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SSC Pacific FY17 annual report on PMRF Marine Mammal Monitoring

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14. ABSTRACT

This report documents Space and Naval Warfare Systems Center Pacific (SSC Pacific) marine mammal monitoring efforts in FY17 for Commander, Pacific Fleet (COMPACFLT) at the Pacific Missile Range Facility (PMRF), Kauai, Hawaii. The overarching goals of these efforts are to fill data gaps and provide a more complete monitoring product to COMPACFLT by conducting passive acoustic monitoring (PAM) at PMRF and collaborating with other marine mammal monitoring efforts. The following tasks were completed in FY17 in support of these goals:
1. Raw acoustic data from 62 bottom-mounted hydrophones at PMRF were recorded on 2 terabyte hard disk drives and backed up onto 8 terabyte hard disk drives and a network attached storage system at the SSC Pacific laboratory. Unclassified data were collected at the full bandwidth sample rate (96 kHz) twice a month during two separate periods of time (for a minimum of 24 hours and up to a maximum of 45 hours) and at a decimated sample rate (6 kHz) between full

bandwidth recordings when possible to increase recording effort for baleen species. Classified data were collected at the full bandwidth sample rate in late January during a separate training event, and in February and August during the Submarine Command Course (SCC) to evaluate the impact of MFAS on marine mammals.

2. Algorithms were developed to semi-automate exposure analyses and the received level estimation process; these algorithms incorporate individual animal tracks, classified ship positional data, and automated sonar localizations from classified raw acoustic data. Cumulative and instantaneous received levels were estimated using the sonar equation with spherical and cylindrical spreading loss and absorption, and were also batch processed with the Peregrine parabolic equation propagation model developed by Ocean Acoustical Services and Instrumentation Systems Inc. (OASIS, Lexington, Massachusetts, United States). Sonar equation estimates agreed well with Peregrine estimates for short ranges and direct paths, but propagation modeling was required for longer ranges that incorporate area-specific bathymetry and variable sound speed profiles. As part of a continuing effort to verify estimated exposure levels from propagation modeling, in situ recordings of MFAS signals were collected from a calibrated hydrophone and recorder deployed from a weapons recovery vessel at PMRF during SCCs. Overall, these results show good agreement and in situ measurements will continue to be collected to refine received level estimation for various source and receiver geometries.

3. Data from 09 March 2007 to 26 August 2017 have been processed to estimate long-term species abundances (results not manually validated unless otherwise stated). In the winter and spring seasons from 2007-2017, minke whales had a consistent abundance of 5-16 tracks per recording, which is relatively higher than abundances for humpback whales at 0-3 tracks, and low-frequency baleen (fin/sei/Bryde's whales) at 2-6 tracks per recording. Blainville's beaked whale results for 2014-2017 (using the most recent algorithms with a subset of data validated for each year) yielded 4.5-6 group foraging dives per hour. Results from 2007-2013 (processed previously using older algorithms; data from 2011-2013 fully validated) yielded 0.55-2.5 group foraging dives per hour. Data from 2007-2013 have been processed with the current version of the data processing algorithm, and the combined dataset will be analyzed in a future report. Results for Cross Seamount-type beaked whales, sperm whales, and killer whales are reported for the first time. Cross Seamount beaked whales results from 2014-2017 found 0.33-1 group foraging dive per hour (these results have been fully validated). Data from 2007-2013 have been processed for Cross Seamount-type beaked whales, and additional analysis is in process to obtain the metric of group foraging dives per hour, while long term trends in abundance will be assessed. Killer whale results from 2007-2017 found 0-4 groups per recording, and have been fully validated. Sperm whales results for 2007-2017 were 13-1587.55 localizations per hour. These variable results could be due to inclusion of false positive localizations but may also be influenced by difference in abundance, calling behavior, and increases in the number of hydrophones capable of detecting sperm whale clicks in later datasets. The sperm whale processing capability and abundance metrics are in the process of being refined.

4. Full bandwidth classified raw acoustic data from February 2017 were processed and analyzed for hull mounted mid-frequency active sonar (MFAS) exposures on minke whales. Thirty-one individual minke whales were automatically tracked and a cumulative sound exposure level (cSEL) was calculated over the duration of 23 animal tracks that overlapped with MFAS from multiple ships. Animal track 10 is highlighted in Figure 18 as it had the highest cumulative received level of 169.8 dB cSEL re: 1µPa2s and the minimum distance to a ship transmitting sonar (4.8 km). This animal appeared to exhibit a decrease in call rate when closest in range to a ship transmitting MFAS but did not exhibit any other acoustically detected behavioral responses, and continued to call for 41 minutes emitting 7 calls after MFAS transmissions ceased.

5. Vessel-based tagging and photo-identification were conducted off Kauai, Hawaii March 17 - 24, 2017 with the intent to tag humpback whales with both LIMPET-configured SPLASH satellite tags from Wildlife Computers (Redmond, Washington, United States) and active high-frequency pinger tags developed in-house. Whales with pinger tags attached and within the hydrophone array would demonstrate the ability to track pinger emissions using the bottom mounted range hydrophones at PMRF. This would provide indisputable confirmation of species, animal locations when they are not actively vocalizing, and evaluation of automated tracking accuracy. The main goal of the project was to capture the habitat use and behavior of humpback whales both on and nearby the PMRF range. Additional goals were to 1) estimate how much time individuals spend on the range; 2) quantify their call/cue rates on the range to inform density estimation; and 3) opportunistically assess any behavioral responses that may occur to the SCC training that was conducted during and after the tagging effort. Seven whales were successfully satellite tagged; unfortunately, due to a permitting issue the pinger tags were not deployed. Results are summarized in Henderson et al. (2017; appended to this report).

APPENDIX ABSTRACT: To better understand the behavior of humpback whales (Megaptera novaeangliae) in the deeper waters of their Hawaiian breeding grounds west of Kauai, seven presumed males were satellite tagged using LIMPET-configured SPLASH tags in late March 2017. All tagged whales were traveling away from Kauai when encountered, heading west towards the island of Niihau, which they circled for 1.0 – 7.9 days. Five whales continued to travel west/northwest, with directed travel over deep water while milling over shallow seamounts and near islands, including Ka'ula Rock, Middle Bank, and Nihoa. Four of the tags stopped transmitting while the whales were at or near these seamounts. Only one whale traveled directly north from Niihau rather than following the Hawaiian archipelago to the northwest. Tags remained attached for 1.6 – 12.3 days, and total distances traveled ranged between 143.5 and

826.4 km, although straight-line distances traveled were far shorter (19.8 – 548.8 km). The median travel speed while near islands or seamounts was 1.1 km/hr, while the median intermediary speed approaching or leaving these areas was 3.0 km/hr, and the median directed travel speed over open water was 5.5 km/hr. Mean dive depth was 33.4 m, while maximum dive depths reached 395.5 m. Dive depths correlated with seafloor depths, with dives over shallow seamounts often using the full extent of the water column, while the deepest dives occurred over open water and usually at night. These results begin to provide insight into the offshore and migratory behavior of humpback whales in Hawaii, and build a baseline of behavior against which to compare potential responses to Navy training activity in this area.

15. SUBJECT TERMS

monitoring, marine mammals, adaptive management review, baleen whales, toothed whales, beaked whales, behavior, diving, mid-frequency active sonar, passive acoustic analyses, Hawaii Range Complex, Pacific Missile Range Facility

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1 Executive Summary

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List of Acronyms

ADC – analog-to-digital converter

BARSTUR – Barking Sands Tactical Underwater Range

BSURE – Barking Sands Underwater Range Expansion

BREVE – ONR project Behavioral Response Evaluation Employing robust baselines and actual US Navy training. Award Number: N000141612859

COMPACFLT – Commander Pacific Fleet

CPA– Closest point of approach

CSM – Cross Seamount-like beaked whale clicks

CY– Calendar year

DCLTDE – Detection, classification, localization, tracking and density estimation laboratory located at SSC Pacific in San Diego, California.

ETOPO – Earth topographic (database)

FY – Fiscal year

HFM – High-frequency modulated vocalizations attributed to killer whales

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

LMR – Living Marine Resources program

M3R – Marine Mammal Monitoring on Navy Ranges, a Naval Undersea Warfare Center program which is 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

NUWC – Naval Undersea Warfare Center, Newport, RI

OASIS – Ocean Acoustical Services and Instrumentation Systems (OASIS), Inc., Lexington, MA, United States, developer of Peregrine, a parabolic equation propagation model

ONR – Office of Naval Research

PAM – Passive acoustic monitoring

Peregrine – Propagation model from Oasis Inc. currently being utilized to estimate receive levels on marine mammals from US Navy MFAS training.

PMRF – Pacific Missile Range Facility, Kauai, HI

SCC – Submarine Command Course training event

SSC Pacific – Space and Naval Warfare Systems Center Pacific

SNR – Signal-to-noise ratio

SWTR – Shallow Water Training Range

3 Introduction

In fiscal year (FY) 2017 the SSC Pacific Detection, Classification, Localization, Tracking, and Density Estimate (DCLTDE) Laboratory (San Diego, California) utilized passive acoustic data recordings from bottom mounted range hydrophones at the Pacific Missile Range Facility (PMRF) to monitor for vocalizing marine mammals both during baseline periods and during U.S. Navy training activities.

