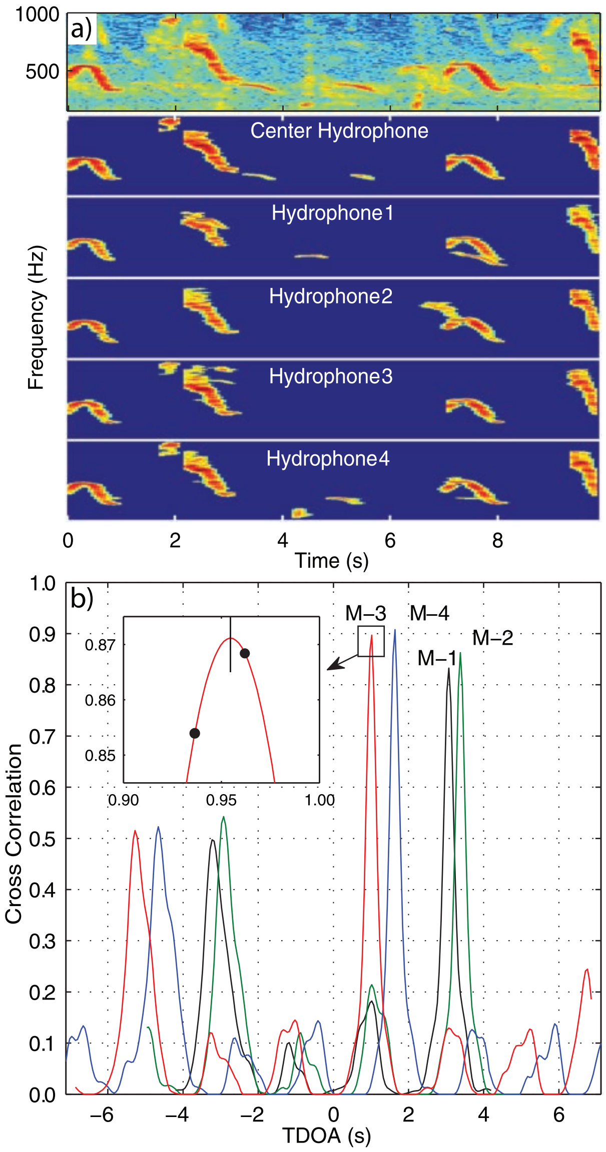

FIG. 2. Original spectrogram (a) for the center hydrophone on subarray D and the resulting template sequences, time aligned according to the highest cross-correlation score between the center hydrophone and each of the four corner hydrophones. Associated cross-correlation (b) revealing peak time delays between the center hydrophone (marked M) and adjacent hydrophones 1–4 for subarray D. The inset shows the interpolation between quantized points in order to obtain a more accurate peak.

Sequences of templated call units as described in Sec. II A are used in the cross-correlation to calculate TDOAs between hydrophone pairs representing varying time windows. An initial sequence is created on the center "master" hydrophone with the desired fixed number of units. The sequence is than cross-correlated with the sequences at each adjacent hydrophone (hydrophones 1–4). The length of the sequence and number of units contained within the sequence at each adjacent hydrophone varies: the sequence contains all the units detected and templated that occur within the time period of the center hydrophone sequence, plus the direct path travel time padding. After the initial set of computations, the oldest unit is then discarded from the left end of the center hydrophone sequence and a new unit is added on the right (first in, first out), and the next cross-correlation computed. This process is repeated until all units detected on the center hydrophone have been processed. Use of a master sequence containing a fixed number of units, but varying duration, is preferable to reliance on fixed time window sections of spectrograms, but with varying numbers of units, for computing correlations. The latter approach is more prone to false peaks in the TDOA matrices and the estimated time delays between hydrophone pairs are typically less accurate. In principle it is possible to further reduce errors in timing delay estimates by considering all possible pairs of hydrophones within the subarray. However, to remain within the paradigm of TDOA based on sequences of units means identifying the identical sequence on a secondary master hydrophone. Such identification requires unique call identification of individual units and in general that is only feasible once a target animal is already localized.

The accuracy of the average time delay inferred from peak correlation improves with an increase in the sequence size, as documented in Sec. II D. For a moving whale, however, the gain of that statistical improvement must be balanced against the growing divergence between the instantaneous trajectory and the smoothed, time-mean, trajectory predicted by use of the sequence. If these two differ by, say, 25 m, then accuracy in the latter of 5 m is a moot point. Thus, the tradeoff of these two dictates a maximum, preferred, sequence size, which depends upon speed of the whale and the average interval between units. In practice, seven units is a suitable number. For data on the PMRF range, most such sequences last between 10 and 20 s.

The sequences in Fig. 2(a) represents a nine second snapshot in which seven units were detected on the center hydrophone while two humpback whale were traveling through subarray D. Additional vocalizations from distant whales are also present. The sequences are time-aligned according to the highest cross-correlation peak between each hydrophone 1–4 and the center "master" hydrophone. Four of the seven humpback units from the center hydrophone are correctly matched with four units on adjacent hydrophones. The full set of cross-correlations between the center hydrophones and adjacent hydrophones can be seen in Fig. 2(b). The peaks resulting in the correct TDOA stand out prominently compared to the peaks from mismatched units. The second highest set of four correlation peaks are caused by the correlation of a unit with a nearly identical repeated unit produced by the whale approximately seven seconds after the first unit. If single units were used in the cross-correlation, these incorrect peaks would be as prominent as the taller (correct) peaks.

The time series used in the processing was resampled to 10 kHz from the originally recorded 96 kHz sampling rate, and 2048 point fast-Fourier transforms (FFTs) with a Hamming window were used with an overlap of 512 points, resulting in spectral bins with duration of 51.2 ms. The inset in Fig. 2(b) illustrates the discrete values (shown as two black dots) resulting from the cross-correlation of the spectral templates with temporal bin size of 51.2 ms. Quadratic interpolation about the discrete peaks was used to improve the accuracy of the estimated time delays.

The generalized TDOA method described in Sec. III A by Nosal[7] describes a post-processing step in which the correct TDOAs are selected from the TDOA cross-correlogram by connecting track lines in the image. When multiple animals are present, a feasible real time alternative is to choose the N most prominent peaks from the TDOA cross-correlogram, allowing up to N position fixes per sequence. The value of N cannot exceed the sequence size and in practice should be limited to the number of peaks consistent with position fixes of acceptable accuracy. Note that when animals are calling simultaneously in numbers greater than the chosen value of N, only N of the animals will be localized per sequence. Because the sequence on the center "master" hydrophone advances by only one unit at a time, well defined tracks for all of the animals can still be expected.

Figure 3(a) shows the TDOA cross-correlogram between the center hydrophone and hydrophone 4 for the full 3.5 h period in which the two humpback whales traversed the subarray. The highest peaks in the cross-correlogram are a result of the correct cross-correlation, while mismatched correlations are suppressed during the entire period. The corresponding TDOA points to the cross-correlogram are shown in Fig. 3(b) for $N = 3$, with the highest peaks for each time step shown in red. One then has to test all N^4 combinations of delays but at most N of these can result in valid localizations. False localizations are rare since the space of valid time delays is a two-dimensional surface and so a random intersection is unlikely. In practice only one or two whales are present within a subarray during the same time period and it suffices to use a single maximum ($N = 1$), which confers a notable advantage in computational speedup. However, $N = 3$ is perfectly feasible when needed.

C. Model-based localization

Localization using the TDOA between hydrophone pairs is accomplished using an established "model-based TDOA".[7,9,11,18,19] Position fixes are computed using the least-squares difference between the measured and modeled TDOAs, defined as

$$\mathrm{LS}(\mathbf{w}) \propto \prod_{ij} \left\{ \max_{k} \left(\exp\left[\frac{-1}{2\sigma_{ij}^2} \left(\Delta t_{ij}(k) - \Delta \hat{t}_{ij}(\mathbf{w}) \right)^2 \right] \right) \right\}, \tag{1}$$

where $\Delta t_{ij}(k)$ is the kth measured TDOA that falls within a given time step for receiver pair i,j and $\Delta \hat{t}_{ij}$ represents the modeled estimate TDOA at position $\mathbf{w}$. Applying the "master hydrophone" formulation noted previously, i is restricted to the center hydrophone of each subarray and j to the four adjacent hydrophones. Additionally, k is restricted to the N largest peaks from the cross-correlation of each sequence. The variance, σ^2, represents errors due to receiver position, measured TDOA, and sound speed profile (SSP). The variances are assumed equal for all hydrophone pairs.

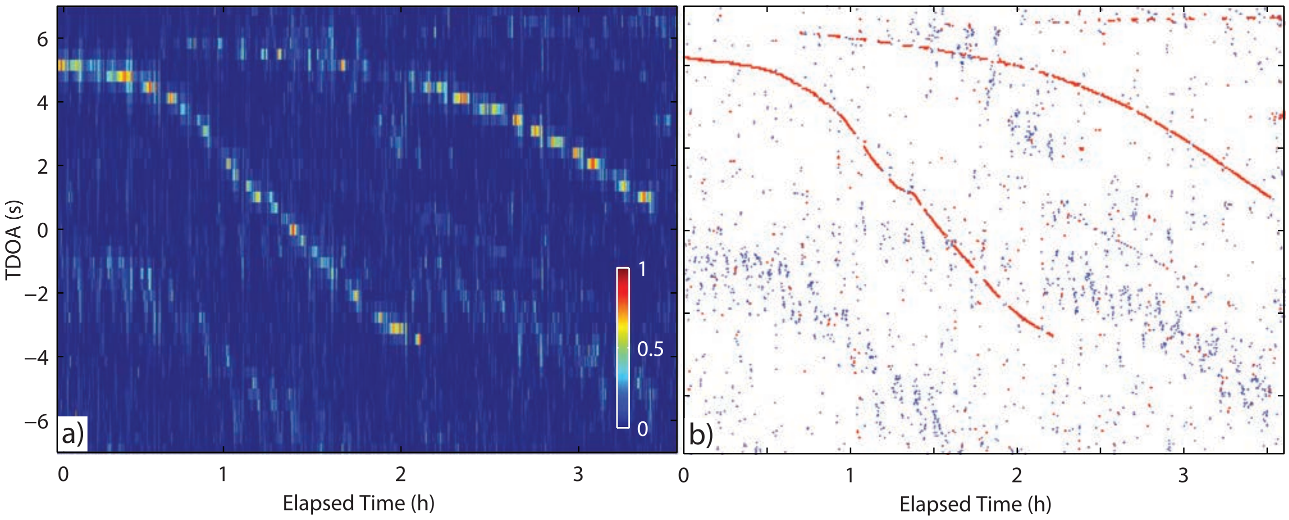

FIG. 3. TDOA cross-correlogram (a) between the center hydrophone and hydrophone 4; the two prominent features represent the TDOA of two whales as they travel through subarray D. The three highest cross-correlation values for each time slice are extracted from the TDOA cross-correlogram and replotted in the right plot (b), representing $\Delta t_{c4}(k)$ in Eq. (1). The peak values are shown in red, and the second and third highest values shown in blue. The TDOAs represented here are also generated for the center hydrophone to the three other corner hydrophones and the combination of delays are used in Eq. (1) to estimate locations.

The exponential form above is the optimal maximum likelihood estimator on the assumption that the measured delays are independent, identical, and Gaussian distributed.

The quantities $\Delta\hat{t}_{ij}$ are first computed across the search grid based on estimated direct path travel time of ray paths[20] using a historical SSP. These travel times agreed within 1 ms of travel times predicted by both Bellhop[21] and a range-dependent acoustic model.[15] Distances are estimated using the World Geodetic System (version WGS84) reference ellipsoid.[22] An initial localization is then computed by maximizing LS($\mathbf{w}$) in Eq. (1) over a grid with spacing of 50 m. This initial localization is then refined by using the Nelder–Meade optimization,[23,24] allowing the position to vary continuously. A more sophisticated propagation model that incorporates multipath travel times is not needed as the direct path is received at all hydrophones when a whale is calling within the predefined search grid. Eliminating solutions based on multipath arrival reduces localization ambiguities without degradation in localization performance.

As remarked in Sec. II B, $N = 3$ results in 81 candidate sets of TDOAs. Each set of delays with the minimum least-squared value [maximizing Eq. (1)] that meets a threshold criteria is deemed a valid localization. Multiple approaches exist for eliminating the few incorrect localizations that result (for any N). The most straightforward approach is to implement a minimum cross-correlation score for each sequence, which ensures that multiple units within a sequence align. A cross-correlation cutoff of 0.4 eliminates all incorrect localizations but at the expense of reducing the number of valid localizations by 20% to 30%. If animals vocalize often enough to ensure that they create traceable track lines and real-time results are not needed, then Nosal's method[7] can also be used to eliminate the spurious points.

D. Sources of uncertainty and limitations

Monte Carlo simulations were used to characterize the performance of the TDOA algorithm as reflected in the accuracy of timing delays and the resulting position fixes. As localization is a parameter estimation problem, the appropriate metrics of performance are the bias and the variance (or standard deviation) of the estimates. From these simulations emerge optimal values for control parameters in the templating and cross-correlation process that maximize the accuracy of the timing delays and hence that of position fixes as well.

For this purpose, a simulated song was constructed from real recorded humpback units on the PMRF range with a repeated two unit phrase, the first a grunt at 330 Hz lasting 0.75 s, the second a tonal at 530 Hz of 1.5 s duration. Interunit spacing was varied between 2.8 and 3.1 s. The SNR of both units was determined by adding white noise of a specified level. The case of "medium-level" noise is defined by the band-limited (restricted to the 150–1000 Hz frequency range over which the GPL detector operates) root-mean-square SNR values of −10.6 dB for the grunt and −7.8 dB for the tonal. The SNR value for the grunt invariably generates a test statistic above threshold for the GPL algorithm. However, about 5% of the time, the detected duration drops below 0.35 s and such units are discarded as false positives. At the SNR level of the tonal, the missed detection rate is about 10%. This higher rate arises both from occasional failure of the test statistic to rise above threshold and/or dropping below the duration limit, when the unit is fragmented in the spectrogram. Figure 4 exhibits instances of all these shortcomings. In practice, real humpback signals originating from within the range always contain SNR values of this level or higher over all noise levels recorded on the range. The templating threshold value of $5\mu_0$ described in Sec. II A is thus set at an appropriate level for templating nearly all direct-path arrival units originating from within the range.

The major shortcoming of these Monte Carlo runs is that transmission loss on the range is not modeled. While all five hydrophones thus receive identical signals, the noise realizations are independent and hence statistical variability occurs in the detection and templating process between hydrophones.

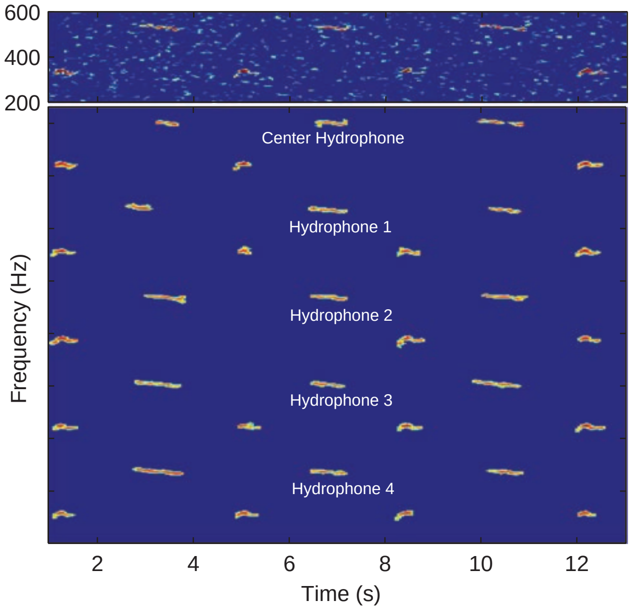

FIG. 4. Example spectrogram and related time-aligned sequences used in the Monte Carlo simulations for the medium-level noise benchmark case (B1). The sequences are aligned according to highest cross-correlation score for the center hydrophone to each of the four corner hydrophones. Band limited spectrograms around the strongest harmonic vary between ±2 dB.

For each trial, the location of the vocalizing whale was determined from a two-dimensional Gaussian spatial probability density function (pdf) with $\sigma_x = \sigma_y = 1$ km and centered at a point 9.25 km NW from the center hydrophone of subarray D. Time delays were determined from the detection, templating, and resulting cross-correlation of sequences of the simulated song units. These empirical TDOAs were substituted into Eq. (1) and the least squares position estimate determined from the best match with predicted direct ray path travel times. The resulting position estimate was then compared against the known vocalization origin point.

Many parameters in the detection, templating, and cross-correlation process affect the accuracy of the timing delays. Based on numerous Monte Carlo simulations, as well as application to real data from the PMRF range, it was determined that the best results are obtained by (1) characterizing units by a single harmonic, (2) basing correlation on (normalized) Fourier amplitude (not amplitude squared) within that harmonic, (3) using quadratic interpolation of the digitized correlation data to refine the peak, (4) using a sequence of seven calls, and (5) using an FFT length of 2048 with an overlap of 75% (bin spacing of 51.2 ms). These parameters define the "benchmark case." Altering any of conditions (1)–(3), or relaxing (4) or (5) (i.e., reducing the sequence size or decreasing the FFT overlap), all degraded the performance.

While it might be thought that *increasing* the overlap beyond the stated 75% would monotonically improve results, finer temporal resolution at fixed FFT length does not improve the accuracy in determining peak correlation time. Statistics for an overlap of 93.75%—a bin spacing of 12.8 ms—are worse. However, doubling the FFT length to 4096 while increasing the overlap to 93.75%—a bin spacing of 25.6 ms—does improve accuracy, but only slightly, while the CPU time increases substantially.

Table I characterizes performance of the TDOA algorithm for various choices of model parameters in terms of σ_t, the standard deviation for time delay errors, σ_x, the standard deviation of the local Cartesian expansion of latitude, and σ_y, the standard deviation of the local Cartesian expansion of longitude. Further comments on characterizing the error appear shortly. Each case represents 1000 trials.

The benchmark case is shown for medium-level noise (B1), low-level noise (defined to be 3 dB down from medium-level noise) (B2), and for the zero noise limit (B3). The zero noise limit case represents the irreducible, intrinsic, errors associated with the benchmark parameter set (1)–(5). The increase in σ_t above this scales linearly with energy in the noise (a factor of 4 from the low-level to medium-level noise case).

Additionally, errors are shown when the benchmark case Fourier amplitude templates are replaced with Fourier amplitude-squared (energy) (T1), and when the templates are solely based on shape (T2). Note that using only the shape as used by Tiemann *et al.*[11] is notably worse. While results in Table I for (T1) are equivalent to (B1), in application to real data, (T1) yields appreciably fewer position fixes and this observation, rather than the Monte Carlo simulations, is the basis for defining amplitude as the benchmark.

Finally, errors are tabulated for varying sequence size with two calls per sequence, containing both the grunt and tonal (S1), and single call sequences for the grunt (S2) and tonal (S3). Note for the single call, the delay errors are considerably worse for the tonal, which exhibits nonnormal statistics with a fat tail, probably arising from call fragmentation.

For the eight cases reported here, a total of 32 time differences of arrival exist for the four hydrophone pairings. The corresponding sample means all lie within ±1.5 times the standard error of the mean, consistent with a uniform assumption of zero bias for the TDOA algorithm, as well as the position fixes subsequently estimated.