The overall goals of this ongoing effort are to: 1) Collect raw acoustic data for detailed verification of automated processing results and to allow future processing with new marine mammal species detection, classification and localization algorithms; 2) Understand occurrence and abundance for multiple marine mammal species; 3) Estimate sound levels that marine mammals were exposed to during Navy training with hull mounted mid-frequency active sonar (MFAS); 4) Investigate behavioral responses to Navy training activities (e.g. changes/cessation in calling, changes to animal kinematics, and overall changes in abundance); and 5) Collaborate with researchers conducting other monitoring efforts (e.g. tagging and visual surveys), along with other U.S. Navy laboratories, to fill data gaps and provide a more complete monitoring data product.

Overall, this report highlights multiple areas where significant progress was made in FY17. Advances were made to the automated algorithms utilized for processing and analyzing the large inventory of raw acoustic data from multiple hydrophones spanning multiple years (Section 4.1.1). Advancements include updates to the killer whale detector to eliminate false positives and combining detected killer whale calls into groups (Section 4.2.1). In addition, changes were made to the beaked whale detector to improve separation of frequency modulated foraging clicks from Blainville's and Cross Seamount-type (CSM) clicks (Section 4.2.1). The capability to track baleen whales was refined to determine the number of individual baleen whales tracked in any given 10 minute period (Section 4.2.2). Semi-automated tools were developed in FY17 that utilize animal tracks in conjunction with classified ship positional data and automatically localized sonar transmissions from classified raw acoustic data. These semi-automated tools streamline the process to estimate cumulative exposure levels for all tracked animals over the duration each individual was acoustically tracked and while in the presence of multiple ships transmitting MFAS. Similar and related efforts investigating minke whale response to MFAS transmissions at PMRF have been documented previously in Martin et al. (2015, 2017). The automated disturbance analysis process is discussed in detail in Section 4.2.3, with detailed results of the February 2017 SCC for minke whales in Section 5.5 The semi-automated tools for tracking animals were applied to baleen whales during unclassified baseline data sets from FY17 (Section 5.3.1) and from historical data from 2007-2011 (Section 5.4.1) to provide current and initial long-term minimum abundances of individual vocalizing species on the instrumented range at PMRF. In addition, the number of group foraging dives for Blainville's and CSM beaked whales for FY17 data are provided in Section 5.3.2. For the first time, results for sperm whales (Section 5.4.2) and killer whales (Section 5.4.3) are presented in the metric of localizations per hour and calling groups, respectively, from 2007-2017.

4 Methods

4.1 Data Collection

4.1.1 PMRF Range Data

Passive acoustic monitoring (PAM) data was recorded on 62 of the PMRF bottom mounted hydrophones (Figure 1) to support analyses of marine mammal vocalizations and MFAS transmission times and locations. An in-depth overview of historical and present hydrophone array configurations, data collection regimes, and hardware specifications (i.e. hydrophone frequency response and data recorder sampling rate) was provided in the previous fiscal year report (Martin et al. 2017). Ten of the BSURE replacement hydrophones failed in June of 2017 and are still nonoperational (white circles in figure 1) which is discussed further in section 4.1.4 of this report. Two types of acoustic recordings were obtained in FY17. Standard full-bandwidth recordings at the 96 kHz native sample rate (frequency response up to ~45 kHz) were requested to be recorded during two separate periods of time (for a minimum of 24 hours and up to a maximum of 45 hours) a month for all 62 hydrophones. During the February and August SCCs, full bandwidth recordings were collected more frequently since personnel from SSC Pacific were present at PMRF to collect sufficient data before, during, and after the SCC for baseline and exposure analyses. In addition, recordings at a reduced sample rate of 6 kHz (referred to as decimated data) providing 3 kHz of bandwidth for baleen whale vocalizations were collected on the broadband hydrophones to increase recording effort (Figure 1). Decimated data allows recording 16 times more data (720 hours vice 45 hours for full band data) on a 2 terabyte disk (which is the maximum capacity disk for the PC based data collection system). While it does preclude analyses of higher frequency sounds, it provides more temporal coverage for species such as Bryde's whales that only seem to be detected once every several days (Helble et al., 2016). Decimated data collections between September 9, 2016 and August 26, 2017 captured 23% of that total time, while full bandwidth collections accounted for 17% of the same non-overlapping total time period.

Data recorded on the 62 hydrophones utilized two analog-to-digital converter (ADC) boards. Inter-Range Instrumentation Group (IRIG) timecode (utilized by the C++ detection algorithms) was recorded on two channels for full bandwidth data, one for each ADC board. For decimated data prior to March 2017, IRIG timecode was only recorded from one ADC board. As of March 2017 the IRIG timecode from the second ADC board has been recorded on an additional channel for decimated data due to occasional asynchronous timing between both ADC boards. This has allowed for the time offset to be characterized so timing between both ADC boards may be resynchronized, and resolved issues when timing between hydrophones on separate ADC boards were used for detection and localization.

In addition to the acoustic data, standard PMRF range data products (e.g., ship positions and expendable bathythermograph data) have been obtained for 14 biannually held SCC training events since February 2011. These data have provided locations for all platforms from the start to finish of training events, but normally not between events when platforms reposition. In August 2017, PMRF provided ship positional data between training events for the first time and at the request of SSC Pacific to support disturbance analyses.

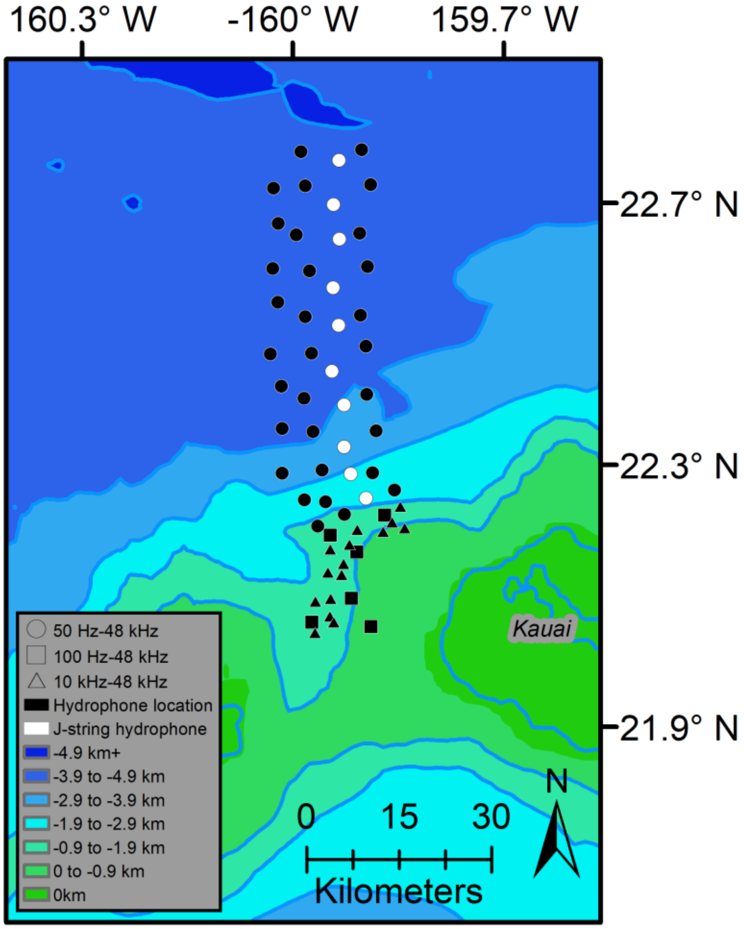


Figure 1: Map showing approximate locations of the 62 hydrophones that have been recorded since August 2012. The 47 broadband hydrophones are depicted as circles (frequency response 50 Hz-48kHz) and squares (frequency response 100 Hz-48kHz). The high-pass hydrophones are depicted as triangles (10 kHz-48kHz). The white circles indicate the J-string hydrophones that went out in June 2017.

4.1.2 Opportunistic Surface Hydrophone Data

During some of the SCC training events there has been a low-cost effort involving PMRF personnel on a weapon recovery vessel to collect recordings using a calibrated hydrophone deployed near the surface along with a time-depth data logger. This effort was to collect MFAS signals near the sea surface in order to validate received levels estimated by the Peregrine parabolic equation propagation model (Heaney and Campbell 2014). Images of the calibrated hydrophone recording equipment deployed over the side of a weapon recovery vessel during the training events in 2014 (Figure 2) and then in 2016-2017 (Figure 3) are provided to highlight some of the differences between the systems. These differences include increased weight in the later system to keep the hydrophone at depth, along with a time depth recorder for accurate depth estimates.

Figure 2: Recording setup deployed for in situ near surface measurements in February and August 2014. Note the one-pound weight and lack of depth recorder. The analog-to-digital recorder was also different from later recordings.

Figure 3: Recording setup used for in situ near surface measurements from February 2016 to present. The five-pound weight for the hydrophone line is not pictured; the time depth recorder (in blue) is visible attached to the hydrophone line on the reel.

This effort has been performed by the weapons recovery craft personnel on an opportunistic and not-to-interfere basis, thus not all data collected may be usable for model validation if data do not contain MFAS signals, or if positional data for both the MFAS transmitting ship and recording platform are not available. Continuing to collect in situ measurements requires a low level of effort. Obtaining measurements for different geometries between a ship transmitting MFAS and the recording platform helps better characterize modeled MFAS received levels.

A preliminary analysis of the first data collections from August and February 2014 was conducted. Data were not collected in August and February 2015 as the calibrated hydrophone and recording setup were not taken to PMRF. In February 2016, the depth logger was added to the hydrophone recording system to provide measured hydrophone depth along with additional weight; however, data were not collected since the weapon recovery vessels were not deployed for much of the training activity due to high sea states. Some data collected in August 2016 contained good recordings of MFAS transmissions; however, these data have not been analyzed since ship positional data were not available during the time when usable recordings were collected. In February and August 2017, the depth logger failed and a measured representative depth from previous deployments was utilized for analyses. Measured received levels for February 2017 agree well with modeled received levels and analysis of August 2017 measurements are in progress.

4.1.3 M3R Packet Recorder Data from PMRF

Ongoing efforts have continued in order to transition from recording acoustic data on a Windows PC recorder (which has been utilized since collection began in February 2002 with some technical refreshments), to a Linux packet recorder node included within the M3R system installed at PMRF. Analysis of concurrent data collections from both recording systems revealed issues with the M3R packet recording system that are being worked on collaboratively with NUWC and SSC Pacific.

4.1.4 Challenges

As of June 2017, 10 of the 41 Barking Sands Underwater Range Expansion (BSURE) broadband replacement hydrophones in the "J" string (second vertical string of hydrophones from the east) failed and are still inoperative. This outage impacted the detection process for all species in the last quarter of FY17 (the data specifically affected in this report were June – August 2017) given the reduced hydrophone effort. Impacts on baleen whale species detection and localization were not expected to be significantly impacted for this report given that most of the species are not present in Hawaii during that time of year, and Bryde's whales' calls propagate longer distances and can be localized with the operational 37 broadband hydrophones. Odontocete (sperm, beaked and killer whales) detections were impacted by reduced spatial effort due to the loss of data from the 10 hydrophones. Beaked whales are present year round, and are sometimes detected on those 10 hydrophones; their detection rates were slightly lower for June through August. In FY18, plans exist to analyze effects of the outage, perform systematic noise analysis on all hydrophones to help identify outages to automatically inform of reduction in data collection efforts, and quantify the impact to processing the various species. In FY18 substitute hydrophones will be assigned to these 10 recording channels if the outage of the hydrophones is expected to last long-term.

4.2 Algorithms and Tools

4.2.1 Automated Detection, Classification, and Localization Algorithms

Multiple algorithms are utilized to process PMRF recorded data to detect marine mammal vocalizations, and localize when possible. A custom C++ detection algorithm automatically processes detections of beaked whales, sperm whales, baleen whales (minke and a low-frequency group of whales [fin, sei, Bryde's, and potentially blue whales]), MFAS sonar transmissions, killer whales, and Blainville's beaked whales, with improved detection of CSM beaked whale signals. When post-processing recorded data different operating points can be utilized, as well as future versions of the algorithms with capabilities to process additional species. For full bandwidth data recordings the custom C++ algorithms process data at rates approximately 5 times faster than real-time. A custom Matlab algorithm separately processes humpback whale song detections and localizations.

These algorithms have been discussed in detail in peer-reviewed journal publications and reports (Martin et al. 2015, Martin et al. 2016, Martin et al. 2017, Manzano-Roth et al. 2016, Henderson et al. 2016, Henderson et al. 2018, Helble et al. 2012, Helble et al. 2015, Helble et al. 2016). The custom Matlab algorithm is also capable of localizing minke whales and low-frequency baleen whales allowing for cross validation between the two methods. Additionally, classification technology is currently being developed under funding from the Living Marine Resources (LMR) program, which should help automatically differentiate species of the current low-frequency baleen whale group.

4.2.1.1 FY17 Updates

The custom C++ detection algorithm used to process the data presented in this report was under version control (i.e. all data were processed using the Baseline 4 version, dated December 5, 2017). Notable changes to Baseline 4 of the C++ detection algorithm are detailed as follows. Firstly, this update improved processing and reporting issues with the IRIG timecode signal. Issues with IRIG timecode signal included periods of data with varying amplitude and incorrect time, which presented issues for detection and localization algorithms. Previously, periods of time with faulty IRIG were manually segmented out of the data. However, refinements made in FY17 resulted in not having to manually segment data with faulty IRIG when processed with Baseline 4, since timecode errors are now characterized better and can be detected, logged, and resolved automatically. Secondly, refinements to the killer whale detector included detection of more high-frequency modulated (HFM) calls without significantly impacting the false positive rate. All data since 2007 was analyzed for killer whales using this updated detector (Section 5.4.3), and all groups were manually validated. Thirdly, ongoing refinements to the beaked whale detector were implemented to improve classification of beaked whale frequency modulated foraging clicks from Blainville's beaked whales, separate classification of CSM clicks (McDonald et al. 2009), and initial detection algorithms of other beaked whale species foraging clicks (e.g. Cuvier's and Longman's) were explored.

The beaked whale click detection process has previously been discussed in detail in Martin et al. (2010) and Manzano-Roth et al. (2016). To review, the beaked whale detector has multiple stages. The first stage detects clicks using signal-to-noise ratio (SNR) thresholds to compare in-band (i.e., within the frequency range of the clicks) signal level over background level and mean in-band signal level over mean out-of-band level. The second stage sets another in-band over background SNR threshold with a smaller FFT and then utilizes click frequency modulation (FM) as a feature for species classification. Changes to the beaked whale detector included increasing the in-band click frequency range, decreasing the in-band over background SNR threshold in the first stage, and increasing the in-band over background SNR in the second (smaller FFT) stage. Significant changes were made in how the SNRs were calculated and new variables for click discrimination were introduced, including duration, bandwidth, minimum and maximum frequency, zero crossings, and click shape features. These changes ultimately resulted in a higher number of true positive clicks and a lower number of false positive clicks for the Blainville's beaked whale detector and the ability to start classifying other species of beaked whales.

The automatic grouping process of spatio-temporally sequencing the detected beaked whale clicks followed by manually sorting these grouped dives (i.e., segmenting or combining automatically grouped dives), as described in Manzano-Roth et al. (2016), is largely unchanged, although the algorithm has been improved such that it requires less follow-on manual sorting. Four FY17 datasets during baseline conditions were chosen at random and manually analyzed to characterize the detector, and were also automatically grouped and the clicks comprising a group were manually checked to determine a true positive, false positive, and false negative rate for the automatically grouped dives. Due to a higher number of clicks detected and correctly classified, and a lower number of false positive clicks detected, a higher number of group dives were detected overall compared to analyses using previous versions.

4.2.2 Tracking and Annual and Long Term Abundance Analyses

A semi-automated Matlab kinematic tracker was utilized to track automated localizations for minke, humpback, and low-frequency baleen whales. The initial step was to spatially filter localizations for a species within a defined study area. Additional filtering required a localized call to be detected on a user-specified minimum number of hydrophones, and with a user-specified minimum least squares error between the modeled and actual times a call arrived at different hydrophones. The next step recursively examined all filtered localizations and pre-defined species specific movement parameters (e.g. distance and time difference between localized calls) to create kinematic tracks. The final step was to threshold tracks based upon the number of calls and was derived from a species-specific inter-call-interval. For example, minke whales typically emit 1 call every 5 to 6 minutes (10-12 calls/hour) at the nominal call rate so a valid track was required to be composed of a minimum of 12 localized calls.

Tracks of individual baleen whales were analyzed via systematic snapshots taken every 10 minutes (Buckland et al., 2001). The logic is that at any instantaneous snapshot time, if a whale is being tracked (i.e. calls before and after the snapshot time) it is counted as present. This provides a census-type abundance estimate of whale counts in the study area at each snapshot time. Overall, this metric is a vast improvement from the metric of localizations per hour that was used in prior reports (Martin et al., 2016; 2017) and now identifies how many whales of different species were present.

The number of tracks and snapshots over time (Sections 5.3.1 and 5.4.1) is a stable metric and tracks that occur over the PMRF hydrophone array are assumed to have: a probability of detecting a calling whale equal to 1.0; a high probability of localizing all calls within a track; and the highest localization accuracy. As one extends the study area beyond the hydrophone array, both localization accuracy and the probability of detecting whale tracks decreases. When conducting detailed analyses (e.g. behavioral response in Section 5.5) or presenting results in a peer-reviewed journal, the automated results are manually verified. Typical refinements correct for potential errors such as multiple tracks established for a single animal, and the potential for two animal tracks being combined. Peer-reviewed journal articles that members of the DCLTDE laboratory authored have manually verified and tracked automatic localizations for humpback (Henderson et al., 2018), Bryde's (Helble et al. 2016), and minke (Martin et al., 2015) whales. Overall, the number of semi-automatically tracked animals compares well with the number of animals that were manually verified and tracked (e.g. the manually selected tracks used in Henderson et al. 2018), leading to high confidence in only manually validating a subsample of the tracks as done for this report.

These tracks can be used to estimate abundances on short-term (over the duration of a training event) to long-term (annual or decadal) scales. These abundance estimates are limited to the number of animals vocalizing, which is often related to behavioral state or role. Most vocalizing or singing baleen whales in Hawaii are presumed to be adult males, while beaked whale echolocation clicks are only produced during deep foraging dives.