The cumulative distribution function (cdf) of benchmark timing delay errors (B1–B3 in Table I) can be fit by the normal form, $\Phi(t) = 1/2(1 + \mathrm{erf}(t/\sigma_t\sqrt{2}))$. For the medium-level noise benchmark case $\sigma_t = 4.85$ ms. This zero bias fit satisfies the two-sided Kolmogorov–Smirnov (K–S) null hypothesis test at a significance level of 0.05 and hence justifies use of the Gaussian distribution in the expression for the maximum likelihood estimator in Eq. (1). Zero bias in the

TABLE I. The standard deviation for time delay errors σ_t and the standard deviation of the local Cartesian expansion of longitude σ_x and latitude σ_y for various cases used in the Monte Carlo simulations.

Case	Description	Noise level	σ_t	σ_x	σ_y
B1	Benchmark	Medium	4.85 ms	6.43 m	5.58 m
B2	Benchmark	Low	1.69 ms	2.25 m	1.96 m
B3	Benchmark	None	0.61 ms	0.98 m	0.64 m
T1	Energy	Medium	4.84 ms	6.52 m	5.68 m
T2	Shape	Medium	9.53 ms	12.95 m	11.16 m
S1	Two unit	Medium	11.40 ms	15.84 m	13.12 m
S2	Single grunt	Medium	9.06 ms	11.48 m	10.76 m
S3	Single tonal	Medium	42.61 ms	58.44 m	48.75 m

timing errors implies zero bias in estimates of longitude and latitude from Eq. (1). The zero bias spatial expectation is confirmed by the K–S test for the respective normal form cdf benchmark fits with $\Phi(x)$ using $\sigma_x = 6.43\,\text{m}$ for latitude and $\Phi(y)$ with $\sigma_y = 5.58\,\text{m}$ for longitude in the medium-level noise case. It is useful to combine the last two standard deviations as a single measure, $\sigma_d = \sqrt{(\sigma_x^2 + \sigma_y^2)/2} = 6.02\,\text{m}$. The related pdf for random vector lengths in the plane is the general Rayleigh distribution with variance $(4-\pi)\,\sigma_d^2/2 = 15.58\,\text{m}^2$ and the mean given by $\bar{d} = \sigma_d\sqrt{\pi/2} = 7.55\,\text{m}$. These values are to be compared to a sample variance of $15.46\ \text{m}^2$ and sample mean of 7.54 m. This Rayleigh distribution is plotted in black and green for the medium-level and low-level noise benchmark cases (B1, B2) in Fig. 5, and the purely empirical pdf's for other cases (T1, T2, S1) are shown in red, blue, and purple, respectively. While (T1) and (T2) are also arguably Rayleigh distributions based on the K–S test, case (S1), the two unit sequence, is manifestly not: it has a tail that decays with a controlling factor of $\exp(-\alpha\, d)$ rather than $\exp(-\alpha\, d^2)$. The time delay errors in that case also have a long tail, one not modeled by $\Phi(t)$.

Without a database of known source locations and accompanying time series, the only way to characterize the distribution of time delay errors is with Monte Carlo simulations. How that distribution translates into errors for latitude and longitude is then directly a function of the array geometry and the sound speed profile. The standard deviations for the errors in position can be calculated by minimizing a quadratic approximation of Eq. (1) based on a first order expansion for $\Delta\hat{t}_{ij}(\mathbf{w})$. Therefore, it is possible to obtain localization error estimates over the entire array, rather than just the small region to which the Monte Carlo results were limited. The expected localization errors in latitude and longitude for subarray D are shown in Fig. 6, with the Gaussian patch for the Monte Carlo simulations marked by a white circle. For the benchmark case (B1) the theoretical predictions using $\sigma_t = 4.83\,\text{ms}$ are $\sigma_x = 6.51\,\text{m}$ and $\sigma_y = 5.67\,\text{m}$. These agree with the Monte Carlo values of 6.43 and 5.58 m to within expected error for 1000 trials. Since the position errors scale linearly with σ_t, the general patterns in Fig. 6 show the relation of position errors for any of Monte Carlo simulations except S1–S3 relative to their magnitude in the rest of the domain for any noise level. As anticipated, errors are largest in the corners and rise sharply outside the borders of the array, though longitude is more sensitive to the east and west and latitude to the north and south.

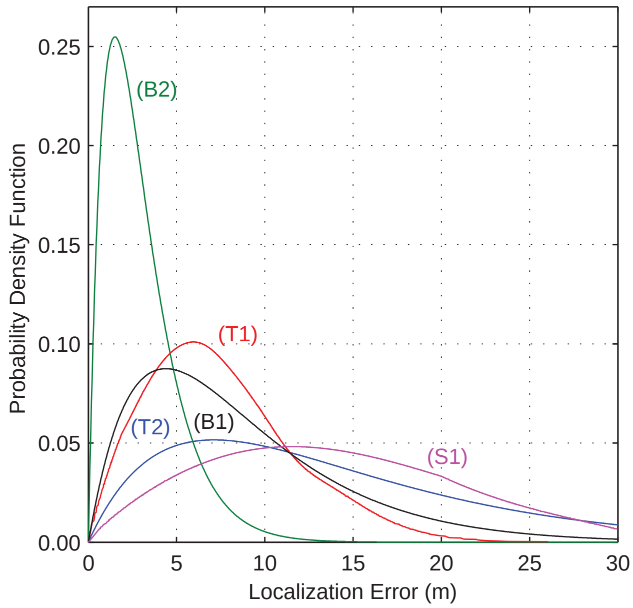

FIG. 5. Probability density function (pdf) localization errors are shown for the benchmark cross-correlation and TDOA parameters for medium-level noise (black) and low-level noise (green) and several alternative cases discussed in Sec. II D. The symbols (B1, B2, T1, T2, S1) correspond to the descriptions in Table I.

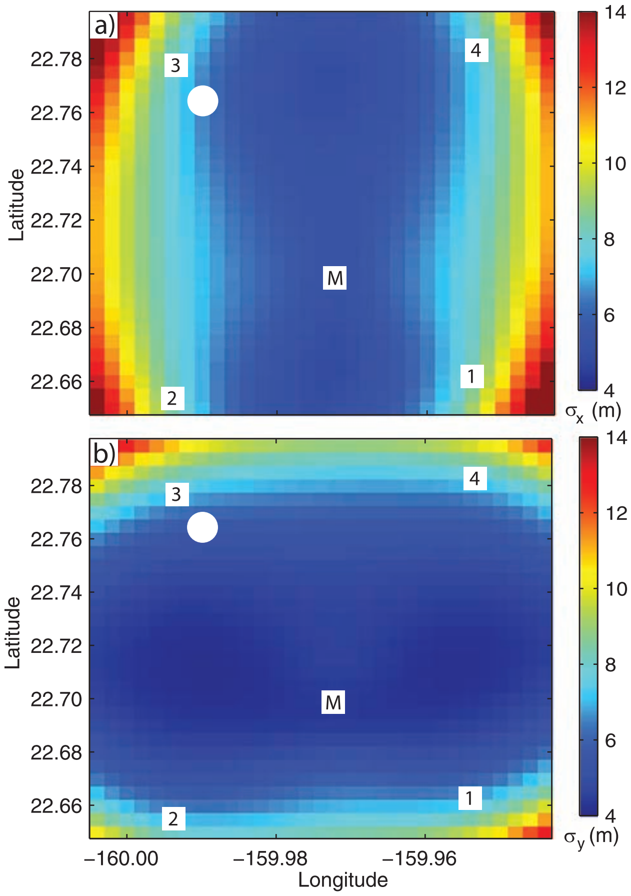

FIG. 6. Theoretical calculation of the standard deviation of horizontal localization errors σ_x (a) and vertical localization errors σ_y (b) as a function of longitude and latitude for correlated random timing delay errors in Eq. (1). Approximate locations for hydrophones (1–4) and center hydrophone (M) are shown for subarray D. The Monte Carlo simulations for distance errors were limited to the 1 km radius patch marked by the white circle.

All the Monte Carlo results were obtained with a spatially stationary whale. Generally, however, the whale is moving along a fairly linear trajectory at a nearly uniform speed. It can be anticipated that such movement degrades the accuracies noted previously. To address this issue, a simulation of 2000 trials was run for the benchmark case (medium-level noise, seven unit sequence, correlation on amplitude) with the position of the whale at $t = 0$ chosen as above, but also an azimuth selected from a uniform distribution on (0°, 360°). The whale was assumed to travel at

6 km/h along a great circle with the given azimuth. For a sequence of calls that spans 18 s, the change in position is thus 30 m. The standard deviation in timing delay increases from 4.85 to 5.40 ms, the mean position error from 8.49 to 9.00 m. Comparable adjustments can be expected for the other cases, with their rank order unchanged.

Finally, as noted above, the time delay errors are well modeled as identically distributed normal random variables. It turns out that they are not, however, independent, presumably because the center hydrophone is common to all four TDOA estimates. Equation (1) is therefore not the best linear unbiased estimator. Rather one should incorporate the inverse of the covariance matrix in the quadratic form inside the exponential. In general the elements of this matrix would depend upon both position in the subarray owing to path dependence of transmission loss, an effect not modeled in the Monte Carlo simulations, and also background noise level. The issue merits further investigation but one can note that the changes to Fig. 6 based on a simple model covariance matrix for the idealized case of the Monte Carlo simulations are modest, with the qualitative variation across the array unchanged.

The goal of the Monte Carlo simulations was to identify optimal methods for estimating time delays from measured time series. But the other half of the problem, predicting time delays, rests on data with other sources of uncertainty, namely the sound speed profile with depth and range, and hydrophone locations and depths. The sound speed profiles shown in Fig. 7(a) were used to calculate the standard deviation and bias for local Cartesian coordinates x and y when a sound speed mismatch is used. The extremal profiles (red and green) represent the variation for 23 measurements taken over all months and spanning several years, while the blue profile is an SSP for February 2013. For the medium-level noise benchmark case (B1), the standard deviations σ_x and σ_y are unchanged when exact measured time delays were computed from the blue SSP and the predicted time delays were based on the green SSP. A second effect of uncertainty in sound speed is the bias in position fixes. This point is illustrated in Fig. 7(b), which shows the bias in the local Cartesian coordinates x and y that results from minimizing Eq. (1) with exact measured time delays computed from the blue SSP and predicted time delays based on the green SSP. The displacements in this case are of the same order as the errors σ_x and σ_y, but the former vary gradually, on a scale of a few km, while the latter vary from one position fix to the next. This disparity means that detailed features in whale trajectories are preserved and merely displaced with a nearly rigid translation. Note that variation between the blue and green SSPs is typical over the course of a month. The maximal variation over all measured seasons and years, i.e. measured time delays from the red SSP and the predicted time delays from the blue SSP, increases the scale in Fig. 7(b) by a factor of 4.

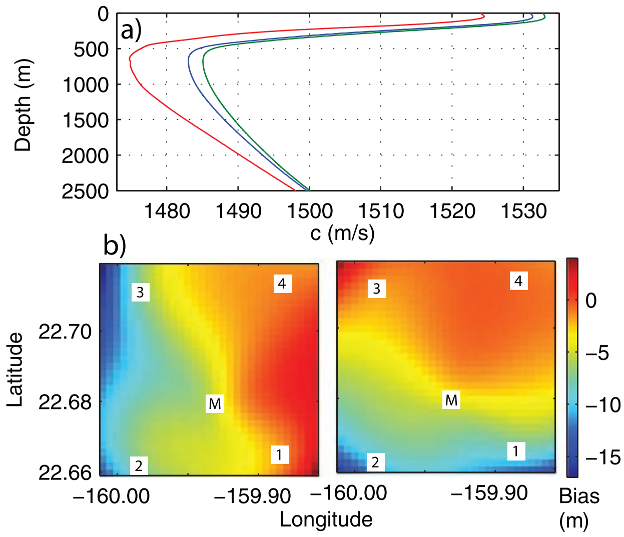

FIG. 7. Representative sound speed profiles (a) showing a February 2013 cast (blue) and maximal variation (red and green) for 28 measurements over multiple years and all seasons at PMRF. The variation between the blue and green curves is representative of typical variation observed over the course of a month on the range. The bias for local Cartesian coordinates x (left plot) and y (right plot) as a function of longitude and latitude is shown in the lower plots (b) for subarray D. For the bias shown, the blue sound speed profile is assumed to be the actual *in situ* profile, but the green sound speed profile is used to calculate the predicted time delays. Approximate locations for hydrophones (1–4) and center hydrophone (M) are shown for subarray D.

A second source in bias arises from the uncertainty in depth of the vocalizing animal. The contours for this bias are broadly similar to those in Fig. 7(b). In the specific case of a whale vocalizing at 100 m depth but assumed to be at 5 m depth there results an induced horizontal root-mean-square bias of 6.1 m averaged over the area enclosed by subarray D.

In the case of the PMRF range, hydrophone locations and depths are well characterized, so errors in hydrophone positions were not explored. In experiments where either sound speed or hydrophone locations are less well known, note that one can bootstrap to good effect by, for example, allowing the locations of $n-1$ hydrophones to vary while holding one fixed and maximizing LS($\mathbf{w}$) in Eq. (1) for $2n$ (or more) position fixes simultaneously. When both sound speed and hydrophone locations are poorly known, bootstrapping will generally yield families of solutions for hydrophone locations and sound speed, rather than a single optimum. As in the case of sound speed mismatch the standard deviations σ_x and σ_y are unchanged.

III. RESULTS

A. Localization

Figure 1 shows the track lines of the two humpback whales that are associated with the template and TDOA examples in Figs. 2 and 3. A total of 3500 valid localizations were computed over the course of 3.5 h. Post-processing (discussed in Sec. III B) reveals that 877 localizations can be assigned to individual units for the western track, and 1060 units can be attributed to the eastern track. Because sequences of units are used to calculate the localizations, an individual unit can contribute to multiple localizations, and hence the higher total localization tally. The average estimated inter-call interval for the western track based on the detected units is 3.3 and 3.2 s for the eastern track. Manual inspection of the original spectrograms over the same period reveals an inter-call interval of song units of approximately

3 s for both whales, suggesting that valid localizations are calculated for nearly every unit produced. A few clusters of incorrect localizations can be seen in Fig. 1, totaling 25 points over a period of 22 h. As noted earlier, such incorrect localizations can be eliminated by implementing a cross-correlation minimum of 0.4 during the calculation of TDOAs, but the number of valid localizations drops from 3500 to 2500. Even with this reduction, both track lines remain well defined with multiple localizations every minute during intervals of vocalization. The incorrect localizations could also be easily removed by implementing one or both of the post-processing steps outlined by Nosal,[7] with the advantage of keeping all valid points along the track line.

The methods outlined in this paper were used to process a total of 40 days of recordings on the PMRF range over the months of December through May, spanning the years from 2011 through 2014. Thirty-one unique humpback track lines were found in the recordings. Manual inspection of the TDOA cross-correlogram revealed that all calling humpbacks in the vicinity were localized consistently. A surprisingly large proportion of detected units originate from off-range locations. While exact position fixes cannot be calculated, analysis suggests these calls originate from near-shore and potentially propagate up to 60 km in some cases. If analysis were done on single hydrophones within the range, the animal density could easily be overestimated in the study area, due to the non-random distribution of animals. The processing of all four subarrays was accomplished five times faster than real-time on a standard dual-core computer with 2.2 GHz processors. A slight time delay is required to amass enough units to construct the sequence, but on average, this delay is on the order of 20 s or less for actively calling whales.

While no data exist to ground-truth the localization coordinates produced from the recorded data, some aspects of the results indicate that the localization accuracies are consistent with those estimated from the Monte Carlo simulations. The inset in Fig. 1(b) shows very tightly clustered localization points along the presumed track. Fitting a trajectory through this trajectory, it was found that no point deviated by more than 100 m from the track, and the standard deviation from the track line was 17 m. These results are consistent with the error estimates predicted from the Monte Carlo simulations. Additionally, during the development of the sequencing process, various sequence sizes were considered. The sequence size can be increased beyond seven, though with diminishing return. A trial computation with a twelve-call sequence for real data from the PMRF range does show perceptibly tighter grouping, particularly in the eastern (off-range) trajectory of Fig. 1(b). However, of some 3500 position fixes based on the same initial unit, latitudes for the twelve-call sequence show an 8.7 m bias to the north and 1.02 m bias to the west. The twelve-call sequences last an average of 10.6 s longer and the northward bias is consistent with a mean northward velocity of 5.9 km/h. The whale on the western track averages 6.7 km/h northward, that on the eastern track averages 5.2 km/h northward. An approximately an equal number of calls are detected from each track and hence the overall bias is accounted for to within a few percent by the average these two speeds. The westward bias is similarly explained. Independent localizations for the western track were computed using both subarrays C and D as the whale transited across the subarray border. A total of 357 localizations from subarray C were compared to positions from subarray D interpolated for the same time (referenced to the whale's position). The comparison yielded a localization agreement with standard deviation of $\sigma = 9.8$ m. The observed cluster tightness, the velocity estimates from sequence comparison, and the agreement of independent localizations all provide excellent evidence that the Monte Carlo simulations with time delay errors of 5–10 ms give a realistic estimate of expected errors. Additionally, the humpback transiting speeds noted above are consistent with observational data for transiting humpback whales.[25]

B. Call association

Once whale tracks have been established, it is possible to post-process the acoustic data and assign humpback song units within a spectrogram to individual singers. The general procedure is to first calculate the expected TDOA between the center hydrophone to adjacent hydrophones for all locations along the track line. Next, the cross-correlation score for each individual unit is calculated between the master hydrophone and each adjacent hydrophone in the vicinity of the expected delay, allowing for a variation of ±5 ms. If the unit has a cross-correlation score of 0.4 or higher on at least two hydrophone pairings, then the unit is assigned to the individual whale on the track of interest. Figure 8(a) shows the original spectrogram on the center hydrophone for subarray D, containing song from the two whales whose tracks are shown in Fig. 1, with the song from at least one more distant

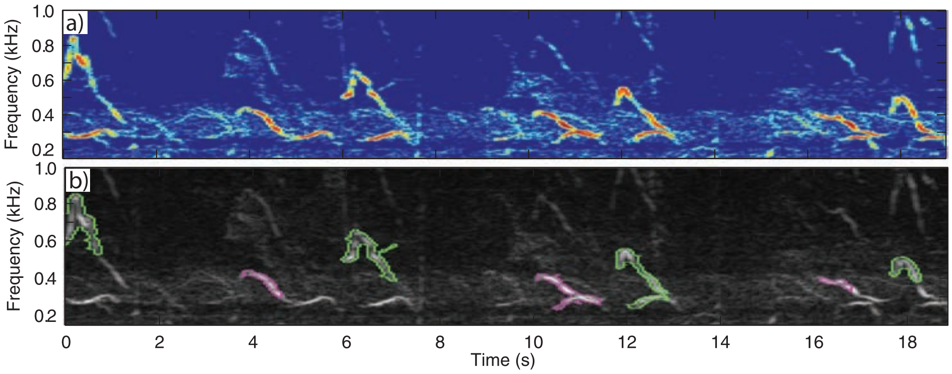

FIG. 8. Spectrogram from the center hydrophone of subarray D (a) recorded during vocalization of two humpback whales as they transit through the subarray (shown in Fig. 1), with additional distant whale vocalizations present. The same spectrogram (b) shown with automated color contours drawn representing the whale from the western track (green) and the whale from the eastern track (purple).