4.2.3 Disturbance Analysis

The disturbance analysis is the process of investigating whether whale tracks overlap with anthropogenic activities such as MFAS transmissions and close proximity of ships, even when not transmitting MFAS, thereby conducting an opportunistic, passive acoustic BRS. When overlap occurs (currently including 10 minutes before and after each PAM whale track) a variety of metrics are calculated/estimated such as whale headings, speeds, call frequencies, call intervals, and distance and angle off the bow of the nearest ship. When ships are transmitting sonar (i.e. during SCC exercises), complex propagation modeling is utilized to calculate cumulative sound exposure levels an animal received from multiple ships over the duration it was acoustically tracked. By comparing track kinematics with baseline data, behavioral responses can be identified such as cessation of calling (Martin et al. 2015), change in direction of travel, or change in call rate. In addition to looking at the behavior of individual whales in response to ships and MFAS, we can also look at the overall impact of the training events on the occurrence and abundance of animals before, during, and after the training. This allows us to assess the response of species we can't track individually (e.g. beaked whales), and to look at the broader response of each species as a whole.

4.2.3.1 Propagation Modeling

Estimating sound levels (in sound pressure level [SPL] and sound exposure level [SEL]) that marine mammals receive from acoustic events, such as MFAS training, requires either 1) having acoustic tags on the whales to directly measure sound pressure levels or 2) utilizing propagation modeling coupled with locations of marine mammals and locations of ships transmitting MFAS and the time of transmissions. To date, no acoustic tags have been attached to marine mammals during SCCs at PMRF to allow direct measurement of the sound levels that whales receive; therefore, propagation modeling is utilized to estimate whales' received levels. The sonar equation has historically been and continues to be utilized to estimate received levels. This method provides good estimates for direct path propagation (the distance for direct path propagation can range from a few kilometers to over 20 km and is influenced by the frequency and location of the signals), and is a simple sanity check for more sophisticated propagation models such as the Personal Computer Interactive Multi-sensor Analysis Tool (PCIMAT) (Wulfeck II et al., 2003) and Peregrine (Heaney and Campbell 2014). The sonar equation utilizes both spherical and cylindrical spreading loss, with absorption as a function of frequency and distance typically with isovelocity water and flat seafloor limitations. While the sonar equation can also be utilized to model indirect path components and simple sloped bathymetry, inclusion of parameters such as detailed bathymetry for a specific area and variable sound speed is best performed utilizing more sophisticated propagation models. Nonetheless, when outputs from various propagation models are significantly different (i.e. > +/- 10 dB) from the sonar equation one should understand the reasons why. Differences can be attributed to various factors such as ducted propagation, sound velocity profile characteristics, multipath propagation, and interactions with detailed bathymetry.

Current efforts utilize Peregrine, a parabolic equation propagation model developed by OASIS, Inc. Peregrine outputs transmission loss from a source (i.e. a ship transmitting MFAS) to a receiver (i.e. a whale) for estimating the receive level at the whale location. Advantages of Peregrine over other methods are that Peregrine provides 1) estimated transmission losses over distance and depth related to the estimated accuracy of the whale location and expected whales depths, which provides statistical description of the sound field versus one fixed estimated whale location; and 2) the ability to perform batch processing of many source-whale geometries, which contributes to automating the process of estimating received levels on whales for all sonar transmissions from multiple ships. Peregrine utilizes databases from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information. These databases include the coastal relief model in 3 arc-second resolution for bathymetry, ETOPO1 (Earth TOPOgraphic [database]) in 1 arc-minute resolution for bottom type, and seasonal temperature and salinity in 1 degree resolution for sound velocity profile characteristics.

4.2.3.2 Semi-Automated Disturbance Analysis

The annual monitoring report from the previous year (Martin et al. 2017) introduced the new disturbance analysis, which includes estimated cumulative sound exposure levels and ship-whale geometries for the duration of an animal's track in the presence of multiple ships transmitting hull mounted MFAS. Since performing this involved significant manual effort, this analysis was performed for a portion of a single track in that report. A projected funded by the Office of Naval Research (ONR [Award Number: N000141612859]) called Behavioral Response Evaluation Employing robust baselines and actual US Navy training (BREVE) developed the initial framework for semi-automated disturbance analyses and the FY17 PACFLT effort streamlined the processing stages to perform them. The BREVE effort has processed minke whale tracks for February 2014 during baseline conditions, performed semi-automated disturbance analyses for minke whale tracks during the SCC exercise, and conducted statistical analyses on baseline and disturbance results. Disturbance analysis is an initial step for the BREVE project, the goal of which is to conduct statistical analyses of metrics such as track kinematics and whale call characteristics in an attempt to quantify any significant changes between animal track kinematics during times with and without MFAS training. The BREVE results are separately reported to ONR; however, no statistical inferences of behavioral responses have yet been reported by the BREVE effort. For the PACFLT effort, the DCLTDE lab has processed the semi-automated disturbance analyses for minke whale tracks for data during the February 2017 SCC which are provided in Section 5.5 of this report. The BREVE effort will include these data into that efforts statistical analysis for behavioral responses.

Automation of disturbance analyses allows the cumulative sound exposure levels and ship-whale geometries for all animal tracks that overlap in time with multiple ships both transmitting, and not transmitting, MFAS to be calculated in a semi-automated manner. The operations performed in the semi-automated process are depicted in a block diagram below (Figure 4). Inputs to the disturbance analysis program included ship positional data, which is a standard data product received from PMRF (e.g., Section 4.1.1). Inaccuracies in the ship positional data required error correction, and was a step requiring significant effort in the disturbance analysis process that has been semi-automated to save time. Manual analysis of the automated minke whale tracks also needed to be performed prior to detailed reporting to correct potentially false positive, combined, and/or split whale tracks. The semi-automated ship position correction scheme is as follows. Since ship positional data should be updated on the order of once a second, if a time difference between updates exceeded 10 seconds, this difference was automatically detected and the data were temporally segmented. In addition, while accounting for typical speeds of Navy combatant vessels with hull mounted sonar and inherent positional error, if the distance moved threshold was exceeded it was automatically flagged for further investigation. When the distance moved threshold exceeded 400 m, an interactive Matlab program displayed the ship track and data points before and after the errant positions. The program suggested a last known good data point, and at the user’s discretion, the last good position update and the next good data point were selected. The positional data were then linearly interpolated between these points.

Mid-frequency active sonar localization outputs from the C++ algorithm described above (Section 4.2.1) needed to meet additional requirements to be utilized (i.e. minimum number of hydrophones in the localization solution, least-squared error between modeled and actual time of arrival below a threshold, and within the latitude and longitude constraints of the study area). Mid-frequency active sonar localizations were then associated with the processed ship positional data points that occurred closest in time and were within 400 m of the ship. This resulted in augmenting individual ship tracks with times when MFAS was transmitted. Without the MFAS localizations, the times at which sonar signals were transmitted and sonar operating characteristics would not be known, since they are not provided as a standard PMRF range data product. Individual animal tracks were then associated with multiple ship tracks to determine ship-whale geometries. For each animal track, estimated received levels from multiple ships were accumulated over the duration of a track which included 10 minutes before the track started and 10 minutes after the track ended. Received levels and cumulative sound exposure levels were initially calculated using the sonar equation with spherical and cylindrical spreading loss and absorption. When time permitted, received levels were also calculated using Peregrine modeling; as mentioned above (Section 4.2.3.1) the received levels estimated with the sonar equation tend to be accurate for direct path ranges and provide a good initial value until Peregrine modeling can be completed. Results for every animal track were then automatically generated in plots and a summary report of fundamental statistics (e.g. Figure 18, Table 3, and Table 4 below).

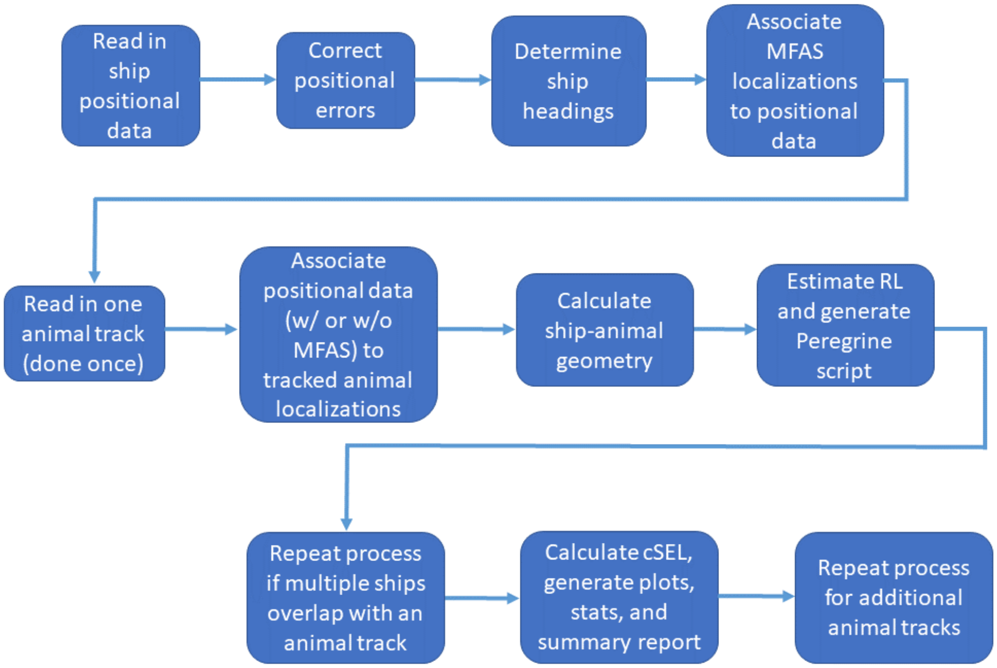


Figure 4: Overview of processes to automatically perform disturbance analysis for a single animal track.