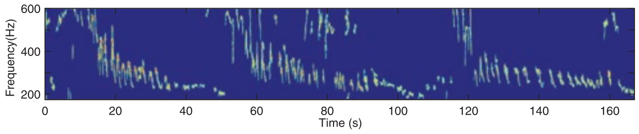

FIG. 9. Automated extraction of humpback units (shown in template form) relating to the western whale track from Fig. 1. Inter-call intervals have been suppressed so that the song sequencing is clearer (actual elapsed time is approximately 10 min).

whale also present. Figure 8(b) shows a grayscale image of the same spectrogram, with the detected unit contours from the templating procedure discussed in Sec. II A highlighted in green for the western track whale and magenta for the eastern track whale. The low frequency units from the third more distant whale occasionally overlap in time and frequency with the units produced by the other two whales, and so sometimes a contour is merged across units originating from two separate whales. While not perfect, this automated assignment of most units to individual whales can be helpful for biologists interested in annotating humpback song, or examining the relationship of song production between conspecifics. Figure 9 shows the templates of the song sequence assigned to the western whale, with the time between units removed. Manual analysis shows that approximately 90% of the units produced by the western whale are templated and assigned correctly, and no units from other whales are included (unless a unit overlaps in space/time with a unit originated from the western whale, in which case some of the contour can be included). Using this technique, automatically extracted relevant song information can be used for analysis. Currently, the center, lowest, and highest frequency of each templated unit is automatically saved. This information may prove useful for automatically harvesting large-scale statistics on humpback calling patterns.

IV. CONCLUSIONS

The techniques outlined in this paper prove to be effective for localizing humpback whale vocalizations on 14 hydrophones five times faster than real-time on the PMRF range with a predicted high level of spatial accuracy. The localization process is robust over a wide range of environmental and noise conditions, and has been shown to work on data collected in the months of December to May over multiple years. Although not discussed in detail, the GPL detection and templating procedure is general enough to be readily adapted to other types of marine mammal vocalizations, and so the same process for obtaining TDOAs between hydrophone pairs can be ported to other species. The model-based localization method outlined in this paper is built on many of the same principles described in other peer-reviewed publications, and has proven to work well over a variety of species, array configurations, and bathymetric and environmental conditions. The post processing methods outlined for call association could prove helpful for matching vocalizations to individual whales, even in the presence of multiple calling animals with similar vocal patterns. One obvious extension of the call association process is to automatically obtain cue rates from existing data sets. Obtaining information on cue rates over a variety of social, spatial, temporal, and environmental conditions is a crucial component for calculating animal densities from passive acoustic data.

ACKNOWLEDGMENTS

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Occurrence and Habitat Use of Foraging Blainville's Beaked Whales (*Mesoplodon densirostris*) on a US Navy Range in Hawaii

E. Elizabeth Henderson, Steve Martin, Roanne Manzano-Roth, Brian Matsuyama

Blainville's beaked whales were detected through passive acoustic monitoring of the hydrophones at the Pacific Missile Range Facility off Kauai, Hawaii from 2011 through 2013. Group dive detections were analyzed for temporal (intra- and inter-annual and diel) and spatial (depth, slope and range extent) patterns, and a habitat model was developed using those parameters as predictor variables in Blainville's beaked whale dive distributions. No monthly or annual trends in dive rates were found, but there was some diel periodicity found in dive rates related to the lunar cycle. In addition, a strong relationship was found between bathymetric features and dive rates, with most dives occurring over steep slopes and depths between 2000 and 3000 m. Dive rates were also compared against Navy training activity to assess whether foraging behavior was impacted by sonar. Similar to other Navy ranges, biannual multi-day training events did decrease dive rates, but all other training activity did not appear to affect dive rates on a monthly or weekly time frame. During the biannual training events dives were consolidated to the southern portion of the range, but throughout the rest of the year dives occurred across the range although were still concentrated in preferred habitat. These results are the first description of baseline behavior for Blainville's beaked whales at PMRF, and provide some insight into habitat use patterns related to both the natural environment and anthropogenic impacts.

Introduction

Beaked whales have come under more scrutiny in the last 25 years (Simmonds & Lopez-Jurado, 1991; Ketten, 2005; Cox et al., 2006; D'Amico et al., 2009; Faerber & Baird, 2010). Prior to this intensive study, this was a relatively unknown family of cetaceans, with several species described only from skulls or stranded animals. With the last two decades of research, new beaked whale species have been discovered (Dalebout et al., 2002; Baumann-Pickering et al., 2010; Dalebout et al., 2014); new vocalizations have been recorded and, in some cases, attributed to likely candidate species (McDonald et al., 2009; Baumann-Pickering et al., 2010; Rankin et al., 2011; Baumann-Pickering et al., 2013); and more information has been gleaned on the better known species, including Blainville's (*Mesoplodon densirostris*), Cuvier's (*Ziphius cavirostris*), and Baird's beaked whales (*Berardius*), and northern bottlenose whales (*Hyperoodon ampullatus*) (Hooker & Baird, 1999; Hooker & Whitehead, 2002; Johnson et al., 2006; Johnson et al., 2008; Falcone et al., 2009; Wahlberg et al., 2011; Dunn et al., 2013; Schorr et al., 2014; Stimpert et al., 2014). The majority of this new information has come through tagging studies, passive acoustic studies, behavioral response studies, and photo-identification studies. However, many of these studies have taken place over short term periods, on the order of hours to days, and can be regarded as snapshots of behavior.

Blainville's beaked whales are the most widely distributed of the *Mesoplodon* species, second only to Cuvier's beaked whales in global distribution of a beaked whale species (MacLeod et al., 2006), and found in tropical and temperate waters in all ocean basins except the Arctic. Despite this global distribution, few studies of occurrence and habitat use have been conducted on this species due to their low visibility and long dive times (Barlow, 1999). Visual surveys (MacLeod & Zuur, 2005; Claridge, 2006) and habitat modeling (Hazen et al., 2011) have been conducted in the Bahamas off Great Abaco Island, while passive acoustic monitoring has been conducted using the bottom-mounted hydrophones at the Atlantic Undersea Testing and Evaluation Center (AUTEC), a Navy range frequently exposed to Navy sonar (McCarthy et al., 2011; Tyack et al., 2011). In the Bahamas studies, Blainville's beaked whales were strongly associated with depths between 136 and 1310 m and slopes from 6 – 30%, and remained within several km of shore. Some photo-identified animals have been resighted over time, indicating some possible residency to the area (MacLeod & Zuur, 2005; Claridge, 2006). Similarly, another possible resident population of Blainville's beaked whales has been photo-identified and tagged off the west coast of the island of Hawaii (Baird et al., 2004; Baird et al., 2006a; McSweeney et al., 2007; Baird et al., 2008; Baird et al., 2009; Schorr et al., 2009). Here, Blainville's beaked whales were associated with depths between 880 and 1455 m (median = 1156 m) and slopes between 0 – 41% (median = 6%), remaining within 50 km of the island (Baird et al., 2006a; Schorr et al., 2009). Tagged animals dove to depths between 800 and 1484 m (Baird et al., 2006a) to forage, presumably on cephalopods and deep water fish (MacLeod et al., 2003) not associated with the scattering layer as they conducted these deep foraging dives equally both day and night (Baird et al., 2008).

For this study, acoustic data was recorded a few days each month using the instrumented range hydrophones at PMRF off the island of Kauai in the Hawaiian archipelago from 2011 - 2013, as well as before, during, and after US Navy training events (Manzano-Roth et al. submitted). This dataset provides the ability to look at long-term trends in Blainville's beaked whale foraging behavior and habitat use on a broad spatial scale. This information is crucial to the estimation of behavioral responses to sonar and other anthropogenic activity at the range; by parsing out natural variations in dive behavior, the changes that occur in response to Navy sonar can be more accurately identified.

The goals of this study were to: 1) describe diel, seasonal, and interannual trends in Blainville's beaked whale foraging dives, and 2) associate these trends with bathymetric and temporal features and anthropogenic noise events in order to identify features that correlate with foraging dives, thereby 3) assessing the habitat use of Blainville's beaked whales at PMRF.

Methods

Acoustic recordings and analysis

PMRF is located off the west coast of the island of Kauai, Hawaii (Figure 1), and has over 200 seafloor mounted hydrophones that support a wide variety of US Navy training and testing activities throughout the year. A subsample of the range hydrophones at PMRF have been recorded since 2003, with an increase to at least two days a month along with the before, during, and after periods of Navy training events since 2011 (Manzano-Roth et al., submitted). The "during" periods will not be utilized in this analysis of baseline behavior, but the before and after periods have been included. From January 2011 through August 2012, 31 hydrophones were sampled, while that number was doubled to 62 recorded hydrophones from late August 2012 through December 2013 (Figure 1). However, only the data from the 31 phones will be examined in order to be consistent across years. These broadband hydrophones were sampled at 96 kHz using 16-bit analog-to-digital converters. The sampled portion of the range varies in depth from 429 – 4877 m, with a mean depth of 2945 m.

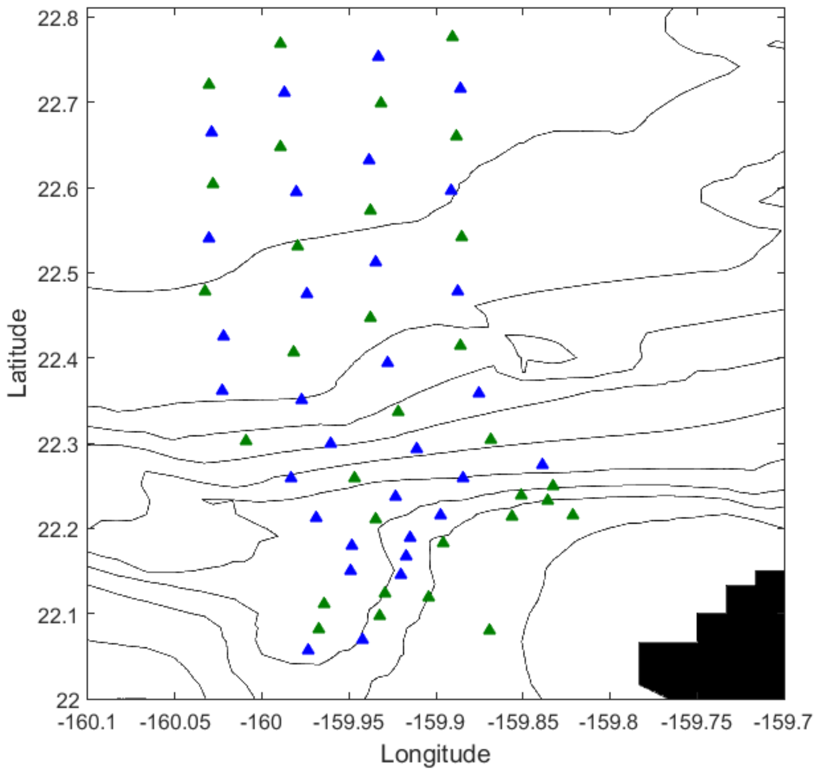

Figure 1 – Map showing approximate locations of original 31 hydrophone locations (in green) recorded from Jan 2011 – Aug 2012, with additional 31 hydrophones (in blue) added in Aug 2012 and recorded through Dec 2013.

The recording process and automated detector used for analysis have been described in detail in Manzano-Roth et al. (submitted) and will only be briefly summarized here. A custom-built C++ algorithm was used to automatically detect Blainville's beaked whale foraging clicks. Blainville's beaked whale clicks have a frequency upsweep from 27 to 45 kHz over a 0.3 ms duration, with a typical ICI of around 0.3 sec (Baumann-Pickering et al., 2014; Manzano-Roth et al., submitted). A high signal-to-noise ratio threshold was used to reduce the likelihood of false positives. In a performance assessment conducted on a subset of data taken from all three years, the probability of detecting an individual click was around 39% (Manzano-Roth et al., submitted). However, all automated detections were manually validated, leading to a final false positive rate of zero, while the likelihood of detecting a group dive remains high due to the spacing of the hydrophones (1.6 – 10+ km apart, with at least one neighboring phone within 6 km when sampling all 62 hydrophones). When clicks were detected on more than one hydrophone in an area and were deemed to have come from the same group, the hydrophone with the most detections was designated as the *primary* hydrophone. Only the primary phone was used for all temporal and spatial analyses.

Habitat use analysis

All detected and validated Blainville's beaked whale dives from the original 31 hydrophones were compiled and normalized by recording effort to assess diel, monthly, and interannual trends in dive behavior. In addition, depth data were taken from the NOAA National GeoPhysical Data Center's ETOPO2 2-min global relief database (http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html). Depth values were selected within a 3 km radius around each hydrophone to determine the minimum, maximum, and mean depth values for each hydrophone area. These data were used to calculate the maximum percent slope of each hydrophone area, calculated as maximum - minimum depth/3000 m*100.

Chi Square goodness-of-fit tests were used to assess the number of normalized dives detected across diel, monthly, and interannual temporal scales to determine if there were significant trends across those time periods. A Generalized Additive Model (GAM) was fit to all temporal and spatial data in order to develop a model that best described the spatio-temporal habitat use of Blainville's beaked whales at PMRF. Blainville's beaked whale dives were grouped into one hour bins based on the start time of the dive, and then GAMs were developed as a function of temporal and spatial variables (Year, Month, Start Hour, Lunar Phase, Depth, and Slope) using the mixed GAM computational vehicle (mgcv) package in R software, vers. 2.14.2 (Hastie & Tibshirani, 1990; Wood, 2006; Team, 2014). To select predictor variables for inclusion in each model, a likelihood-based smoothness selection method was applied with the restricted maximum likelihood (REML) criterion (Patterson & Thompson, 1971; Wood, 2006). Each predictor variable was tested for inclusion in the model using a smoothing function defined by a cubic regression spline. The best model was selected after sequentially dropping the single term with the highest non-significant P-value and then refitting the model until the REML score and explained deviance were maximized.

Training activity at PMRF

Multi-day training events occur at PMRF every February and August that utilize multiple types of sonars, including hull-mounted sonars, and are more intensive than training that occurs throughout the year. The number and spatial occurrence of foraging Blainville's beaked whale dives that occur before, during, and after these events has already been studied in detail (Manzano-Roth et al., submitted). However, there are a number of other, smaller training and testing events that take place at PMRF throughout the year that may utilize a variety of sonars or generate explosive sounds during a portion of the event. The hours of all training events that took place at PMRF from 2011 through 2013 that may have emitted sonar or an explosive sound were tallied. These were compared against the number of beaked whale dives each month using a Spearman's rank test to determine if there was any impact to the number of Blainville's beaked whale foraging dives throughout the year from these shorter events. In addition, to assess impacts at reduced temporal scales, all training hours within 7 days of a baseline recording were summed and normalized into a per hour metric based on the number of days of training and then compared to the number of dives per hour in the subsequent recording period. This was conducted both with and without the inclusion of a time lag term to account for the number of days between training and acoustic recording periods, giving more weight to training events that had occurred just before the recording period. A Spearman's rank test was also used for this analysis.

Results

Temporal dive patterns

There was a total of 2328.8 hours recorded over the three year period, with 2958 Blainville's beaked whale foraging dives detected (Table 1) on 31 hydrophones. There were twice as many dives detected on all 62 phones after August 2013. Overall, there were a mean of 39.4 dives per recording and 1.3 dives per hour of effort (4 – 125 dives total; 1.3 – 3.3 dives per hour) on 31 hydrophones, and 54 dives per recording and 2.1 dives per hour of effort (9 – 108 dives total; 0.7 – 3.7 dives per hour) on 62 hydrophones. The number of detected dives per recording period was significantly different than expected (χ=494.57, $p<0.0001$), indicating broad intra-annual variability in dive occurrence patterns, although this number varied greatly within and across years (Figure 2). On a monthly basis, dive counts ranged from 11 to 226 on 31 hydrophones, with a mean of 84.5 (0.5 – 2.3 dives per hour, Figure 3). The observed number of dives per month for all years combined was significantly different than expected given the level of effort (χ=57.64, $p<0.0001$), indicating within-year seasonal variation. There was no clear pattern to this intra-annual variation, although there seemed to be an increase in dives in spring and again in late summer (Figure 3). The observed number of dives per year for all months combined was also significantly different than expected given the level of effort (χ=54.97, $p<0.0001$), with more dives than expected in 2011 and fewer than expected in 2013 (Figure 2).

Finally, although the apparent diel pattern in Blainville's beaked whale dives was slight, the normalized number of dives per hour was significantly different than expected (χ=47.13, $p = 0.002$), with a small decrease in dives during crepuscular periods (Figure 4).

Table 1 – Recording effort and number of detected and validated Blainville's beaked whale dives by year.

Year	31 Hydrophones			62 Hydrophones		
	Recording Effort (Hours)	Dive Count	Dives per Hour	Recording Effort (Hours)	Dive Count	Dives per Hour
2011	733.9	1088	1.5	NA	NA	NA
2012	849.8	1089	1.3	180.5	453	2.5
2013	745.1	781	1	745.1	1490	2.0
Total	2328.8	2958	1.3	925.5	1943	2.1

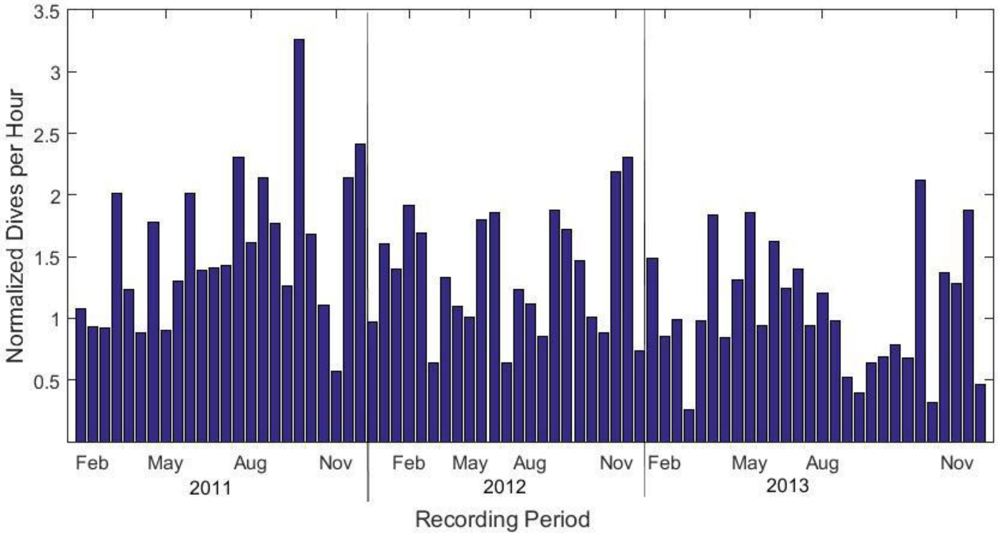

Figure 2 – The number of Blainville's beaked whale dives per recording period on 31 hydrophones, normalized by the recording effort per period.

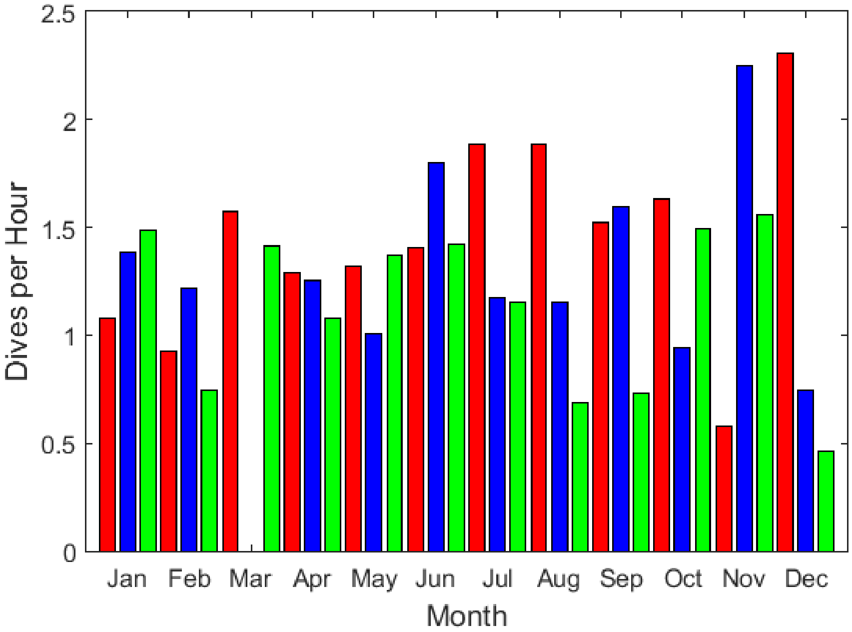

Figure 3 – The number of Blainville's beaked whale dives, normalized by recording effort to dives per hour, per month in 2011 (red), 2012 (blue), and 2013 (green) detected on 31 hydrophones.

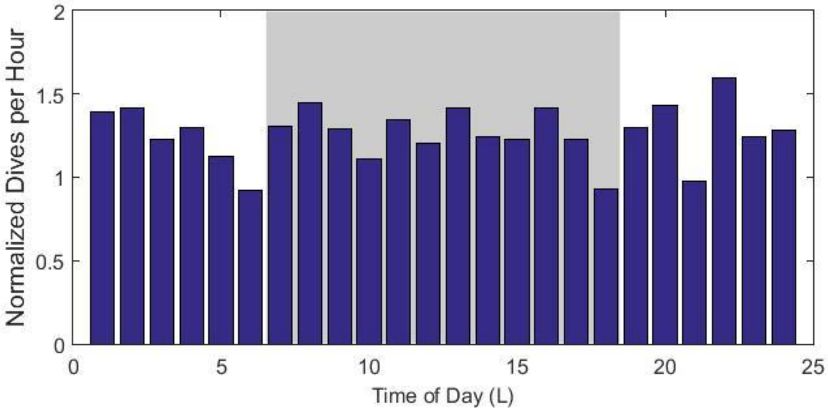

Figure 4 – The number of Blainville's beaked whale dives per hour from 31 hydrophones, normalized by the number of hours recorded. The grey background indicates daylight hours.

Spatial dive patterns

Blainville's beaked whale dives did not occur evenly across the range (χ=2375.43, p<0.0001). Figure 5 demonstrates the strong differences in the number of dives detected on each of the 31 hydrophones across each month. The majority of dives (68%) occurred on phones located on the southern portion of the range, where the depth increases rapidly from 600 to 3000 m along a steep slope. The phones in this region of the range are located 9.8 - 32 km from the island of Kauai. Blainville's beaked whale dives were strongly correlated with the area around the 2000-m depth contour, with a peak in dives occurring between 2000 and 3000 m (mean = 2612 m, median = 2329 m, Figure 7), although dives occurred at all depths from 648 – 4716 m. Dives were also strongly correlated with steep slopes around 25% grade (mean = 23%, median = 25%; Figure 7), although occurred at all slopes from 2% to 47%.

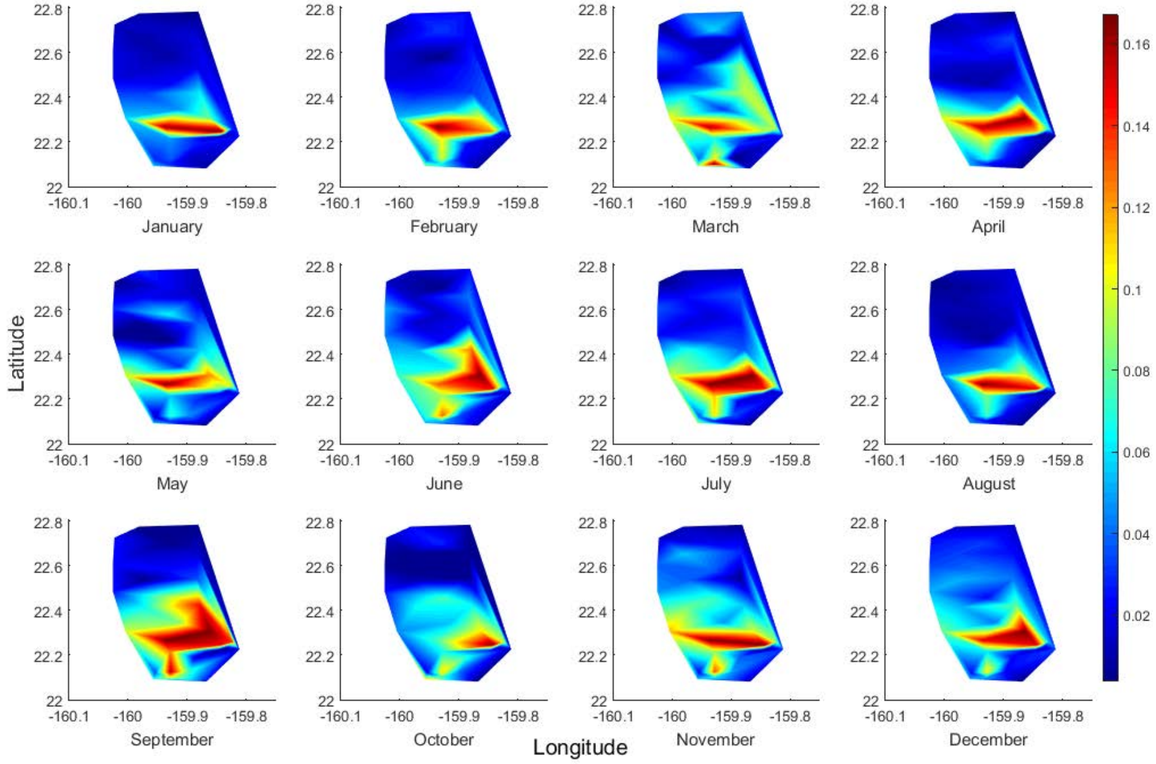

Figure 5 – Map of Blainville's beaked whale dive locations across the range for each month, combined across all years and normalized by the monthly recording effort.

Spatio-temporal habitat model

GAMs were developed initially using temporal variables of Year, Month, and Start Hour, and spatial variables of Depth, Slope with an interaction term between the two since there is high correlation between those parameters. If no interaction term was included, the final model included Start Hour and Depth, whereas if the interaction term was included, the final model included Start Hour and the interaction between Depth and Slope (Figure 6). The REML scores (119.3 and 118.9) and deviance explained (12.3% and 14.1%) were similar between the two models (Table 2), with a fairly low value for deviance explained in both cases.

The diel pattern resulting from the model differs from that observed in the normalized dive per hour data. In the model, dives occur most often in the first half of the day, peaking in the morning and then decreasing in the afternoon. The variance becomes very wide for the night-time dives, such that although the majority of dives continue to decrease, there is broad variability in that pattern. To explore this further, lunar phase data was added to the model, both as a separate variable and as an interaction term with Start Hour. In this case, the final model that maximizes the REML score only includes the interaction term between Start Hour and Lunar Period. However, the explained deviance increases (from 22.6 to 30%) and the REML score decreases only slightly (from 108.0 to 104.8) if the Depth and Slope interaction term also remains in the model (Figure 6).

Table 2 – Generalized Additive Model results describing Blainville's beaked whale spatio-temporal habitat use. REML = restricted maximum likelihood.

Model	Predictor Variables	P-value	REML score	Explained Deviance
1	Start Hour Depth	0.07 0.02	119.3	12.3%
2	Start Hour Depth/Slope	0.07 0.03	118.9	14.1%
3	Depth/Slope Start Hour/Lunar Phase	0.03 0.08	104.8	30.0%
4	Start Hour/Lunar Phase	0.04	108.0	22.6%

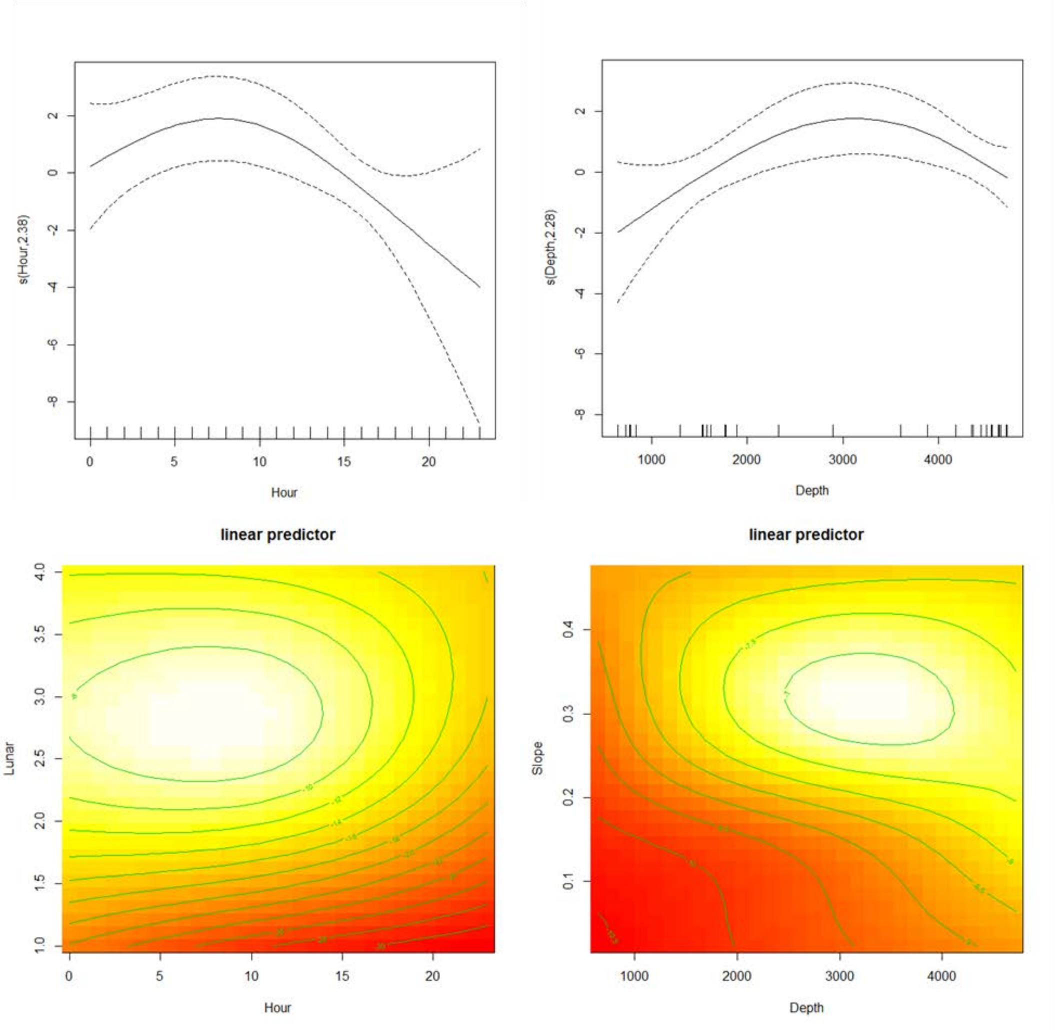

Figure 6 – Predictor variables from the Generalized Additive Models of Blainville’s beaked whale habitat use, including Start Hour (top left), Depth (top right), an interaction between Start Hour and Lunar Period (bottom left) and an interaction term between Depth and Slope (bottom right). Lunar periods were: 1= new moon, 2 = first quarter moon, 3= full moon, and 4= third quarter moon.

Impact of sonar activity

The hours of training and testing activities that could involve sonar or explosive sounds for some portion of the activity at PMRF were summed for each month (Table 3), and are plotted against the normalized number of dives per month in Figure 7. When a Spearman’s rank test was used to determine if a correlation existed between the number of normalized dives and the hours of training activity on a monthly basis across each year, no correlation was found (Table 4). When data from all years combined was tested, there is still no significant correlation, although the months of February and August start to drive the signal (Figure 7).

This pattern holds true when looking at any training activity in the week before an acoustic recording period (Table 4). In 2011 and 2012, there is still no correlation between the number of training hours normalized by the number of days of training and the number of dives per hour, even when a time lag factor is included to give increased weighting to training that may have occurred directly before a recording period. In 2013 the correlation becomes significant when the time lag is included, and this significance continues when all the data is combined. However, this again is driven by the high number of training hours in February and August, and when those are removed from the data the correlation is no longer significant. This indicates that for most of the training that is conducted at PMRF that may include sonar or explosive sounds, there is no subsequent decrease in Blainville's beaked whale foraging dives. Since the impact of those extended training events in February and August has already been examined in detail for Blainville's beaked whales (Manzano-Roth et al., submitted), it lies outside of the scope of this paper.

Table 3 – Hours of training and testing activities at PMRF that could involve sonar or explosive sounds for a portion of the activity from 2011 through 2013.

Month	2011	2012	2013
Jan	36.5	69	43.5
Feb	217	167.5	194.5
Mar	116.5	35	45
Apr	82.5	48.5	26
May	27	38	40
Jun	44	47	87
Jul	38	99.5	51
Aug	180.5	227.5	207.4
Sep	37	54.5	43.5
Oct	62.5	98.5	70.5
Nov	58	63	90
Dec	20	24	51
Total	919.5	972	949.4

Table 3 – Correlation test results of the number of dives per month against the hours of training activity per month, tested for each year and all data totaled, and of the training activity per hour in the week prior to a recording period against the number of Blainville’s beaked whale dives per hour in that recording period, tested with and without a time lag for each year and tested with and without the months of February and August for all data. Significant p-values are highlighted in bold.

Test	Statistic	2011	2012	2013
Monthly	Rho	-0.2	0.01	0
	p-value	0.54	0.99	1
All data by Month (with Feb and Aug)	Rho	-0.5		
	p-value	0.1		
All data summed (without Feb and Aug)	Rho	-0.15		
	p-value	0.68		
Single recording (no time lag)	Rho	-0.15	-0.09	-0.34
	p-value	0.5	0.67	0.08
Single Recording (with time lag)	Rho	-0.13	-0.21	-47
	p-value	0.53	0.34	**0.01**
Combined Single Recording Data (with Feb and Aug)	Rho	-0.29		
	p-value	**0.01**		
Combined Single Recording Data (without Feb and Aug)	Rho	-0.14		
	p-value	0.27		

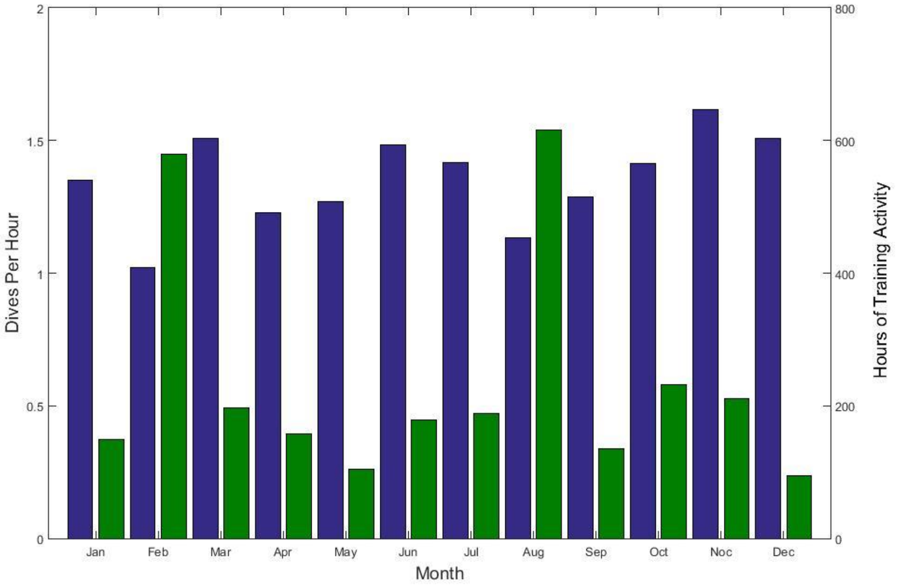

Figure 7 – Dives per hour (in blue, on the left y-axis) plotted with the number of hours of training activity at PMRF that may involve sonar or explosive sounds (in green, on the right y-axis).

Discussion

Blainville's beaked whales were acoustically detected performing deep foraging dives year round at PMRF, with a strong preference for steep slopes and depths from 2000 to 3000 m. While there was intra-annual variability in the number of dives detected per month, there was no clear seasonal trend, nor was there an inter-annual trend. Passive acoustic monitoring efforts have continued through to the present time; ongoing analyses will help determine the longer-term trend in dive rates of Blainville's beaked whales at PMRF.

The habitat use patterns observed for Blainville's beaked whales at PMRF are similar to those observed for other populations of beaked whales. The mean depth and slope for these animals was 2612 m and 23%, respectively, although the habitat model showed a hotspot between 2300 and 4000 m depth and 26% and 38% slope. This population is found in deeper water than in the Bahamas where animals were always found in depths between 100 and 1300 m, with a mean of around 500 m (MacLeod & Zuur, 2005; Claridge, 2006; Hazen et al., 2011). The PMRF population is also found in deeper waters than the population off the west coast of Hawaii island, which was typically observed in waters between 250 and 2000 m deep (Schorr et al., 2009; Abecassis et al., 2015). Slope is also an important bathymetric feature for this species, as all three populations, including the animals presented here, were associated with slopes between 6% and 25% (MacLeod & Zuur, 2005; Claridge, 2006; Schorr et al., 2009).

Habitat modeling indicates that the region off Hawaii island most heavily utilized by Blainville's beaked whales is characterized by upwelling and weak surface currents, where local circulation patterns would accumulate prey (Abecassis et al., 2015). Blainville's beaked whale distributions were also determined to overlap with the depth region of high micronekton density in the scattering layer (Dalebout et al., 2014). Hazen et al. (2011) also found Blainville's beaked whale dives in the Tongue of the Ocean to occur in areas of highest scattering layer densities. MacLeod et al. (2003) found both cephalopod and demersal and deep-water fish remains in the stomach contents of *Mesoplodon* whales, and a stranded beaked whale in Hawaii had equal parts fish and squid in their stomach (McCarthy et al., 2011). Primary and secondary production is often retained or enhanced at seamounts and regions of steep slopes due to physical processes including currents, upwelling, and reduced sedimentation (Boehlert & Genin, 1987; Pitcher & Bulman, 2007). The entrained or increased producers attract predators, including demersal and mid-water fish, cephalopods, sharks, sea turtles, and marine mammals (Pitcher et al., 2008). No prey data or proxy data such as temperature or salinity were included in the models presented here, limiting their efficacy in predicting Blainville's beaked whale foraging patterns. While temporal and spatial patterns are also important to the distribution of Blainville's beaked whales, they are likely responding directly to the behavior of the prey, and therefore without data on the prey themselves any habitat model will be limited. Future efforts at incorporating oceanographic and prey metrics into a model are planned.