4.2.4 Noise Analysis

In November 2017, the DCLTDE laboratory began working on a noise analysis for PMRF acoustic data. The goal is to characterize noise in relevant frequency bands of interest, and look for changes in noise over a wide variety of spatial and temporal scales. Ocean noise is an important parameter that is often overlooked in marine mammal acoustic analyses. Ocean noise can affect the probability of detecting a marine mammal signal, and therefore can influence the number of localizations recorded (and possibly the number of tracks counted). The DCLTDE Laboratory has chosen a study area in which signals should have enough SNR so that tracks are counted consistently through most ocean noise conditions, but a detailed analysis has not yet been conducted. Additionally, ocean noise can influence marine mammal behavior, and so characterizing ocean noise before, during, and after Navy training exercises will be important for behavioral response analyses.

5 Results and Discussion

Many of our FY17 goals in assessing baseline occurrence and abundance (short- and long-term) were accomplished and are presented here. First, baleen whale metrics are now being generated for counts of individual calling whales, as compared to prior metrics of the number of localizations, or calls, per hour. This allowed us to estimate minimum abundances of calling whales both for FY17 and for historical data from 2007-2016. Second, the improvements to the beaked whale detection process have improved the probability of detecting Blainville's beaked whale foraging clicks with reduced false positives, and Cross Seamount beaked whale type foraging click detections are now being separated out with good performance in terms of probability of detection and reduced false positives. This allowed us to process data for both species for FY17, will enable us to process 2007-2016 data for both species in the future, and will improve future reporting of statistical metrics for various parameters (e.g. duration, sweep rate, start frequency, click intervals). Third, improvements to the killer whale high frequency modulated click detection allowed us to process multiple years of data from 2006-2017 and report their abundance. Fourth, work has begun on improvements to the sperm whale detection and reporting process, although their abundance from 2006-2017 is presented herein as a first look at the data. Finally, a new noise analysis has helped identify unknown periods of "off – effort" due to periods of missing hydrophone data while having valid IRIG data, and is being implemented as a standard processing component and metric. Processing of historical data back to 2003 has some challenges in terms of what species can be detected in older data due to lower sample rates and bandwidths, as well as for direct comparison with newer data due to different hydrophone locations and capabilities. For example, detecting and classifying the low frequency baleen group was not possible until late 2010/early 2011 when the 41 new BSURE replacement hydrophones were installed with capabilities for processing frequencies under 100 Hz (as low as 20 Hz but with reduced output due to high pass filtering). Likewise, earlier recordings with a 44.1 kHz sample rate (data from 2003 – 2005) have insufficient bandwidth (maximum 22 kHz) to detect beaked whale foraging clicks and require modifying current algorithms (designed for full band 96 kHz sample rate) to detect sperm whale clicks and killer whale high frequency modulated calls. This is due to frequency band ratios being utilized in full band (96 kHz sample rate or 48 kHz maximum bandwidth) data for comparing in-band data with out of band data. These modifications to our algorithms were not accomplished in FY17, but will be undertaken in FY18 in order to analyze as much historical data as possible.

We also achieved our goals related to estimating received levels and assessing behavior responses of marine mammals to SCC training events. Propagation models using the Peregrine algorithm were tested and improved, increasing our received level estimation capabilities. The detection analysis algorithms developed through the ONR BREVE effort were applied to the February 2017 SCC training event data to detect behavioral and vocal responses by individual minke whales, as well as assessing overall changes in occurrence patterns. When individual whales experienced repeated exposures to periods of MFAS, the cumulative SEL and potential behavioral effects could also be evaluated. These initial analyses will be extended in the future to additional species and training events, leading to a powerful assessment of behavioral responses via passive acoustic monitoring.

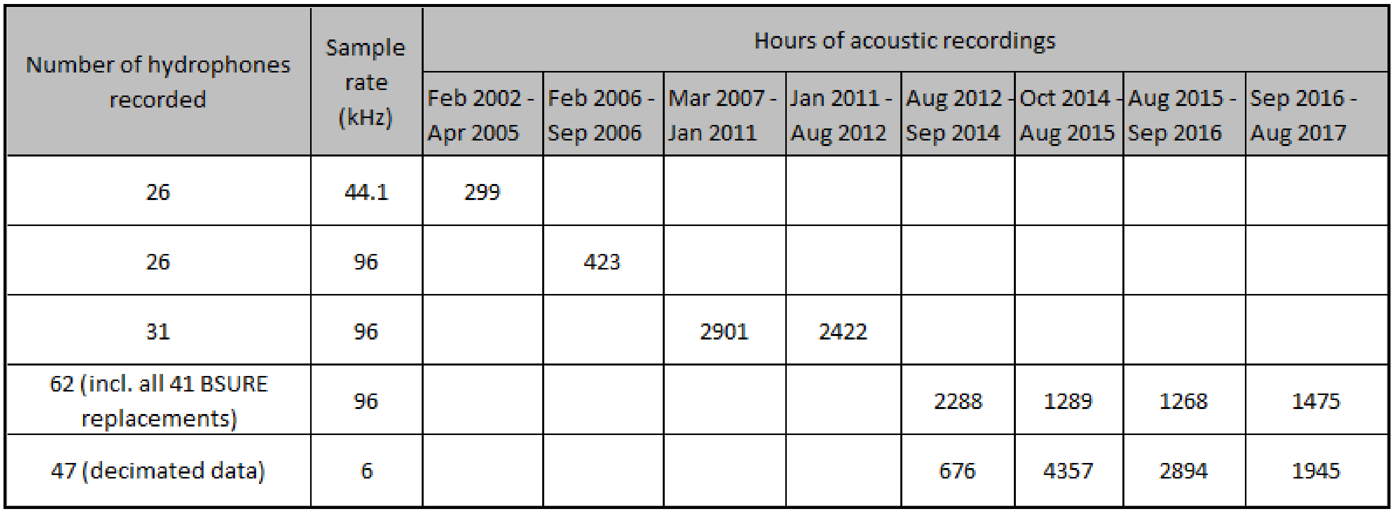
5.1 PMRF Range Data Collection Results

The hours of recorded data collected since initial efforts in 2002 are summarized through August 26, 2017 in Table 1. The hours of recordings for different periods highlights the amount of data collected under varying conditions (e.g. different hydrophone configurations and number of channels recorded, and changes to data collection and recording equipment). In addition, the number of hours of recordings utilized in FY15 (October 2014-August 2015), FY16 (August 2015-September 2016), and FY17 (September 2016-August 2017) reporting are segmented to highlight trends in recent efforts for comparison.

As a broad overview, data collection efforts prior to 2006 were conducted on a limited basis by an ONR effort coinciding with aerial surveys for marine mammals associated with the North Pacific Acoustic Laboratory program, and the first few years of that effort are described in Mobley (2005). Data collections from 2006 and onward had a goal of recording at least 24 hours of full-bandwidth 96 kHz sample rate data during two separate periods a month, which is evident as an increase in the number of hours of recordings in Table 1. Starting in February 2011, classified data were collected during SCCs to investigate potential impacts of MFAS utilized during Navy training on marine mammals. The SCC is held biannually in February and August, during which personnel from the DCLTDE laboratory are present to collect near continuous full bandwidth recordings. This ensures that all data before, during, and after the SCC are collected to better study and understand any potential impacts of MFAS utilized during Navy training. In August 2012, the number of hydrophones recorded increased from 31 to 62. Since August 2014, decimated data at a 6 kHz sample rate have been collected on 47 broadband hydrophones and has resulted in an increase in the number of hours of recordings for baleen whale analyses.

There was an increase in the number of hours of full bandwidth data collected in FY17 compared to FY16 (200 more hours than last year). Although decimated data was recorded in the latter half of FY17, it was not received until after the analyses were conducted herein and therefore is not reflected in the presented results in Section 5.3 and Section 5.4, but all hours of recording effort from FY17 are in Table 1.

Table 1: Approximate number of hours of multiple channel hydrophone data since data collections started in 2002.