Although no prey data was included in the model, the lunar phase proved to be an important predictor variable, likely linked to the behavior of squid and other scattering layer organisms to remain in deeper water during full moon periods (e.g., Gilly et al., 2006; Benoit-Bird et al., 2009). Blainville's beaked whales at PMRF, much like other *Mesoplodon* and *Ziphius* beaked whales, are likely utilizing the steep slope habitat to forage throughout the day and night, but may increase their nighttime diving during the full moon when more prey is available at depth. Blainville's and Cuvier's beaked whales off the island of Hawaii (Baird et al., 2008) and Blainville's beaked whales in The Bahamas (Hazen et al., 2011) did not show any diel periodicity to their foraging dives, although lunar phase was not included in those studies. Although there was no diel pattern in dive behavior, Blainville's beaked whale dives did occur in slightly more shallow, near-shore waters at night than during the day off the island of Hawaʻi; this indicates they were likely tracking the mesopelagic boundary community found in the Hawaiian islands that migrates both horizontally and vertically (Benoit-Bird et al., 2001; Benoit-Bird & Au, 2004, 2006; Abecassis et al., 2015). Spinner dolphins (*Stenella longirostris*) have been shown to track this migration while foraging at night (Benoit-Bird & Au, 2003), and short-finned pilot whales (*Globicephala macrorhynchus*) appear to do so as well (Abecassis et al., 2015).

The training events that occur every February and August at PMRF have been shown to impact Blainville's beaked whale foraging behavior and spatial occurrence (Manzano-Roth et al., submitted). Blainville's beaked whales at AUTEC in the Bahamas have also been shown to reduce their foraging dives during periods of sonar. These whales may be leaving the ranges during active sonar periods and returning shortly thereafter, as was demonstrated by one tagged whale during a sonar playback study (Tyack et al., 2011). This pattern can also be observed in the spatial distribution of dives across the range each month. In February and August, the dives are more clearly compressed to the southern portion of the range, while in almost every other month of the year they occur more broadly across the range. While the majority of Blainville's beaked whale foraging dives occurred within 32 km of Kauai, there were dives detected throughout the range, even on the northernmost phones in depths over 4500 m.

This broad distribution of dives, coupled with a lack of correlation in dive counts relative to smaller training events, seems to support the idea that the ongoing smaller scale events seem to have little to no impact on foraging dives, at least on the sampling scales analyzed here. Cuvier's beaked whales in southern California have been photo-identified and tagged using both acoustic recording tags (e.g. Dtags) and satellite time-depth recording tags (e.g. SPLASH10 Limpet tag) (Baird et al., 2004; Baird et al., 2006b; Schorr et al., 2014). Photo-identification work has demonstrated the potential for a resident population of Cuvier's beaked whales to inhabit San Nicholas Basin and adjacent waters (Falcone et al., 2009), similar to the resident populations of Blainville's beaked whales in the Bahamas on and near AUTEC (MacLeod & Zuur, 2005; Claridge, 2006), and the resident populations of both Blainville's and Cuvier's beaked whales off the west coast of the island of Hawaii (Baird et al., 2006a; McSweeney et al., 2007; Baird et al., 2008). The San Nicholas Basin includes much of the Southern California Offshore Range (SCORE) and is also an area frequently used for US Navy MFAS testing and training. While the tagged Cuvier's beaked whales moved throughout the southern California Bight, they spent 36% of their time within the bounds of the range (Schorr et al., 2014). Some of the longest and deepest dives on record were recorded for Cuvier's beaked whales in this region; although these dives could have occurred during sonar activity, the tags at the time were not acoustic and so no direct connection can be made (Schorr et al., 2014). It may be that some populations of beaked whales habituate to sonar and other acoustic activity, particularly those resident to range areas, and the beaked whales at PMRF seem to be one of those populations.

The population of Cuvier's beaked whales in the southern California Bight, along with a few Baird's beaked whales also in the area, have been the subject of an ongoing Behavioral Response Study (BRS) in which these and other cetacean species have been exposed to both simulated and real Navy sonars after being tagged, with the goal of capturing individual behavioral responses (DeRuiter et al., 2013; Stimpert et al., 2014). Similar BRS efforts have been conducted on northern bottlenose whales in Norway (Miller et al., 2015), and Blainville's beaked whales at AUTEC (McCarthy et al., 2011; Tyack et al., 2011). Monitoring marine mammals during real Navy training exercises creates a "real-world" behavioral response study, albeit without the control over many variables that can be maintained during a playback study. Nevertheless, monitoring efforts at PMRF, both during baseline periods as described here as well as before, during and after US Navy training events (e.g. Manzano-Roth et al. submitted), are essential for understanding marine mammal responses to noise impacts and provide a low-cost, information-rich alternative to large scale BRS efforts. By conducting this kind of observational BRS, the responses of numerous individual calling animals or cohesive groups can be correlated with received levels from and distances to sound sources, and tagged animals could be tracked even when not vocalizing (e.g., Tyack et al., 2011; Baird et al., 2014). The behavior during training events can be compared against baseline behavior when no activities are occurring to better understand the observed responses, and over many years of monitoring, the long-term consequences of these repeated activities can be estimated.

In conclusion, Blainville's beaked whales regularly conduct foraging dives across the extent of the PMRF hydrophone range, with most dives occurring in depths between 2000 and 3000 km and along steep slopes. There is no annual or seasonal pattern to the dives, but there is a slight diel pattern, with more dives occurring at night during full moon phases. Other than the two major training events in February and August, the routine training that occurs on the range throughout the year that may include sonar or explosive sounds did not appear to impact the number of foraging dives on the range. Continued monitoring and more detailed analyses of the smaller training events are needed to assess impacts on shorter (hours to days) and longer (years) time frames, and to look for any potential long-term or population level consequences.

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Impacts of U.S. Navy training events on Blainville's beaked whale (*Mesoplodon densirostris*) dives in Hawaiian waters

Roanne Manzano-Roth[1], E. Elizabeth Henderson[1], Stephen W. Martin[2], Cameron Martin[2], and Brian Matsuyama[2]
[1]SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, CA 92152
Email: Roanne.Manzano@navy.mil
[2]National Marine Mammal Foundation, 2240 Shelter Island Dr., #200 San Diego CA 92106

Abstract

Blainville's beaked whales (*Mesoplodon densirostris)* were detected in recorded acoustic data collected before, during and after February and August U.S. Navy training events in 2011, 2012 and 2013 at the Pacific Missile Range Facility, Kauai, Hawaii. An automated beaked whale click detector was developed and manual verification of the detections was performed to ensure they fit characteristics of foraging echolocation clicks. More dives were detected before training events than during or after the training events, and dives were detected more on edge hydrophones and hydrophones in the southern portion of the range during sonar activity. However, there were also interannual differences in dive counts across periods, indicating that baseline periodicity in Blainville's beaked whale dives must be distinguished from reduced dive activity due to sonar to understand the true impact of sonar.

Keywords: Blainville's beaked whales**,** *Mesoplodon densirostris,* beaked whale behavior, navy activity, mid-frequency active sonar, Hawaii beaked whales, beaked whale dives

Introduction

Beaked whales (family *Ziphiidae*) consist of at least 21 different species in six genera with relatively little known about many of the species. In 2000, a mass stranding of beaked whales occurred following a U.S. Navy training event in the Bahamas (England 2001). The incident resulted in an increase in research on this odontocetes family with an emphasis on the two species involved in the stranding, Blainville's (*Mesoplodon densirostris*) and Cuvier's (*Ziphius cavirostris*) beaked whales. The U.S. Navy have also invested in research on these species to understand the effects of Navy activities on the populations that inhabit Navy ranges and to prepare monitoring for Navy testing and training in compliance with the Marine Mammal Protection Act and the Endangered Species Act.

Beaked whale foraging dive behavior has been identified using data from a variety of tag types and reported in the literature (Baird et al., 2006, 2008; Johnson et al., 2006; Tyack et al., 2006). Blainville's and Cuvier's utilize foraging echolocation clicks (Johnson et al., 2004) with frequency modulation characteristics and relatively consistent inter-click-intervals (ICIs). These two species are known to only produce foraging clicks while at depths greater than 200 m during foraging dives, with dive vocal durations approximately 30 to 57 min per dive (Johnson et al., 2004; Tyack et al., 2006) and the interval between foraging dive vocal periods is on the order of 2 hours or more (Tyack et al., 2006, 2011). The foraging dive vocalizations include two types of echolocation clicks: foraging clicks for finding prey and rapid buzz clicks for short range prey capture. Foraging echolocation clicks can be generally characterized as short waveforms (0.175 to 0.4 ms upswept pulses) with relatively flat spectrums between 30 kHz and 50 kHz, source levels over 200 dB re 1 μPa and mean ICIs on the order of 0.3 to 0.5 s (Johnson et al., 2004; Moretti et al., 2010). Shallower dives are observed between the foraging dives with no click activity present. Much of these dive and click characteristics come from data from other regions of the world, however Baird et al. (2006; 2008) reported dive characteristics for both Blainville's and Cuvier's species off the island of Hawaii, with similar findings.

Further research has identified echolocation click characteristics for several beaked whales from different areas of the world based upon both tag data and passive acoustic monitoring data (Zimmer et al., 2005; Johnson et al., 2006). Acoustic characteristics have also been reported for the following species: Baird's (*Berardius bairdii*), Cuvier's (*Ziphius* cavirostris), Gervais' (*Mesoplodon europaeus*), and Longman's (*Indopacetus pacificus*) beaked whales as reported in the literature (Dawson et al., 1998; Zimmer et al,. 2005, Gillespie et al., 2009; Rankin et al., 2011, respectively). A common characteristic of many of the reported beaked whale species foraging clicks are short duration signals (< 1 ms) with frequency modulated sweeps from as low as 15 kHz to over 50 kHz. Longman's species in Hawaii have also been reported to use lower frequency clicks with no appreciable FM characteristics (Rankin et al., 2011).

Given the available information of beaked whale click characteristics, a variety of beaked whale click detection methods have been developed to enable automated processing of passive acoustic data to detect these clicks (Yack et al., 2010). The use of automated detectors for beaked whale clicks allows large volumes of data to be processed from many sources (e.g. survey vessel towed hydrophones, long term acoustic recording packages and U.S. Navy training ranges' hydrophones cabled to shore). Passive acoustic monitoring methods for beaked whales can be used to estimate density based on acoustic click (cue) counting techniques (Marques et al., 2009) and whale foraging dive counting (Moretti et al., 2010).

The acoustically determined beaked whale dive count method of density estimation shows reduced dive activity and abundance at the Atlantic Undersea Test and Evaluation Center (AUTEC) located in the Bahamas (Moretti et al., 2010; McCarthy et al., 2011; Tyack et al., 2011) during mid-frequency active sonar (MFAS) activity as compared to before the training events. These efforts demonstrated that Blainville's beaked whales appeared to depart an area where MFAS is occurring and gradually return over a two to three day period after sonar activities cease. While this study is similar to the work conducted at the AUTEC naval range, this study differs in detection methodology and is in a different geographic area. This paper describes the methods utilized to acoustically detect Blainville's beaked whale group vocal activity coincident with MFAS activity at the Pacific Missile Range Facility (PMRF) and analyzes the differences in dive characteristics before, during, and after MFAS activity to assess the impact of MFAS on dive behavior.

Methods

Data Collection

PMRF, located off the west coast of Kauai, Hawaii (Figure 1), hosts a variety of U.S. Navy training events every year and has on the order of two hundred hydrophones mounted on the seafloor and cabled to shore to support performance analysis for U.S. Naval systems. PMRF has supported U.S. Navy funded monitoring of marine mammal acoustics for over a decade before and after training events. However, in some cases it is possible to obtain ship locations and recorded acoustic hydrophone data during training events to support marine mammal monitoring efforts post-event for analysis.

Acoustic data from 31 hydrophones, along with an analog time code signal, were provided for before, during, and after training events in February and August, 2011, 2012, and 2013, while an additional 31 hydrophones were sampled in February and August of 2013. The hydrophone recordings were simultaneously sampled at a rate of 96 kHz using 16 bit analog-to-digital converters. The data were stored as sequential data files, each containing approximately

10 minutes of data. The recorded time code signal allowed precise alignment of acoustic data with ship positions in post-event analysis.

Figure 1 shows the approximate locations of the 62 hydrophones recorded and utilized in this analysis. Spacing between the hydrophones used in the data collection varies from less than 1.6 km in one cluster area to more than 10 km in areas farther offshore. Water depths vary from 650 m to over 4700 m, with a steep slope just off the island of Kauai that progress to a more gradual slope then a relatively flat bottom in deeper waters. Recorded hydrophones have three different frequency responses: ~50 Hz to 48 kHz, ~100 Hz to 48 kHz, and ~10 kHz to 48 kHz.

[Place Figure 1 here]

Acoustic Detection, Classification and Verification

Automatic Beaked Whale Click Detection and Classification – Beaked whale foraging clicks were automatically detected using a custom C++ algorithm which processes recorded raw hydrophone data for frequency modulated clicks. The algorithm has a first stage detection which processes the 96 kHz sampled data with 16k FFTs slipped by 1024 samples. The first stage detection employs thresholds for both the signal level in the click band of 28 to 44 kHz over the background level and the ratio of the in-band mean level compared to the 5 to 28 kHz out-band mean level. When a signal passes the first stage detection process it is then processed with a second stage to determine how much frequency modulation (FM) is in the click. Multiple species of beaked whales, notably Cuvier's and Blainville's, are somewhat unique in that their foraging clicks, which are on the order of 250 to 300 microseconds in duration, exhibit over 10 kHz of FM. The FM is utilized as a feature for beaked whale clicks bounded by a lower sweep threshold of 40 kHz/ms and bounded by an upper 140 kHz/ms sweep threshold. Clicks which meet the second stage FM requirement are identified as beaked whale clicks.

Thresholds in both stages were purposely set high to reject more false positives at the expense of detecting fewer actual beaked whale clicks. The logic for this is that if a group of beaked whales are actually diving in the area, there will be multiple animals, each producing thousands of foraging clicks in a typical foraging dive. Thus, even considering the relatively narrow beam pattern of Blainville's foraging clicks (Shaffer et al., 2013) there should be hundreds of opportunities to detect clicks when individuals are looking towards a bottom mounted hydrophone. Thus, even though the probability of detecting a single click may be small the probability of detecting a dive is high.

The beaked whale foraging click detection algorithm operates both with real-time data input and works approximately10 times faster than real-time when processing recorded data. The algorithm provides outputs including: the start time of the detections, the hydrophones that had detections, duration, sweep rate and optional file outputs of the detection spectrogram and time series for verification purposes.

Manual Verification of Automated Detections – Utilizing time series waveforms, spectrograms, and spectra of the clicks, automatically detected signals were manually verified as individual beaked whale foraging clicks. Analysts ensure that the waveforms, spectrograms and spectra fit with published results for beaked whales (e.g. Baumann-Pickering et al., 2014). In addition, the inter-click-intervals are evaluated looking for consistency with published intervals for different beaked whale species (e.g. approximately 0.3 s for Blainville's and 0.4 s for Cuvier's whales (Johnson et al., 2004; Zimmer et al., 2005). A final species check of the time period of beaked whale clicks was consistent with the dive vocal periods for the species (Zimmer et al., 2005; Johnson et al., 2006; Tyack et al., 2006). When all of these factors are in agreement, one is very confident in declaring detection of a beaked whale group dive (assuming a probability of detection = 1.0 if the dive occurs within a few km of a bottom mounted hydrophone).

Performance Characterization of Automated Detector — The performance of the automated detector was assessed to determine the actual probability of detecting a beaked whale click. Automated beaked whale detector performance was quantified by comparing automatic detections to manually-obtained detections for a random sample of recorded data files. Average signal levels for manual and automatic detections were calculated by computing a 64 point FFT centered on the signal with a Hanning window and averaging the spectrum in the beaked whale foraging click band (i.e. 28 to 48 kHz). The average noise level was calculated in a similar manner but averaged over a one second long noise sample for each file. Automatic detections that were within 1.5 ms of a manual detection were considered correct detections and manual detections without a corresponding automatic detection were considered missed opportunities.

Blainville's Beaked Whale Dives and MFAS

Dive groups – Group sizes for Blainville's beaked whales in Hawaiian waters are reported as 3.6 whales per group (Baird et al., 2006). Multiple animals in a group provide more opportunities to detect beaked whale clicks from a group dive. The number of clicks detected for a beaked whale dive is related to the distance of individual whales from the hydrophone, the number of animals in a group, the beam pattern of the foraging clicks, and the orientation of the animal with respect to the hydrophone. The distance of the animal from a hydrophone determines how much propagation loss is experienced (spreading losses and absorption of sound in the seawater). Ultrasonic signals, such as beaked whale foraging clicks, were assumed to not be detected on bottom hydrophones at distances much over 6 km due to transmission loss. The 6 km maximum detection distance was selected based upon Zimmer et al. (2008), who reported a maximum detection distance of 4 km for hydrophones located close to the surface, and Ward et al. (2008) who reported a maximum detection distance of 6.5 km for bottom mounted hydrophones at AUTEC. Orientation of the animal relative to the hydrophone affects the apparent source levels of the clicks due to their directional nature and spectral content.

Beaked whale dive vocal periods are approximately 23 to 33·min (Johnson et al., 2004), and the group foraging dives are on average 47 minutes in duration, but can last up to 57 min (Tyack et al., 2006). Blainville’s beaked whales will also spend between 66 to 155 min in the upper 50 m of the water column after a foraging dive and in preparation for the next deep dive (Baird et al., 2006). The hydrophones utilized in this analysis have in some cases very wide separation and can be over 4 km deep, which cannot guarantee detection of all beaked whale dives on the range. Therefore, the number of clicks detected and the estimated dive vocal period durations may be less than what could actually be produced from an acoustic tag on a tracked animal. For this analysis, concurrent detected beaked whale foraging dives on adjacent hydrophones less than 6 km apart are considered the same dive; while this assumption could potentially bias the number of dives, it provides the most conservative estimate of dive counts. The hydrophone with the most manually-verified beaked whale clicks for a dive was termed the primary phone and was considered the closest to the group of foraging beaked whales. The lack of detected clicks before and after a dive vocal period also provides supporting behavior typical of beaked whales. Although individual dives may be located a large distance from the primary hydrophone and have an apparent short duration, decreased high frequency content due to absorption and few clicks detected, the overall mean for all the dives may be indicative of changes before, during and after MFAS training events.

Mid-Frequency Active Sonar and Navy Training Events – MFAS in the frequency range of 1 to 10 kHz was present during the training event. A *Matlab* (Mathworks, Natick MA) based detector was developed to detect MFAS transmissions in order to know precisely when the sonar signals are present. The detection threshold was set such that the majority of these sonar pulses were detected with very few false positives, and manual inspection was performed to verify MFAS activity.

Data collection occurred before, during and after the Submarine Commander's Course (SCC) training events from February and August 2011 to 2013. The Hawaii Southern California Training and Testing Activities Final Environmental Impact Statement/Overseas Environmental Impact Statement (HSTT EIS/OEIS) details the SCC training scenarios (U.S. Department of the Navy, 2015). As described in Martin et al. (2015), each training event was separated into Phase A and Phase B. Phase A occurred during the initial portion of the training events and focused mainly on submarine-on-submarine scenarios, without MFAS from surface ships. Phase B occurred after Phase A and included MFAS from surface ships, sonobouys and dipping sonars. Surface ship MFAS activity is defined when a ship begins MFAS transmission of typically one pulse per minute. Both phase A and B include range support platforms (helicopters and surface ships) for recovering exercise torpedoes and performing range safety related tasks.

Results

Data Collection

Passive acoustic data were collected continuously for 31 hydrophones over 1648.8 hours in February and August of 2011, 2012, and 2013 (Table 1). In February and August of 2013 there were 62 hydrophones recorded; only the original 31 hydrophones were used for the overall analysis. There were 396.2 hours of total data were collected for the Before periods, and 405.6 hours in the After periods. Phase A, without MFAS from surface ships, consisted of 335.2 hours and Phase B, with MFAS pulse activity from surface ships in the 1-10 kHz bandwidth, consisted of 367.7 hours . There were also two weekend (‘Between phase’) in February and August of 2013 (144.1 hours). Over all six training events, there were 127 periods of MFAS activity lasting 12 to 161 min (mean 63 min), for a total duration of 122.1 hours, or 33.2% of the total Phase B period. These exposures took place equally day and night across the three-day periods.

[Place Table 1 here]

Both phases of the training event consisted of multiple event scenarios with different objectives. Ship GPS positions were obtained for the time period of each scenario; ship positions were not available for the periods of time between scenarios. Nearly all MFAS activity occurred during Phase B event scenarios; therefore the lack of continuous ship position was not a major issue. There were similar levels of submarine activity for all exercises during Phase A, but for Phase B, February 2011 had the most surface ship activity, while August 2012, February 2012 and 2013 had lesser activity and August 2013 has the least amount of surface ship activity.

Acoustic Detection, Classification and Verification

Figure 2 demonstrates the characteristics of a typical click classified as a Blainville’s beaked whale click, including the frequency upsweep (~ 27 to 45 kHz) over the nominal 0.3 ms duration (top spectrogram). The time series (lower left) has several cycles of amplitude modulated frequency upsweep character, while the histogram (lower right) demonstrates a strong ICI mode of 0.3 ms. In the process of verifying beaked whale clicks, a few dives were observed to have different click characteristics reminiscent of the beaked whale clicks detected at Cross Seamount by McDonald et al. (2009). These were removed as they were out of the scope of this analysis, but will be examined in future efforts.

[Place Figure 2 here]

A random sample of 22 data files from 17 hydrophones representing different water depths and distances from shore was utilized for performance characterization from the February 2011, 2012, and 2013 data sets and were not concurrent with Phase A or Phase B. Of the manual detections with SNR's under 15 dB, very few signals were automatically detected. A total of 2787 clicks were manually detected and 1229 had at least a 15 dB SNR or higher. Of those, 485 were automatically detected. For a SNR over 25 dB, the standard level used in this detector, the probability of detecting clicks was 0.39. The one-second average noise level in the band reduced the 'noise' level over instantaneous levels but was utilized as it was similar to the normalization process the automatic detector utilized. The false positive rate was assumed to be zero since false positives were removed during manual verification.

Blainville's Beaked Whale Dives and MFAS

When the data from all six training events were combined, 562 Blainville's beaked whale dives were detected before the training events (Before period), 404 during all Phase A periods, 158 during all Phase B periods (with MFAS), 332 after the training events (After period), and 119 over the two weekend periods (Between period) in 2013 (Table 1), which equates to an overall mean of 1.4 dives per hour of effort Before, 1.2 dives per hour during Phase A, 0.4 dives per hour during Phase B, 0.8 dives per hour After, and 0.8 dives per hour during the two Between phases. A chi-square goodness of fit test showed that these dive counts are significantly different than expected ($\chi^2 = 191.6$, $p < 0.0001$); in other words, there are far more dives in the Before period and fewer dives in the other periods than expected when the proportions are compared.

While MFAS pulse activity was present 20 – 53% of the time during the Phase B periods, the number of dives detected during MFAS activity generally represented about 25 – 40% of the total dive count during that time period (158 beaked whale dives during pooled Phase B periods, 50 co-occurred with MFAS activity). The number of dives recorded concurrently with MFAS was generally proportional to the amount of time MFAS activity occurred during Phase B. The exceptions to this were August 2012, when only 2 dives co-occurred with MFAS activity (~10%), and August 2013 when only 4 dives co-occurred with sonar (27%). While dives did co-occur with sonar, more of the dives during Phase B were detected on hydrophones on the edge of the range than expected ($\chi^2 = 7.76$, $p = 0.0053$), indicating that beaked whales may be moving to the edges or off of the range during sonar activity.

When the data from each of the six training events is analyzed separately (Table 2), the overall pattern still holds, with a reduced number of dives detected in Phase A and a further reduction in Phase B. Chi-square goodness of fit tests indicated that the number of dives per sampling period (relative to the amount of time sampled) within each training event were significantly different than expected for all six training events (χ^2 ranged from 18.53 to 82.66, p ranged from 0.001 to < 0.0001). In most cases the dives began to increase immediately after the training events were completed, as evidenced by the increase in dive rates in the After period, although in none of the years was there a long enough time frame sampled post-training to reach the number of detections prior to each training event. However, analyses of baseline beaked whale presence on the range has shown full recovery within a week or two (Henderson et al., 2013; in prep), and the dives counts increased even during the two weekend periods in 2013 (Table 2).

Chi-square tests conducted across training events also showed significant differences, indicating that seasonal and inter-annual differences in occurrence patterns also exist. For example, a comparison of the total number of dives within each period (e.g. all Before dives) that were recorded across all six training events against the expected number of dives per period (given the sampling effort) showed significant differences ($\chi^2 = 268.25$, $P < 0.0001$). When each sampling period was examined across all six training events, the Before, Phase A, and After periods all had significantly different numbers of dives than expected ($\chi^2 = 39.88$, 212.06, and 75.19 respectively, $p = 0.0012$, <0.0001, and <0.0001 respectively), indicating inter-annual variability within each training event period. Interestingly there was no significant difference in the number of dives during Phase B ($\chi^2 = 8.9$, $p = 0.11$); in this case all the dive counts were similarly low.

The distribution of dives across the range in each of the training event periods was also examined using ANOVA tests to compare dive counts across phones. In all years, the results were significant (p-values ranged from 0.008 to <0.001), with the dives more concentrated in the southern portion of the range during Phase B than during any other period (Figure 3). Diel dive patterns were also examined for all years combined, with the expected dives per hour of the day (normalized by effort) compared to the observed dives per hour using a Chi-square goodness of fit test. The number of dives per hour did not vary significantly for all combined Before periods ($\chi^2 = 1.60$, $p = 0.44$), but were significantly different for the Phase A ($\chi^2 = 28.95$, $p < 0.001$), Phase B ($\chi^2 = 10.97$, $p = 0.03$), and After ($\chi^2 = 9.95$, $p = 0.02$) periods. Overall there were fewer dives than expected in those periods, with slightly more dives than expected in the morning and afternoon hours (Figure 4).

[Place Table 2 here]

[Place Figure 3 here]

[Place Figure 4 here]

31 vs 62 hydrophone comparison

Beginning in 2013, an additional 31 hydrophones were recorded. Table 3 shows the increase in the number of dives detected using the additional hydrophones. These differences show an increase in dive group detected on the order of 30 –70% greater when all 62 hydrophones were used compared to only 31 hydrophones. However, the overall trends are still the same, with fewer dives in Phase A and B, and an increase in dives between the phases and after the training event.

[Place Table 3 here]

Discussion

The data presented here demonstrate that beaked whale dives continued to occur at PMRF while MFAS activity was occurring, although in reduced numbers. Blainville's beaked whale dives were detected across the range before the training events, and predominantly in the area concentrated near the 22.3° N latitude portion of the range. During the training events, the overall number of dives decreased and were detected mostly south of the 22.2° N latitude and also increased detections on the edge hydrophones compared to before the training events. The hydrophones between 22.1° N and 22.3° N latitude are located in the portion of the range with the steepest slopes, which agrees with water depths and steep bathymetry typically associated with beaked whale foraging dives (Tyack et al., 2006; Henderson et al., in prep). Therefore while beaked whales dives were more spread across the range before the training events, the beaked whales may be concentrating in an area of preferred foraging habitat, as well as moving away from the ship traffic and sonar noise during the training events.

The observed acoustic characteristics of most detected clicks appear to fit with reported information for Blainville's species, and so have been cautiously classified as such. However, much is still unknown about beaked whale species in Hawaiian waters and in general. Blainville's, Cuvier's, and Longman's species are known to be present in Hawaiian waters, but it is possible that additional species could also be present (e.g. Baird's, Ginkgo-toothed (*Mesoplodon ginkgodens*), Hubb's (*Mesoplodon carlshubbi*) and pygmy (*Mesoplodon peruvianus*)) (Macleod et al., 2006).

Baird et al. (2008) found that deep foraging dives by tagged Blainville's and Cuvier's beaked whales in Hawaii occurred at similar rates both day and night, with similar dive durations (48 to 68 min). Other tagged beaked whales have also shown no diel difference in foraging patterns (Arranz et al., 2011; Hazen et al., 2011). In contrast, Au et al. (2013) found a distinct diel pattern to beaked whale foraging dives in the same region. During this study, dives occurred equally day and night before the training events, but seemed to shift slightly to have morning and afternoon peaks during and after the training events.

This analysis was conducted under the assumption that the Before periods represented a baseline of behavior; however, while training events are not continuously ongoing, there is appreciable activity at the range. In order to address this issue, true baseline data needs to be identified and used to compare with behavior during training events to really capture any behavioral responses to MFAS and an increase in ship traffic (e.g. Henderson et al., in prep). The relatively large separation between hydrophones utilized in this analysis, as well as the deeper depths of the hydrophones in the northern portion of the range, may result in detecting only a fraction of a beaked whale group's vocal period. Therefore the dive vocal period durations were not analyzed, and only dive counts were utilized. In addition, with many dives occurring over widely spaced hydrophones or at the edge of the range, and with highly directional beam patterns and high attenuation rates inherent to echolocation clicks, it is more than likely that many clicks were missed during each dive, and therefore absolute click counts were also not analyzed. It was also demonstrated that with the additional 31 hydrophones added in 2013, there was an increase in detected beaked whale dive counts, which would not be detected with the original 31 hydrophones.

PMRF has on the order of 200 bottom-mounted hydrophones; however, most are located close to shore and in shallower water. It may be possible in the future to record more hydrophones, which will decrease the spatial separation between phones in some locations and increase the likelihood of detecting more of the dives on the range. Additional efforts also in progress include calculating the density of Blainville's beaked whales, estimating sonar exposure levels from MFAS sources for beaked whales detected by various methods (i.e. passive acoustics , sighted by observers, and tagged animals), and examining the other beaked whale clicks detected at PMRF. All of these additional analyses represent an ongoing examination into the habitat use of this region by beaked whales before, during, and after training events as well as during baseline periods.

Acknowledgments

This work was supported with funding from the U.S. Navy Commander Pacific Fleet N01CE1 (Julie Rivers). Research resulting from the Office of Naval Research efforts enabled efficient detailed analysis of the large data sets involved. The ongoing support in data collection efforts by personnel at the Pacific Missile Range Facility (Jim Hager, Frank Hay, Eliseo Bolosan and Robin Higuchi) is greatly appreciated.

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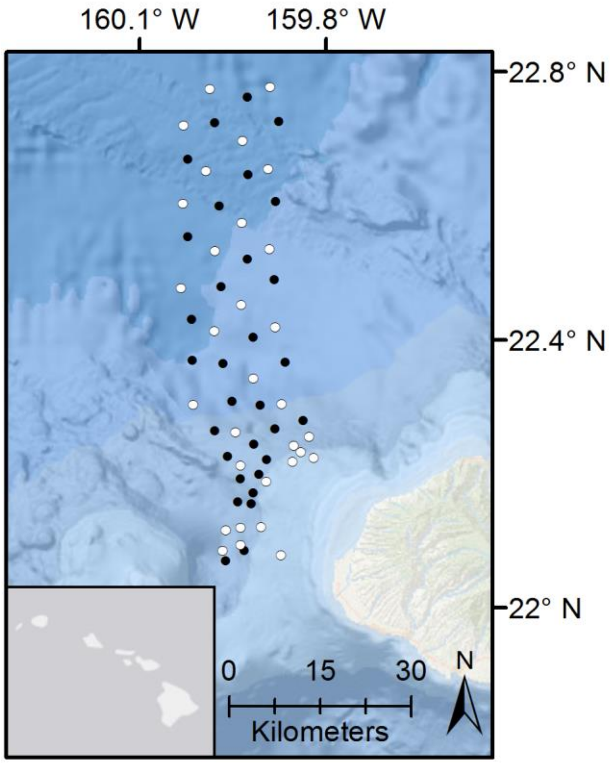

Figure 1. Approximate locations of the 62 recorded hydrophones used in this study at the Pacific Missile Range Facility, Kauai, Hawaii. The original 31 hydrophones are shown in white, while the 31 hydrophones added in 2013 are shown in black.

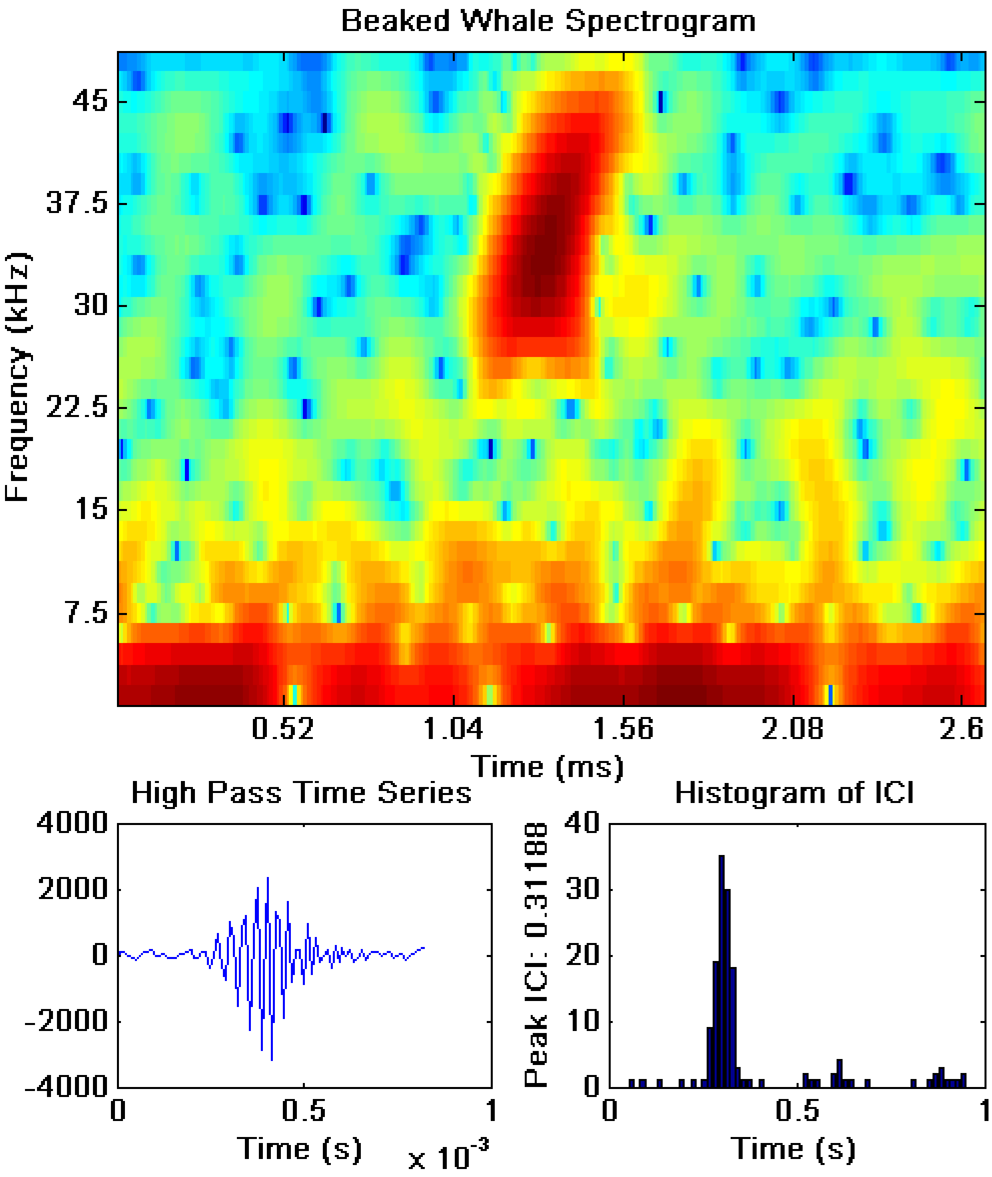

Figure 2. Spectrogram (0 to 48 kHz over 2.6 ms) of a beaked whale click from the pre-event data (top). Time series (amplitude in counts over 1 ms) of the same beaked whale click (lower left). Histogram of the ICI (0 to 1 s) of the beaked whale clicks in the previous 10 minutes (peak value 0.3 s) (lower right).

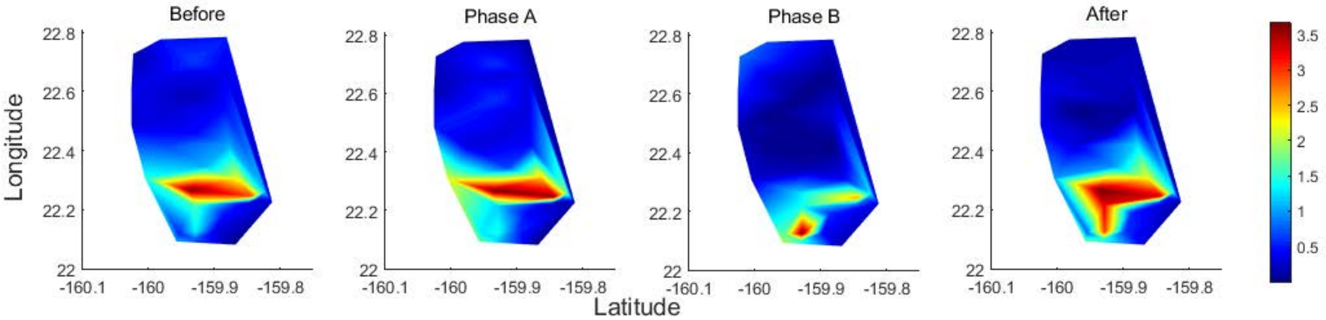

Figure 3. Maps of the distribution of Blainville's beaked whale dives (normalized as the number of dives per hydrophone per hours of effort) across the range for all training event periods combined (Before, Phase A, Phase B, and After) for 2011-2013, showing an overall reduction in dives and a shift in distribution of dives to the southern and edge phones during Phase B.