Number of hydrophones recorded	Sample rate (kHz)	Hours of acoustic recordings							
		Feb 2002 - Apr 2005	Feb 2006 - Sep 2006	Mar 2007 - Jan 2011	Jan 2011 - Aug 2012	Aug 2012 - Sep 2014	Oct 2014 - Aug 2015	Aug 2015 - Sep 2016	Sep 2016 - Aug 2017
26	44.1	299							
26	96		423						
31	96			2901	2422				
62 (incl. all 41 BSURE replacements)	96					2288	1289	1268	1475
47 (decimated data)	6					676	4357	2894	1945

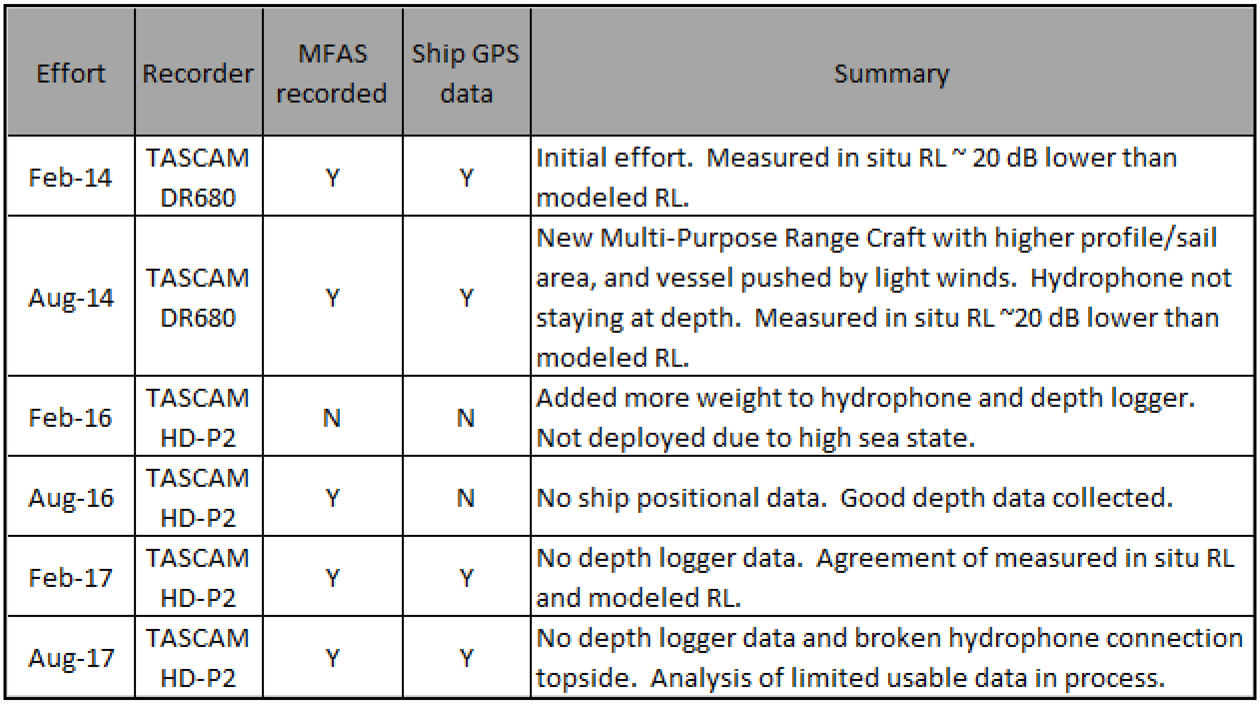
5.2 Opportunistic Surface Hydrophone Data Results

A systematic in-depth analysis of the surface acoustic data collected during the February 2017 SCC has been performed, and an analysis of the August 2017 SCC training event surface acoustic data is in process. Overall, measurements in February 2017 agree well with Peregrine estimates. A total of 19 MFAS pulses were sampled from a 46 minute long data file and analyzed. Multiple pulses clustered in time were analyzed to obtain an average received level for comparison with an average Peregrine modeled received level. Each Peregrine modeled received level had a low (<0.08 dB re: 1μPa) standard deviation and agreed well with the in situ measurements.

Data collected in August 2017 are currently in the process of being analyzed. Only one data file recorded in August 2017 contains good MFAS signals for analysis. All other recordings do not contain any data due to a broken connection from the hydrophone to the recorder, which has since been repaired. In addition, ship positional data during the time of the good recording were not initially delivered from PMRF, which delayed analysis. However, this has been resolved with range support personnel and the positional data have been delivered to SSC Pacific. Analysis of August 2017 recordings will be conducted in early CY18.

Usable acoustic data with MFAS signals were collected in August 2016 (Table 2); however, ship positional data were not recorded during the time the acoustic data were recorded. Efforts were made in FY17 to obtain ship positional data from PMRF and the U.S. Coast Guard so the August 2016 could be analyzed, and in the event ship positional data become available, the August 2016 data will be analyzed. Analysis of the February and August 2014 data had a lower received level than those modeled in Peregrine. This was due to the hydrophone being too close to the surface where the signal was attenuated by bubbles and surface turbulence, and has since been fixed as mentioned in Section 4.1.2.

Table 2: Summary of near surface in situ data collection efforts to date



Effort	Recorder	MFAS recorded	Ship GPS data	Summary
Feb-14	TASCAM DR680	Y	Y	Initial effort. Measured in situ RL ~ 20 dB lower than modeled RL.
Aug-14	TASCAM DR680	Y	Y	New Multi-Purpose Range Craft with higher profile/sail area, and vessel pushed by light winds. Hydrophone not staying at depth. Measured in situ RL ~20 dB lower than modeled RL.
Feb-16	TASCAM HD-P2	N	N	Added more weight to hydrophone and depth logger. Not deployed due to high sea state.
Aug-16	TASCAM HD-P2	Y	N	No ship positional data. Good depth data collected.
Feb-17	TASCAM HD-P2	Y	Y	No depth logger data. Agreement of measured in situ RL and modeled RL.
Aug-17	TASCAM HD-P2	Y	Y	No depth logger data and broken hydrophone connection topside. Analysis of limited usable data in process.

5.3 FY17 Abundance Results

Results from the latest fiscal year data collection (i.e. October 2016 to end of September 2017) are reported separately from long-term abundance results to highlight the newest data results, and because some species have only been analyzed for this year at this time. Data from January 2011 to August 2012 consisted of 31 hydrophone data, so direct comparison to 62 hydrophone data from 2012-present can only be done by processing the subset of the 62 hydrophones that were available. The spatial locations and capabilities of the older BSURE hydrophones (used between March 2007 and January 2011) does not allow direct comparison with data collected from the new BSURE hydrophones used from January 2011 and later, however normalization factors can be applied in an effort to compare results.

5.3.1 Baleen Whale Abundance (2016-2017)

The number of calling minke, humpback, and low-frequency baleen whales via systematic snapshot analyses every 10 minutes are provided in Figure 5, Figure 6, and Figure 7 respectively (blue lines). The results presented herein as the number of individually tracked baleen whales is a different metric than localizations per hour as previously reported (Martin et al., 2016, 2017). Semi-automated tracking and snapshotting processes described in Section 4.2.2 have significantly reduced the time and effort required to obtain the more stable metric of individually tracked animals. This allows conducting an analysis of relative minimum abundances of vocalizing whales on PMRF. Two longer gaps are apparent in recorded data from 08 December 2016 to early 10 January 2017 and 19 February to 10 March 2017. The first gap was due to a failure of the original data disk, this has occurred on the order of three times over the past dozen years, which could be partially addressed in the future if PMRF personnel were to immediately examine recorded disks, and if any disk errors occur, a new recording could be collected so as to not lose data. The second apparent gap from 19 February to 10 March was due to a three week period between recordings, although both February and March 2017 had over two days a month recorded. This will be discussed with PMRF personnel who conduct the majority of recordings to reduce data gaps.

Of the baleen whales tracked at PMRF, vocalizing minke whales have the highest abundance and frequency of occurrence, while singing humpback and other vocalizing low-frequency baleen whales have a lower abundance and are tracked less frequently. Note that the ratio of calling animals to all animals is variable and unknown for these species while in Hawaii, so the number of vocalizing animals relative to the total number of animals present is unknown and can only be estimated. The vast majority of these baleen whale species' calls being detected have been shown, or are assumed, to be from males and related to breeding. The proportion of humpback males singing at any given time is variable from season to season and low relative to the total number of males present (e.g., 172 singers recorded out of 2091 whales observed (8%) migrating past the east coast of Australia [Noad et al. 2017]). In addition, there are typically twice as many males than females present in Hawaii, and approximately half of the females will have calves (Craig and Herman 1997). Therefore if a population of 1000 animals is assumed present, about 572 animals would be male, 286 would be female, and 143 would be calves. If 8% of the male whales are singing at a given snapshot period, then only 46 of the 1000 animals present would be counted using the acoustic tracks as the abundance metric. The number of calling minke whales is even less well known. These calculations are beyond the scope of this report, but are worth keeping in mind when looking at the following results. It also is important to remember that the majority of the hydrophones with the necessary frequency response for detecting these baleen whales (broadband BSURE hydrophones) are located offshore in typically 4 km water depth. In the nearshore areas (e.g. Southern BSURE and BARSTUR) there are fewer broadband hydrophones and the shallower nearshore environment has considerable environmental background noise. Localizing and tracking humpback whales are especially difficult in this nearshore environment due a lower SNR and the high density of humpback whale calls. Higher densities of singing humpback whales are known to occur inshore (Frankel et al. 1995); it is unknown what the typical distributions are for vocalizing minke and other low-frequency baleen whales, as these species have been observed both within 70 km of shore and well offshore (Mobley et al. 1996; Smultea et al. 2010; Rankin and Barlow 2005; Rankin et al. 2007) but are rarely observed nearshore.

Automated snapshot analyses for FY17 for minke, humpback, and other low-frequency baleen whales shows a clear seasonal presence, with the maximum number of individual whales present and calling on the PMRF range at one time up to 13 minke whales, 4 low frequency baleen whales, and 2 humpback whales. Minke whales are present from late October to early May, humpbacks are present from early November to late April, and other low-frequency baleen whales are generally present late October to early April. Although not present in Figure 7, some peaks for low-frequency baleen whale localizations that have occurred out of the expected seasonal trend for migratory baleen whales have in the past corresponded to the presence of Bryde’s whales, which may be present year round (Martin and Matsuyama 2014, Helble et al. 2016). Interestingly, both minke and humpback whale abundances peak in February to late March, while the low-frequency baleen whales appear to peak earlier in the year (November and January in FY17).