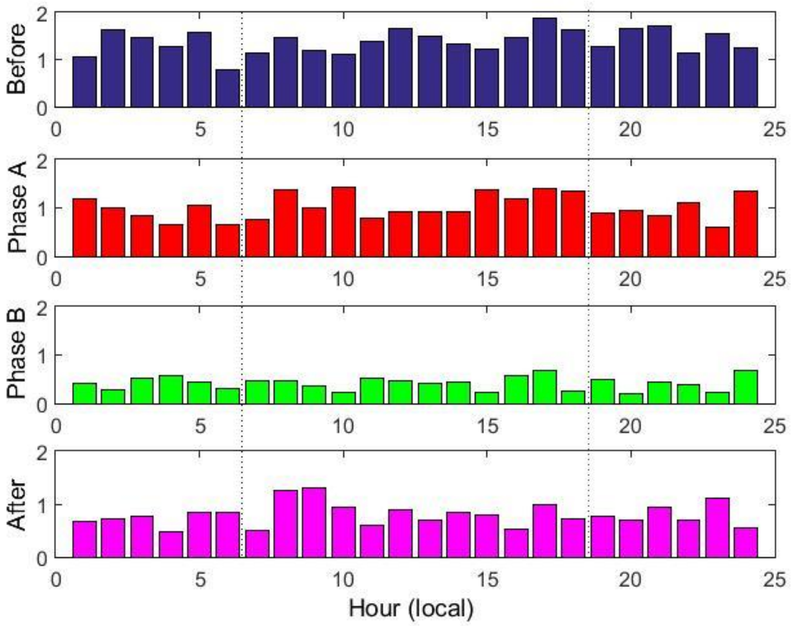

Figure 4. Blainville's beaked whale dives per hour for each training event period for all years combined, normalized by recording effort. Dives per hour were decreased in all subsequent periods relative to the Before period, and were generally lower than expected in the Phase A, Phase B, and After periods, with slightly greater than expected dives in the morning and afternoon hours.

Table 1. Blainville's beaked whale dive detection data from the combined Before, during Phase A, during Phase B (with MFAS), and After periods relative to the training events on PMRF in February and August 2011 - 2013.

	Before	Phase A	Between	Phase B	After
Hours of data	396.2	335.2	144.1	367.7	405.6
Verified dives detected	562	404	119	158	332
Dives per hour	1.4	1.2	0.8	0.4	0.8

Table 2. Blainville's beaked whale dive detection data from the Before, during Phase A, during Phase B (with MFAS), Between, and After periods over all six training events for the original 31 hydrophones.

Training Event	Period	Duration (hours)	Dive Count	Dives per Hour	Sonar Duration (hours)	# dives with sonar
Feb 2011	Before	89.65	87	0.97		
	Phase A	43.96	21	0.48		
	Phase B	69.61	36	0.52	21.38	12
	After	77.25	72	0.93		
Aug 2011	Before	71.00	140	1.97		
	Phase A	78.92	214	2.71		
	Phase B	64.08	42	0.66	22.52	15
	After	48.00	85	1.77		
Feb 2012	Before	94.84	166	1.75		
	Phase A	54.60	67	1.20		
	Phase B	62.62	30	0.48	16.50	8
	After	90.50	59	0.65		
Aug 2012	Before	92.29	107	1.25		
	Phase A	50.35	36	0.71		
	Phase B	64.49	21	0.33	12.87	2
	After	55.33	47	0.89		
Feb 2013	Before	28.60	37	1.29		
	Phase A	52.42	23	0.44		
	Between	71.89	56	0.78		
	Phase B	62.58	14	0.36	25.09	12
	After	22.32	6	0.27		
Aug 2013	Before	19.78	25	1.26		
	Phase A	54.91	43	0.78		
	Between	72.20	63	0.87		
	Phase B	44.53	15	0.42	23.78	6
	After	112.17	64	0.57		

Table 3. A comparison of Blainville's beaked whale dive detection data from the combined Before, during Phase A, during Phase B (with MFAS), and After periods in 2013 with 31 vs. 62 hydrophones.

Training Event	Period	Dive Count (31 Phones)	Dives per Hour (31 Phones)	Dive Count (62 Phones)	Dives per Hour (62 Phones)
Feb 2013	Before	37	1.33	75	2.62
	Phase A	23	0.44	33	0.63
	Between	56	0.78	126	1.75
	Phase B	14	0.36	24	0.62
	After	6	0.27	19	0.85
Aug 2013	Before	25	1.26	35	1.77
	Phase A	43	0.78	85	1.55
	Between	63	0.87	113	1.57
	Phase B	15	0.42	24	0.68
	After	63	0.57	146	1.30

Swim track kinematics and calling behavior attributed to Bryde's whales on the Navy's Pacific Missile Range Facility

Tyler A. Helble,[1, a)] Stephen W. Martin,[2] and Glenn R. Ierley[3]
[1]*SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, California 92152-5001*
[2]*National Marine Mammal Foundation, 2240 Shelter Island Drive, Suite 200, San Diego, California 92106*
[3]*Scripps Institution of Oceanography, University of California at San Diego, La Jolla, California 92093-0701*

(Dated: February 29, 2016)

Time difference of arrival (TDOA) methods for acoustically localizing multiple marine mammals have been applied to recorded data from the Navy's Pacific Missile Range Facility in order to localize and track calls attributed to Bryde's whales. Track kinematic information such as swim speeds, bearing information, track duration, and directivity index were recorded for 16 individual tracks during the months of Aug-Oct, 2014. The intercall interval was also established for most of the tracks, providing cue rate information for this species that may be useful for future acoustic density estimate calculations.

PACS numbers: 43.30.Sf, 43.30.Wi, 43.60.Jn

I. INTRODUCTION

The National Marine Fisheries Services defines a Bryde's whale (*Balaenoptera edeni*) Hawaii stock with the latest estimated population size of 798 (CV=0.28)[1]. Due to limited prior estimates with higher CVs there is insufficient data currently available to assess any population trends. Limited information is available on this species and the Bryde's taxonomy is poorly characterized - the scientific name Balaenoptera edeni is commonly used to refer to the species in the Bryde's whale complex which currently consists of B. brydei, B. edeni, and B. omura. Visual confirmation of Bryde's whales has not occurred in conjunction with the recorded signal at PMRF, but the burst type pulses recorded are extremely similar to those reported from other locations.

Automated localization of signals attributed to Bryde's whales on the Navy's Pacific Missile Range Facility (PMRF) provides a unique insight into both the acoustic and kinematic behavior of these animals in an offshore region that is rarely accessible by human observers. Processing methods for localizing whales using the time difference of arrival (TDOA) have been established on the PMRF range[2]. The techniques were initially developed for humpback whales, but have since been expanded and used successfully for Bryde's, sei, fin, blue, and minke whales. The TDOA method is facilitated with use of the generalized power-law (GPL) detector[3] and enhanced with a spectral "templating" procedure to characterize individual vocalizations by extracting a fundamental for each vocalization and setting the remainder of the spectrogram to zero. Cross-correlations of the templates allow localization of multiple animals concurrently with an incorrect localization rate of 2% or less. Additional software was developed in order to positively associate each whale vocalization with a location. This step was necessary in order to accurately obtain the intercall interval (ICI) of the Bryde's calls, which is an important metric needed for density estimation.

The objective of this paper is to describe the acoustic and kinematic metrics for 16 Bryde's whale tracks occurring during the months of Aug-Oct, 2014. Section II provides an overview of the localization techniques described in detail in Helble et al.[2], with Sect. II.A describing the modifications necessary to localize Bryde's whales rather than humpback whales. Section II.B describes the suspected Bryde's whale call and provides comparison with other known Brdye's whale call types. Section II.C describes the techniques used to positively identify each whale vocalization with a location, necessary for obtaining accurate ICIs. The section also describes the methods and rules used for identifying tracks and extracting the track kinematics. Section III describes the results for the track kinematics and ICIs for the 16 whale tracks, and The final section summarizes the conclusions from this work.

II. METHODS

The PRMF range is located off the west coast of the island of Kauai in the Hawaiian islands. Thirty-one time-synchronized hydrophones from the PMRF underwater range have been recorded on a sample basis of approximately two days a month over the past several years at a 96 kHz sampling rate, with additional days of recordings associated with U.S. Navy mid-frequency sonar training events. More recently, long-term opportunistic recordings spanning several weeks have been recorded at 6 kHz sampling rate. Of these 31 hydrophones, 14 offshore hydrophones were selected for localization purposes, ranging in depth from 3,150 meters to 4,700 meters, and covering a rectangular-shaped grid approximately 11 km to the east/west and 52 km to the north/south. The 14 hydrophones were subdivided into 4 subarrays (A,B,C,D), each containing five hydrophones as shown in Fig. 1. The TDOAs are computed between the center hydrophone of each subarray and the nearest four corner hydrophones.

[a)] Electronic address: `tyler.helble@navy.mil`

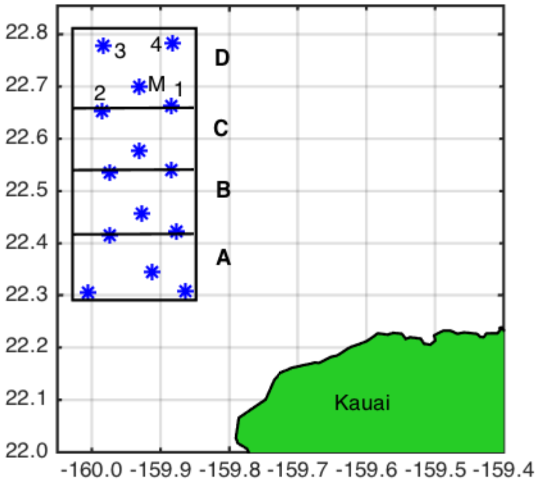

FIG. 1. (color online) Approximate positions of PMRF hydrophones illustrating subarrays A-D. The center hydrophone is marked on subarray D (M) and the 4 adjacent hydrophones (marked 1-4).

The maximum allowable time delay between the center hydrophone and each adjacent hydrophone in the subarray is limited to the direct path propagation time between them. The subarray configuration was originally chosen such that a direct path solution on 4 hydrophone pairs always exists across the monitored area for the noise conditions present on the PMRF range for humpback whales. It was discovered for Bryde's whales that subarray A contains gaps in spatial coverage, and so subarrays B-D were used for the Bryde's whale analysis. The process for obtaining whale locations can be subdivided into three steps: detection and feature extraction, cross-correlation of those features to obtain TDOAs, and TDOA-based localization. These steps are outlined in detail using humpback whale calls in Helble et al.[2] and therefore are not repeated in this paper.

A. Modification of TDOA algorithm for Bryde's whale signal

Minor modifications were made to the methods outlined in Sect. II of Helble et al.[2] in order to calculate Bryde's whale localizations. The frequency range of the templating process was changed to monitor the 10-50 Hz frequency band instead of the 150-1000 Hz band described in Sect. IIA of Helble et al. Additionally, single templates were used (rather than using a sequence of templates) during the cross-correlation process described in Sect. IIB of Helble et al. For humpback whales, vocalizations occur so frequently that cross-correlation of single units produce a high number of false localizations. Bryde's whale calls occur much less frequently, and so single call templates are more appropriate. If multiple vocalizations were utilized, the whale could move a significant distance between vocalizations and the resulting localization is compromised from the whale's true location. The downside to using fewer vocalizations in the cross-correlation process is that the timing delay errors can become greater than when multiple signals are utilized. However, Helble et al. showed that for single tonal humpback calls, the timing delay errors were on the order of 40 ms, resulting in less than a 60 m localization standard deviation. The Bryde's calls recorded on PMRF have more transient structure than the humpback tonal calls tested, and so it is expected that the timing delay errors are no worse than those for the humpback single unit tonals.

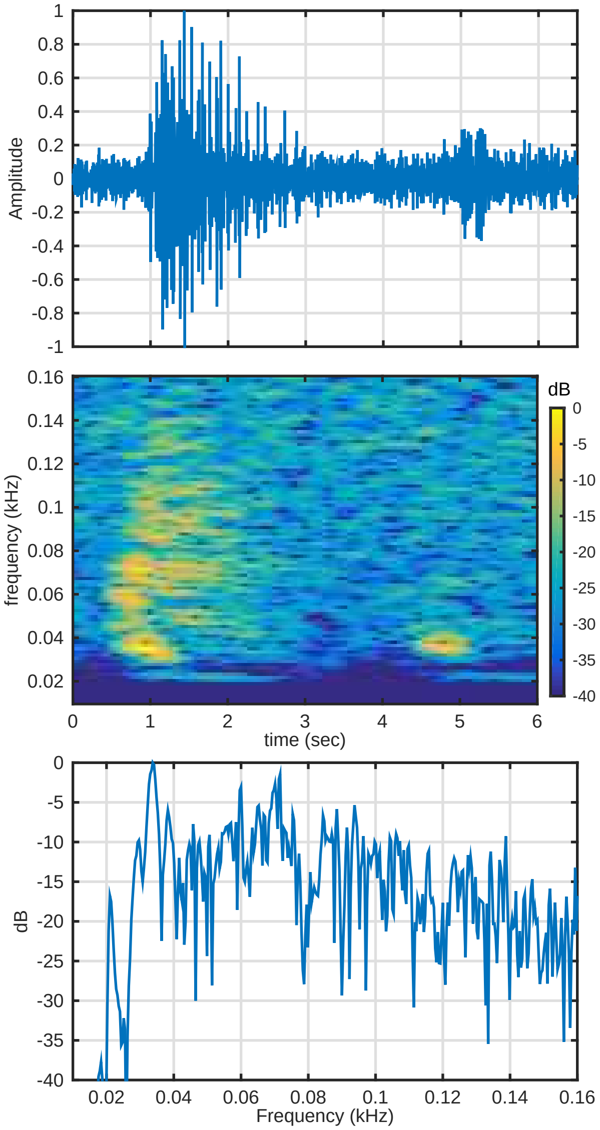

FIG. 2. Example time series (upper plot), spectrogram (middle plot), and spectra (lower plot) of typical Bryde's whale signal as received on the middle hydrophone of subarray B at PMRF. Second signal occurring at 4.5 is the bottom-surface-bottom multipath arrival of the direct path signal.

B. Signal description

An example acoustic signal attributed to the Bryde's whale can be seen in Fig. 2, shown as received at the center hydrophone in subarray B at the whales closest point of approach (approx 2 km from overhead) in 4.5 km water depth. The upper plot shows the time series of the call bandpass-filtered between 10 and 160 Hz. The middle plot shows the spectrogram of the call using a 2048 point FFT hanning window with 87.5% overlap, with a sampling rate of 6 kHz. The lower plot shows the spectrum of the call using a 16,000 point FFT and hanning window. A second signal arriving at 4.5 seconds in the spectrogram and time series can be attributed to the bottom-surface-bottom multipath arrival of the direct path signal. The received signal's peak frequency, as observed on the seafloor mounted hydrophones, is approximately 33 Hz. Secondary peaks reminiscent of pulse repetition rate harmonics (amplitude modulated sidebands at rates of approximately 4 Hz), are present at multiple frequencies (e.g. 29, 37, 21 and 12 Hz). It is important to note that the hydrophones are high-passed filtered at 50 Hz, and so levels less than 50 Hz are artificially depressed. Given the roll-off at lower frequencies, the 21 Hz component is likely only slightly lower in level, potentially higher, than the observed peak level at 33 Hz.

Bryde's whales are known to make a variety of signal types that appear to differ among populations. Earlier descriptions of Bryde's acoustic calls all have the majority of energy content above 90 Hz[4,5]. Cummings et al.[4] reported calls from the Gulf of Mexico with frequencies of approximately 124 Hz and 0.4 s duration with estimated source levels of 152-174 dB rms re 1 μPa @ 1 m. It is interesting to note that the spectrum shown in the Cummings et al. paper also shows a secondary peak at approximately 25 Hz which appears less than 5 dB below the level of the 124 Hz peak signal reported, however it is uncertain if this was produced from the whale. Edds et al.[5] reported on sounds from both a captive juvenile which stranded off the Gulf Coast of Florida and free-ranging Bryde's in the Gulf of California, however the lowest frequencies reported for pulsed sounds was 90 Hz.

More recently detailed description of lower frequency Bryde's calls have been reported by Oleson et al[6] for calls received in the presence of confirmed Bryde's whales in the Eastern Tropical Pacific. A total of 104 calls over 21.7 h of data was utilized to characterize Bryde's calls into six call types (Be 1 through Be 6). The most abundant call type with 37 calls for the region was termed Be1 which had a mean duration of 2 s and was a complex two-part frequency modulated call that began with a upper frequency component of approximately 37 Hz with a delayed accompanying lower-frequency component of approximately 21 Hz. Oleson et al. also reported a Be3 type call (N=18) with a mean duration of 1.7 s and a peak frequency of 25.6 Hz. The Be 1 and Be 3 calls are the most similar to the call type recorded at the PMRF range. In addition, acoustic only observations of suspected Bryde's calls have also been reported from recordings at several different sites in the Eastern Tropical Pacific[7]. The calls were short duration (under 3 s) and low-frequency (less than 80 Hz) and characterized with predominant tone and secondary tone components. The sounds were grouped into five categories: harmonic tonal, swept and non-swept alternating tonal, and low and high burst-tonal. Over 1100 sounds were characterized and compared to those reported by Oleson et al.[6] While there were similarities, the precise frequencies varied and the call intervals still exhibited large variations.

Bryde's calls have also been reported off the coast of New Zealand, and one of the two call types is similar to the call recorded at PMRF[8]. The call consists of an impulsive broadband sound at the start of each call and a down swept frequency from 25 to 22 Hz. The calls were reported to not have regular repeat intervals evident. The calls were reported to be similar to Olesons Be3 type call as well as down swept calls reported by Kibblewhite et al.[9] for New Zealand.

Description of Bryde's whale calls off the coast of Southeast Brazil reveal 5 additional call types (PS1, LFT, FMT, TM1, and TM2)[10]. The TM1 call type is described as a flat tone at 55 Hz with two harmonics, and two secondary flat tones, not harmonically related, between the fundamental and the first harmonic. Of the 5 calls described, the TM1 call is most similar to the call type recorded at PMRF.

It is important to note that the described call types were recorded on a variety of acoustic recording devices in widely varying ocean acoustic environments, and so a direct comparison of signal attributes is not possible. However, throughout the literature a call similar to the call recorded at PMRF has been described and attributed to Bryde's whales in multiple geographical locations. Additionally, Bryde's whales are the only species of baleen whales known to inhabit the region during the month of August that are capable of producing such low frequency sounds.