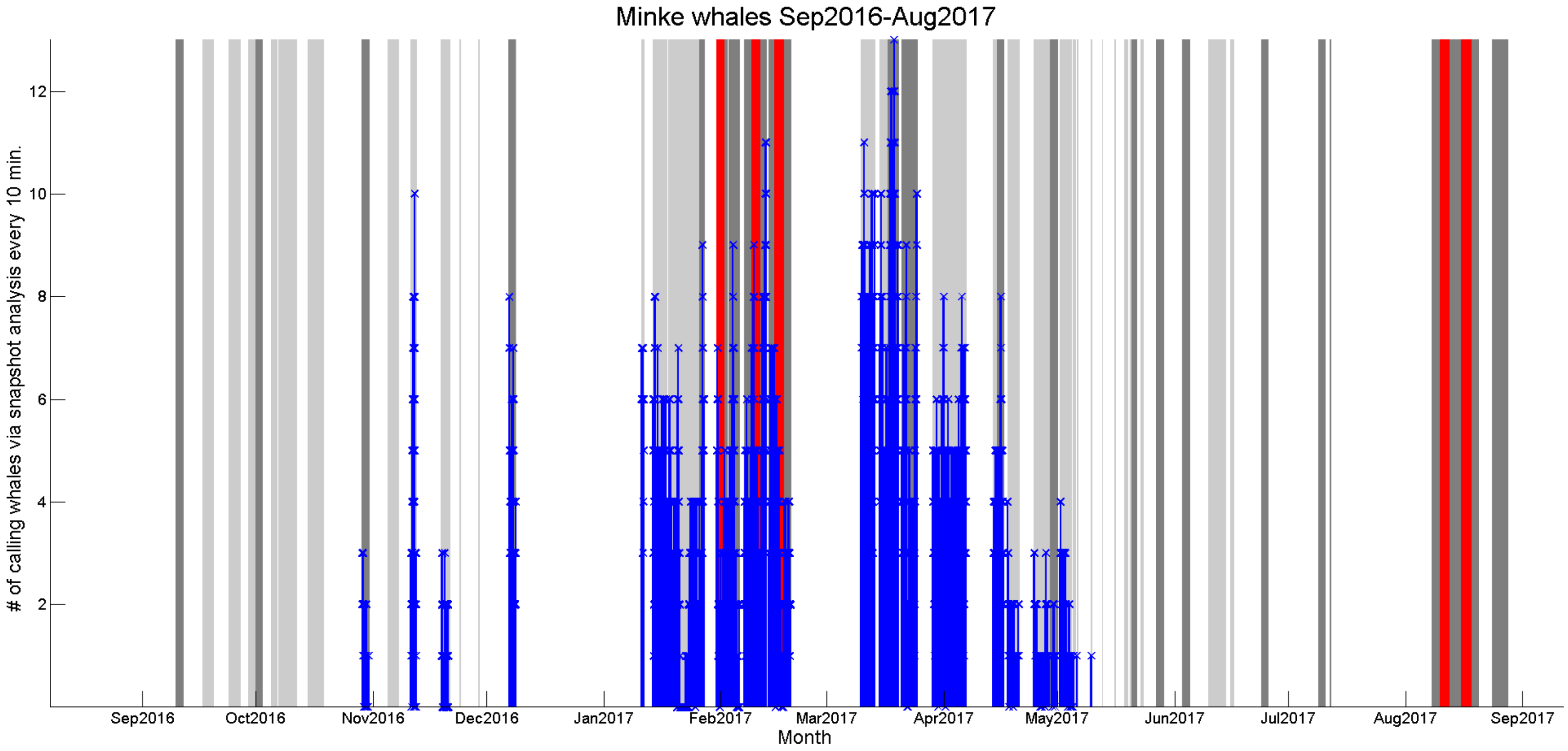


Figure 5: The number of automatically tracked individual calling minke whales in 10 minute snapshots from Sep 2016 to Aug 2017. The counts of whales in each snapshot are indicated by blue markers. Gray shaded regions indicate availability of full bandwidth data (dark gray) or decimated data (light gray). White indicates periods of time when no data were collected. Red shaded regions indicate when classified full bandwidth data were collected, typically during the Feb and Aug SCC training event, and highlights abundance during known training activity. The red bar at the end of Jan 2017 indicates a classified data collection during a separate training event. The first red bar in each pair in Feb and Aug corresponds to the first phase of the SCC that does not utilize hull mounted MFAS, while the second red bar corresponds to the second phase of the SCC that does utilize hull mounted MFAS. The time between the first and second phase of the SCC are separated by an unclassified data collection that typically corresponds to a weekend. Regions that are shaded gray or red, but do not have blue bars, indicate that zero whales were tracked during that time.

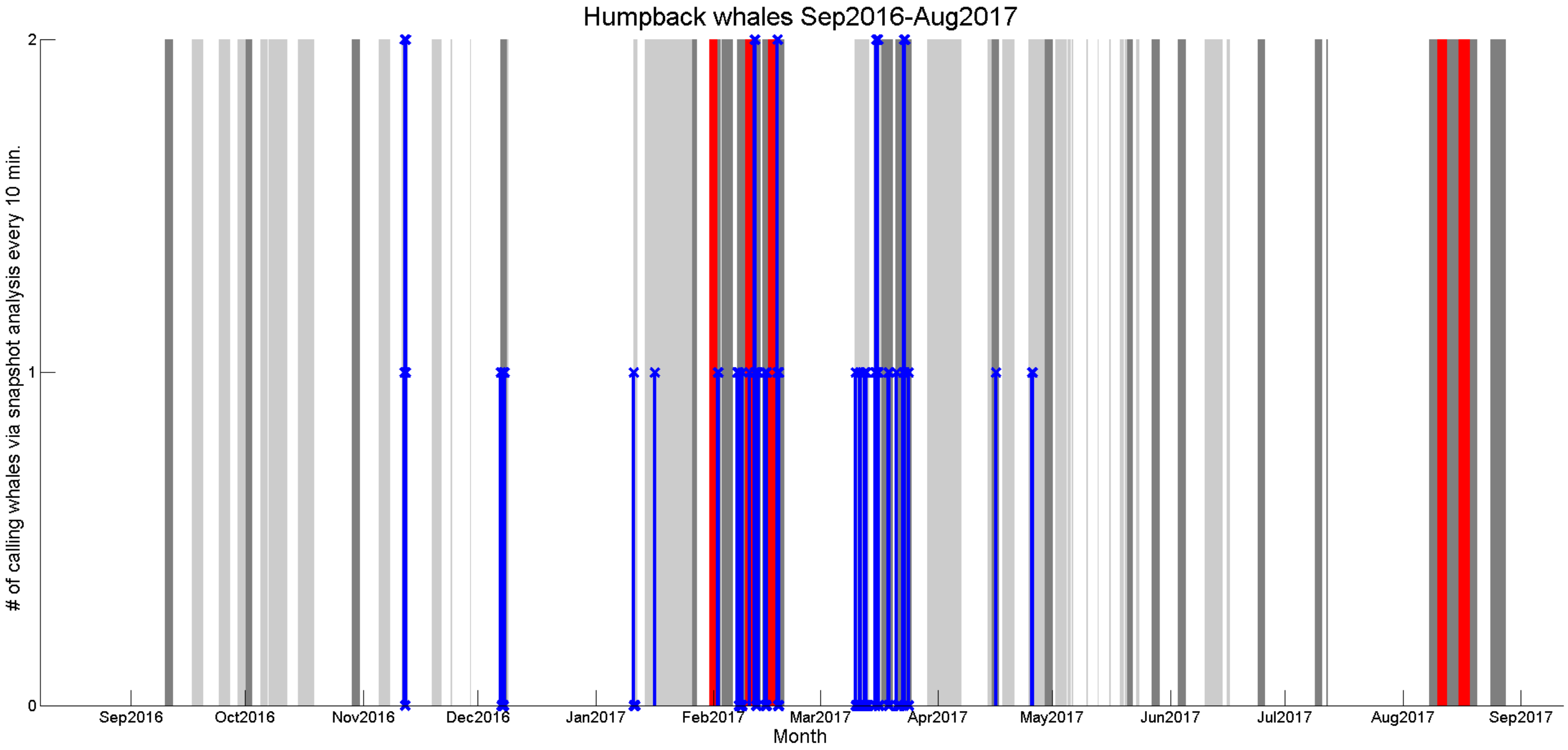


Figure 6: The number of automatically tracked individual singing humpback whales in 10 minute snapshots from Sep 2016 to Aug 2017. The counts of whales in each snapshot are indicated by blue markers. Gray shaded regions indicate availability of full bandwidth data (dark gray) or decimated data (light gray). White indicates periods of time when no data were collected. Red shaded regions indicate when classified full bandwidth data were collected, typically during the Feb and Aug SCC training event, and highlights abundance during known training activity. The red bar at the end of Jan 2017 indicates a classified data collection during a separate training event. The first red bar in each pair in Feb and Aug corresponds to the first phase of the SCC that does not utilize hull mounted MFAS, while the second red bar corresponds to the second phase of the SCC that does utilize hull mounted MFAS. The time between the first and second phase of the SCC are separated by an unclassified data collection that typically corresponds to a weekend. Regions that are shaded gray or red, but do not have blue bars, indicate that zero whales were tracked during that time.