C. Assignment and validation of tracks

The automated localization software described in Helble et al.[2] has strict criteria for determining a localization: The call must be templated on all 5 hydrophones, and the cross correlation score between all 4 hydrophone pairs (center hydrophone and each of the 4 supporting hydrophones) must be greater than 0.4. Over 95% of the calls emitted by the Bryde's whale within the range adhere to this criteria, but, for the purpose of measuring ICIs every call emitted by the whale must be included. Additional software was thus developed for the purposes of accurately measuring the intercall intervals of each whale track. First the initial localizations produced by the localization software were manually grouped together into tracks (labeled A-K in Fig. 3). Localizations that are within 5 km of each other on similar trajectories and with gaps less than two hours are considered to collectively make up a track. The track is presumed to be from a single vocalizing Bryde's whale, and, while there is no way to independently verify this assumption, it is likely true do to the relative isolation of each track in space and/or time. A second software package was

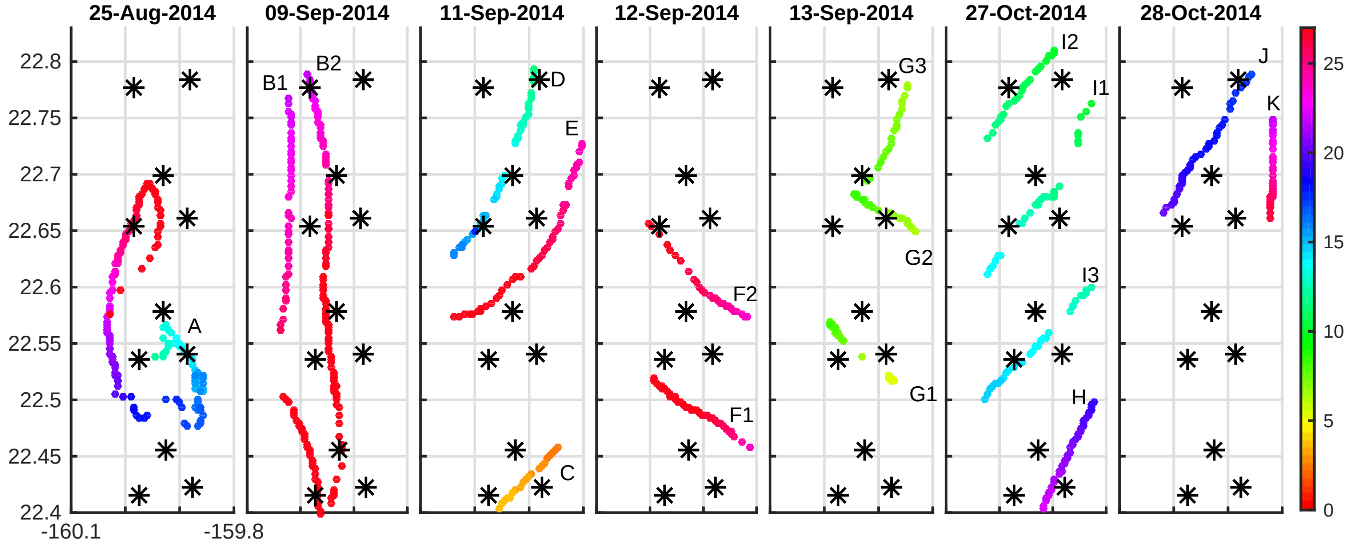

FIG. 3. (color online) Bryde's tracks formed from TDOA acoustic localizations on the Navy's Pacific Missile Range Facility. Individual tracks are labeled A-K, tracks with the same letter represent tracks that occurred at the same time. The letter position indicates the beginning of the track. The shading gradient represents the time elapsed since midnight local time for each subplot.

TABLE I. Track kinematic information for tracks shown in Fig. 1. N_{calls} represents the number of calls that make up the track, E_{time} is the elapsed time of the track (in hours), SLD is the straight line distance between the first call and last call (in km), TDT is the total distance traveled along the track (in km), D_{index} is the ratio of SLD to TDT, v_{min} is the 10th percentile velocity measurement for the track (in kph), v_{max} is the 90th percentile velocity measurement for the track (in kph), v_{mean} is the mean velocity measurement for the track (in kph), Bearing is the average bearing for the track (in degrees), and ICI_{mean} and ICI_{median} are the mean and median intercall intervals for the track.

Track	Start Time (local)	N_{calls}	E_{time}	SLD	TDT	D_{index}	v_{min}	v_{max}	v_{mean}	Bearing	ICI_{mean}	ICI_{median}
A	8/25/14 11:52 AM	179	17.98	10.06	70.87	0.142	0.15	15.26	3.94	309.26	363.73	295.48
B1	9/9/14 9:42 PM	99	7.51	41.23	43.31	0.952	4.90	6.80	5.78	171.44	278.99	266.67
B2	9/9/14 9:50 PM	110	10.86	42.60	43.94	0.970	3.65	4.46	4.07	173.39	381.28	300.68
C	9/11/14 2:12 AM	20	1.59	12.84	12.87	0.997	3.74	12.31	8.20	243.09	300.55	293.29
D	9/11/14 11:20 AM	44	4.66	24.17	24.82	0.974	4.52	6.21	5.32	217.21	382.02	288.22
E	9/11/14 11:38 PM	46	4.81	29.62	31.04	0.954	5.84	7.82	6.45	233.60	384.54	364.41
F1	9/12/14 10:09 PM	45	6.40	20.23	20.30	0.996	0.38	5.00	4.44	292.69	523.88	306.95
F2	9/12/14 11:36 PM	27	4.12	21.24	21.43	0.991	3.67	6.71	5.20	302.40	570.26	475.65
G1	9/13/14 5:11 AM	52	2.99	13.45	13.55	0.993	0.22	5.26	4.43	298.91	NA	NA
G2	9/13/14 5:38 AM	25	2.76	12.32	12.48	0.986	0.52	6.22	4.57	291.73	414.76	308.74
G3	9/13/14 6:17 AM	20	1.67	12.06	12.28	0.982	5.45	10.14	7.41	213.51	316.86	281.52
I1	10/27/14 9:50 AM	31	4.04	3.03	3.04	1.000	6.88	7.54	7.19	229.73	308.18	282.27
I2	10/27/14 9:53 AM	25	1.91	15.58	15.64	1.00	7.07	10.32	8.19	231.83	NA	NA
I3	10/27/14 12:16 PM	30	2.46	14.16	14.26	0.993	6.75	15.84	10.59	242.36	247.45	313.70
H	10/27/14 7:03 PM	38	3.07	14.56	14.61	0.997	4.41	5.39	4.78	223.61	298.32	240.31
J	10/28/14 5:10 PM	38	2.76	21.55	22.00	0.979	3.14	14.12	8.22	227.82	268.45	263.88
K	10/28/14 9:36 PM	43	4.73	9.71	9.74	0.996	1.39	2.69	2.00	183.02	405.67	310.82

developed to ensure that all calls along the track were included. First, each localized call along the the track is identified on the center hydrophone in the subarray for which the call occurred. Next, each unassigned call received on the center hydrophone is assumed to be a missed call along the track. The approximate geographical location of the missed call is estimated by assuming a constant velocity trajectory between the previous known call along the track and the next known call along the track. The expected time delays for the unassigned call are then computed between all hydrophone pairs, with a user defined tolerance. If cross correlation delays are computed between hydrophone pairs within the user defined tolerance, the call is included in the track. The user can also set the number of hydrophone pair matches required for the unassigned call to be included, relaxing the initial 4 hydrophone pair solution requirement to 3 pairs. In practice, relaxing the timing delay tolerance to 170 ms and requiring a match on 3 hydrophone pairs was sufficient to include any missed calls. This bootstrap method is beneficial because the localization parameters can be relaxed along the whales apparent trajectory, without relaxing the localization requirements across the entire array, minimizing false localizations. For the final step, manual analysis of the raw spectrograms were utilized to ensure all vocalizations in the acoustic record were correctly assigned to a track. To do so, RAVEN Pro 1.5 software[11] was used to display the spectrograms of the audio channels of the four center hydrophones in the array. Color coded boxes were automatically placed on the spectrograms of the raw data corresponding to the start and end time of each vocalization within a track, with each track assigned a unique color. In almost all cases the localization software identified each vocalization correctly without double assigning vocalizations or missing vocalizations. Occasionally, a vocalization was unassigned by the software and thus assigned manually by the analyst. In most cases an unassigned call was easily assigned to the correct whale track by noting the time of arrival pattern of the call on multiple spectrogram channels. This pattern could then be matched with the pattern of nearby calls that were automatically assigned to a track. For a few cases, it was difficult to choose the correct track for an unassigned vocalizations, and for these tracks the ICI was not computed.

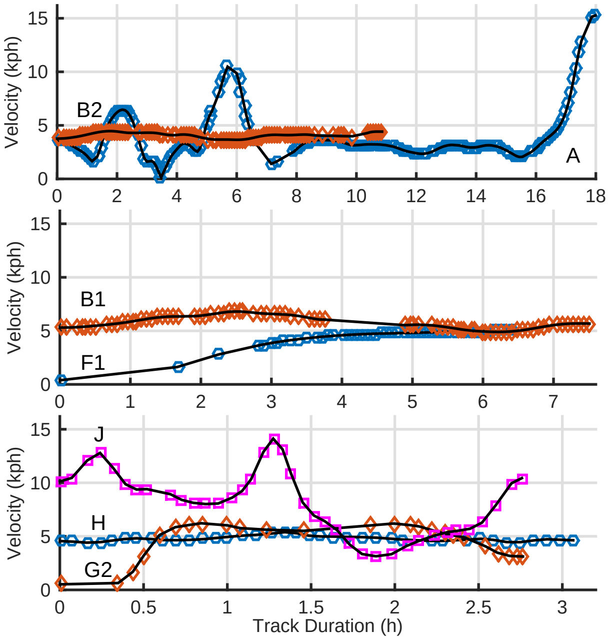

FIG. 4. Velocities for 7 of the 17 tracks shown in Fig. 2. Markers indicate emission time of acoustic call by the whale. Tracks are grouped by similar track duration for scaling purposes. The apparent gap in track B1 is due to the whale transiting off-range, and so exact position and speed is unknown during this period.

D. Track kinematic extraction

The process of extracting the whale track kinematics (bearings, velocities, directivity, etc) can be problematic because unlike a physical tag the sampling of the track is limited to the calling rate of the whale. Additionally, there is some (although likely minimal) localization error and bias between the recorded location and the true location of the call. In the extreme example, a whale could vocalize twice - once at the beginning of a track and again at the end of the track. In such a scenario, only one bearing and velocity could be calculated, and the directivity index (the straight-line distance traveled divided by the total distance traveled) would always be equal to one. There is no way to know the animals movements between calls, and therefore the kinematics presented in this paper are the minimum known movements of the animal. In general, the ICIs of the calling animals are similar for the 17 tracks analyzed, allowing for comparison of kinematics between animals, but its important to note these sampling differences when comparing track kinematics.

Curve fitting tools were utilized in order to minimize the effects of sampling differences and localization uncertainty. Each track is parameterized such that latitude is a function of time and longitude is a function of time. Both the latitude and longitude coordinates are fitted separately with a cubic smoothing spline interpolation with adjustable tolerances. The tolerance selected is a tradeoff between the data misfit and the smoothness of the curve as represented by the integral of the curvature (2nd derivative squared). Tracks were fitted so that no unphysical accelerations were allowed between data points along the track. This was accomplished while keeping the along track errors (distance from fitted curve to location of measured vocalization) to within 100 meters. The continuous representation of the fitted track is a convenient means to derive along track sample points that are equally spaced in time for the purpose of computing and comparing track kinematics.

III. RESULTS

A. Track Kinematics

A total of 17 tracks attributed to Bryde's whales can be seen in Fig. 3. The shading of the tracks indicates the number of hours since midnight for each listed date. The tracks are labeled with a letter (A-K), and tracks occurring with overlapping time are indicated with the same letter and a number to indicate the overlap (i.e., tracks B1 and B2 transit with overlapping time through the range). A total of 7 days contained tracks out of the 17.7 days monitored between Aug 25, 2014 and Oct 28, 2014. Tracks were present for 47.17 h of the total 424.8 h of monitored time. The clustering of tracks in time suggests the whales are traveling in groups, with individual calling whales spaced 5-20 km apart. In most scenarios, tracks occurring at the same time tend to be parallel in nature, suggesting the whales may be using vocalizations to maintain spacing. However, there are a few scenarios where whale tracks appear parallel in nature with this same spacing structure even though one whale may completely transit through the range before the lagging whale enters the range, such as tracks D and E. There are two events that suggest encounters between two calling Bryde's whales: tracks B1 and B2 intersect each other in the southern portion of the range, and tracks G2 and G3 intersect each other in the northern region. A single track emerges from the intersection of G2 and G3 transiting westward, but the track is not plotted since it is unclear which whale the track can be attributed to.

Table. I shows track kinematics for the 17 tracks shown in Fig. 3. The number of calls that make up the track (N_{calls}), the elapsed time of the track (E_{time}), the total distance traveled (TDT), straight line distance traveled (SLD), directivity index (SLD/TDT), 10th percentile (v_{min}), mean (v_{mean}), and 90th percentile (v_{max}) velocities, and intercall intervals (ICI_{mean} and ICI_{median}) are given for each of the tracks.

All of the tracks have directivity indices of 0.95 and higher except for track A, indicating that the whales followed very straight trajectories. Track A's meandering track was anomalous when compared with the other tracks, and it is unclear what drives this differing behavior. Additional data should be collected earlier in the summer to study whether this change in track behavior could vary depending on the season.

Velocities varied between 0.15 kph to over 15 kph, with the average velocity of all 17 tracks equal to 5.93 kph. Fig. 4 shows the velocities versus elapsed track times for tracks A, B1, B2, F1, G2, H, and J. The tracks are grouped into subplots of similar track duration so that the details of the track velocities can be seen. Some tracks maintain very constant velocities, such as track B2, while others velocities vary widely over the duration of the track, such as tracks A and J. The markers on the plot indicate each time the whale emits a vocalization, and show that the whales generally increase the time between calls during periods of fast transit or periods of rapid acceleration or deceleration. The apparent gap of acoustic calls in track B1 is due to the animal transiting just outside the range before transiting back in. Calls for track B1 were manually tabulated while the whale was outside of the range for the purpose of obtaining the intercall interval, but localizations were not obtained for B1 outside of the range boundaries.

B. Intercall Interval

The intercall interval (ICI) for each track was computed using the methods outlined in Sect. II.C. ICIs were not included for tracks G1 and I2 because each call could not be confidently assigned to the correct whale. The mean and median ICIs for each track can be seen in Table. I. The upper plot in Fig. 5 shows the 10th percentile, 90th percentile, mean, and median ICI for each track. The lower plot shows a histogram of the aggregated ICIs in 30 second bin increments for all the tracks for a total of 746 calls. The tallest bin (mode) is between 240 and 270 seconds, containing 163 calls. Further reducing the bin size to one second bin width reveals the highest peak to be approximately 270 s. The intercall intervals described by Oleson et al.[6] showed considerable variability by call type and also within a call type. The Be1 and Be3 calls (most similar to the calls recorded at PMRF) had mean ICI's of 75 s and 137 s respectively, and with ranges of 12-264 s for Be1 and 27-519 s for Be3. Oleson et al. also noted that the Be1 call appeared to occur in the presence of other calling whales also producing the Be1 call, and suggested a possible call and countercall behavior. An analysis of the calling behavior of tracks occurring at the same time doesn't reveal an exact call and countercall pattern, i.e., a whale does not necessarily respond with a call as soon as as a call is heard from a conspecific. However, for all tracks occurring at the same time (B1-B2, F1-F2, G1-G2-G3) there are time periods along the tracks where the ICIs become very synchronous for several hours at a time. For example, in the case of B1 and B2, the ICIs are nearly identical for the first portion of the track before B1 veers off-range. While off-range, the two ICIs drift apart slightly before falling back in synch as the whale returns to the range. The ICIs from B1 and B2 then stay at nearly identical rates until B1 stops calling, at which point the ICI from B2 immediately increases for the remainder of the track. The synchronization of the tracks ICIs, combined with the synchronization of track speeds as described in Sect. III.A indicates the vocalizations are likely used as a means of maintaining travel cohesion with conspecifics.

Nearly all tracks (except for the cessation of either G2 or G3) appeared to persist for the entire duration of time it took for the whale to transit across the range, and faint calling recorded on the hydrophones as the animal transited into and out of the array boundaries suggests that the whales vocalize for extended periods of time. Both the fraction of the population that is capable of being vocally active and the fraction of time those whales produce sounds would need to be known in order to derive density estimates from the tracks localized at PMRF. These numbers still need be obtained from either acoustic tags or from ship or air based observations in combination with acoustic recordings. In the meantime, track counting could prove useful for obtaining minimum density estimates at PMRF - the number of transiting tracks reveals the absolute minimum number of whales that are present. This metric could prove to be stable when looking for changes in populations over time.

IV. CONCLUSIONS

A new call type attributed to Brdye's whales has been recorded and described in the offshore region of Kauai on the Navy's Pacific Missile Range Facility. The call type is similar to those described for Bryde's whales in other regions, but the spectral characteristics and the intercall interval are notably different. Long calling bouts in combination with the call's repetitious nature allow for swim kinematics to be calculated for the whales. Of the 16 tracks analyzed, 15 appear to be very directional transit tracks with average speeds varying between 2 and 10.5 kph. The tracks appear on the range in a clustered na-

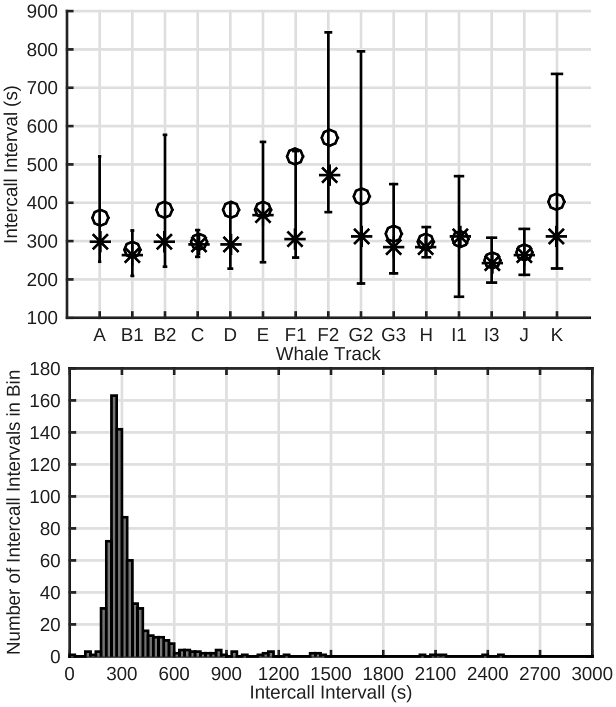

FIG. 5. Intercall intervals for each Bryde's track (upper plot) showing the mean (circle) and median (asterisk). Error bars represent the 10th and 90th percentile intercall interval for each track. The histogram (lower plot) shows the aggregated intercall intervals for all 746 calls, the tallest bin is between 240 and 270 seconds, with 163 calls. The mean and median for all aggregated intercall intervals is 363 s and 290 s respectively.

ture - with several whales transiting through the range over the course of a few days, followed by several days of inactivity. This pattern suggests the whales are traveling in groups and may use acoustic vocalizations to maintain group cohesion and spacing. The proportion of calling whales within the population is unknown on the PMRF range, but the vocally active whales produce sounds continuously as they cross the range with most ICIs occurring every 4.5 minutes. The swim kinematics and calling behaviors outlined in this paper could prove useful for future acoustic density studies.

Acknowledgments

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