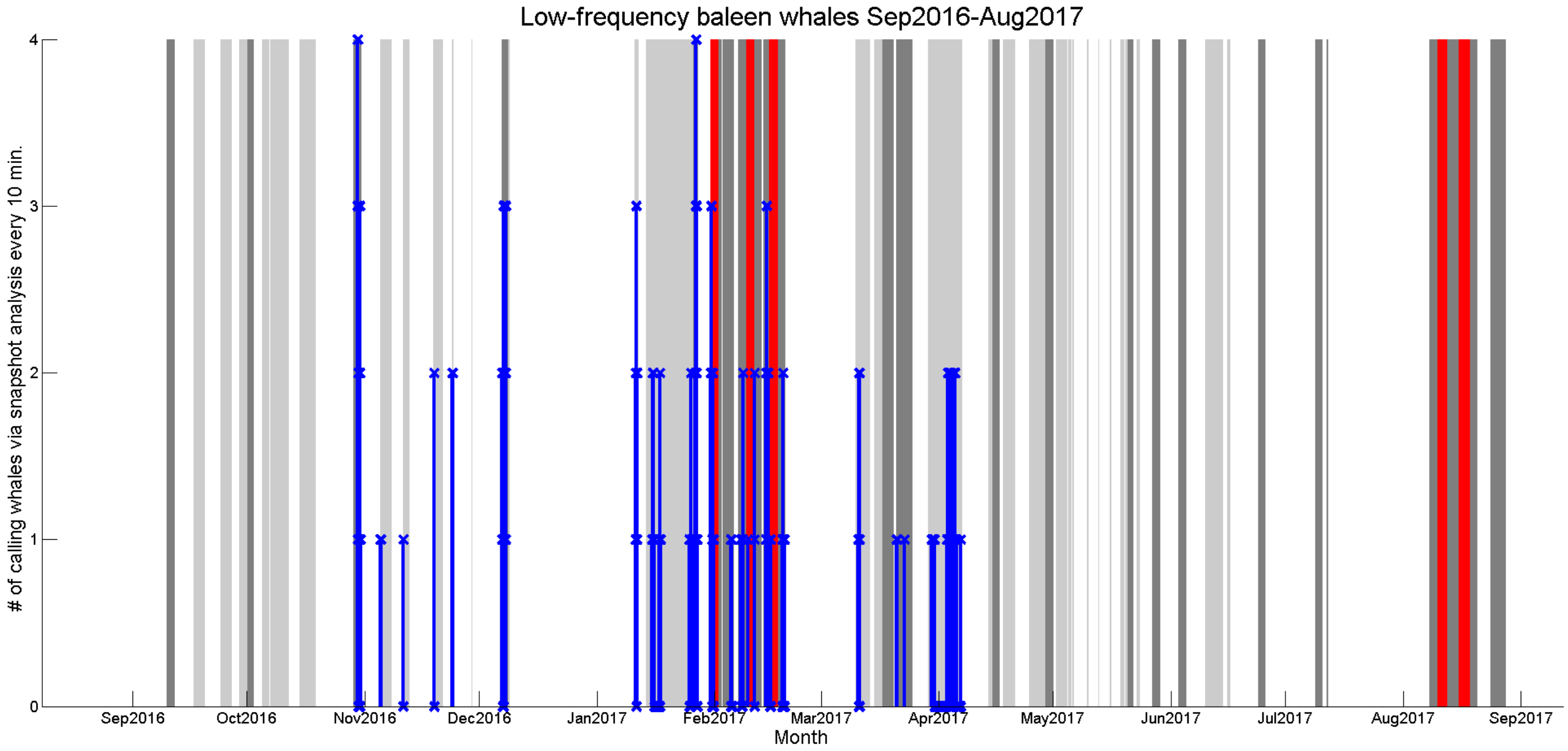


Figure 7: The number of automatically tracked low-frequency calling baleen whales (fin/sei/Bryde's combined) in 10 minute snapshots from Sep 2016 to Aug 2017. The counts of whales in each snapshot are indicated by blue markers. The counts of whales in each snapshot are indicated by blue markers. Gray shaded regions indicate availability of full bandwidth data (dark gray) or decimated data (light gray). White indicates periods of time when no data were collected. Red shaded regions indicate when classified full bandwidth data were collected, typically during the Feb and Aug SCC training event, and highlights abundance during known training activity. The red bar at the end of Jan 2017 indicates a classified data collection during a separate training event. The first red bar in each pair in Feb and Aug corresponds to the first phase of the SCC that does not utilize hull mounted MFAS, while the second red bar corresponds to the second phase of the SCC that does utilize hull mounted MFAS. The time between the first and second phase of the SCC are separated by an unclassified data collection that typically corresponds to a weekend. Regions that are shaded gray or red, but do not have blue bars, indicate that zero whales were tracked during that time.

5.3.2 Beaked Whale Abundance (2016-2017)

The number of automatically grouped beaked whale group foraging dives, normalized per hour over the duration of each dataset, are provided for Blainville's (Figure 8) and CSM (Figure 9) beaked whales, respectively. A reminder that 6 kHz decimated long-term data recordings, as previously shown in the baleen whale abundance figures, are not included in these plots since those data recordings have insufficient bandwidth to detect beaked whale clicks.

Four datasets from FY17 that contained automatically grouped Blainville's beaked whale group foraging dives were randomly selected and manually validated to characterize Baseline 4 processed results, since considerable changes were made to the beaked whale detectors as described in Section 4.2.1. Overall, for FY17 using Baseline 4 processing, 86.3% of automatically grouped dives were composed of Blainville's beaked whale clicks, while 3.1% of the dives were composed of false positive clicks, 0.3% of the dives had false negative (i.e. missed) clicks, and 10.4% of the dives were composed of a mix of Blainville's beaked whale clicks (majority) and false positive clicks. For this subset of validated data, the total number of validated dives was the sum of dives composed of Blainville's beaked whale clicks and dives composed of mixed detections of Blainville's beaked whale clicks and false positive clicks (Figure 8) resulting in a true positive rate of 96.4%, a false positive rate of 3.6%, and a false negative rate of 0.3%. These four datasets represented 179.3 hours of acoustic data and contained 373 validated true positive dives, 12 validated false positive dives, and 1 validated false negative dive, which equates to 2.1 validated true positive dives per hour. These results compare well to published manually validated baseline results from August 2012 to December 2013 that had a mean of 2.1 dives per hour (Henderson et al., 2016) and baseline results before the February 2012 SCC that had 1.7 dives per hour (Manzano-Roth et al., 2016). Between both studies there is support for the stability of Blainville's beaked whale foraging dives during baseline conditions over a span of at least 5 years.

The results presented in prior reports (Martin et al., 2016; 2017) exhibited a similar trend of year-round presence of Blainville's beaked whales at PMRF, with large inter-annual differences that follow no seasonal pattern. In the FY17 data (Figure 8), there was an average of 2.2 Blainville's beaked whale foraging dives per hour automatically detected (min = 0.3, max = 4.6, st dev = 1). Compared to FY16 (average = 2.1, min = 0, max = 6.4, st dev = 1.7) and FY15 (average = 1.4, min = 0, max = 6.7, st dev = 1.6), there is an overall fairly consistent number of automatically grouped dives per hour in the last three years. Data from 2007 through 2017 can now be processed for Blainville's beaked whales to begin examining long-term trends in abundance and to estimate density.

The CSM beaked whale dives (Figure 9) were automatically grouped and, due to their low abundance and a slightly higher false positive rate than for Blainville's beaked whale detections, all group dives were manually validated. There is almost an order of magnitude fewer CSM dives than there are Blainville's beaked whale dives per hour (average = 0.12, min = 0, max = 0.6, st dev = 0.14). In FY17, CSM beaked whale group dives were also detected year-round, with wide inter-annual differences in presence. In the past, recorded data have not been processed specifically for CSM beaked whales, and their group dive abundance has not been provided in prior annual reports, although their clicks (Figure 10) have been documented and investigated at PMRF (See Manzano-Roth et al. 2013). Future data collections and data prior to FY17 can now be processed for CSM beaked whale clicks and automatically grouped to examine long-term abundances and trends. CSM clicks are characterized by longer durations than Blainville's beaked whale clicks, with lower start frequencies, broader bandwidth, and slower sweep rates. When grouped into dives, fewer dives per hour are typically detected and the inter-click-intervals are shorter than Blainville's and Cuvier's beaked whales and more variable. As this is a new capability, future reporting will provide some standardized metrics for this species. It is unclear if this is a different species of beaked whale or one of the known beaked whales utilizing other types of echolocation clicks for different prey or in different contexts.

Blainville's beaked whales foraging dives per hour have been observed to decrease during the first part of the SCC training event, increase slightly over the weekend, and then decrease to their lowest extent during the second, MFAS portion of the training event (Figure 8; Manzano-Roth et al. 2016). In contrast, the CSM click detections actually appear to increase at the end of the first portion of the training event (Figure 9), then decrease over the weekend and increase again slightly during the periods of MFAS. It is unknown why this slight increase may occur; a more detailed look at the phone locations, water depth, and time of day of CSM clicks compared to Blainville's beaked whale clicks will be conducted to explore this further. . This trend will be explored further as the long term data is analyzed for both species.

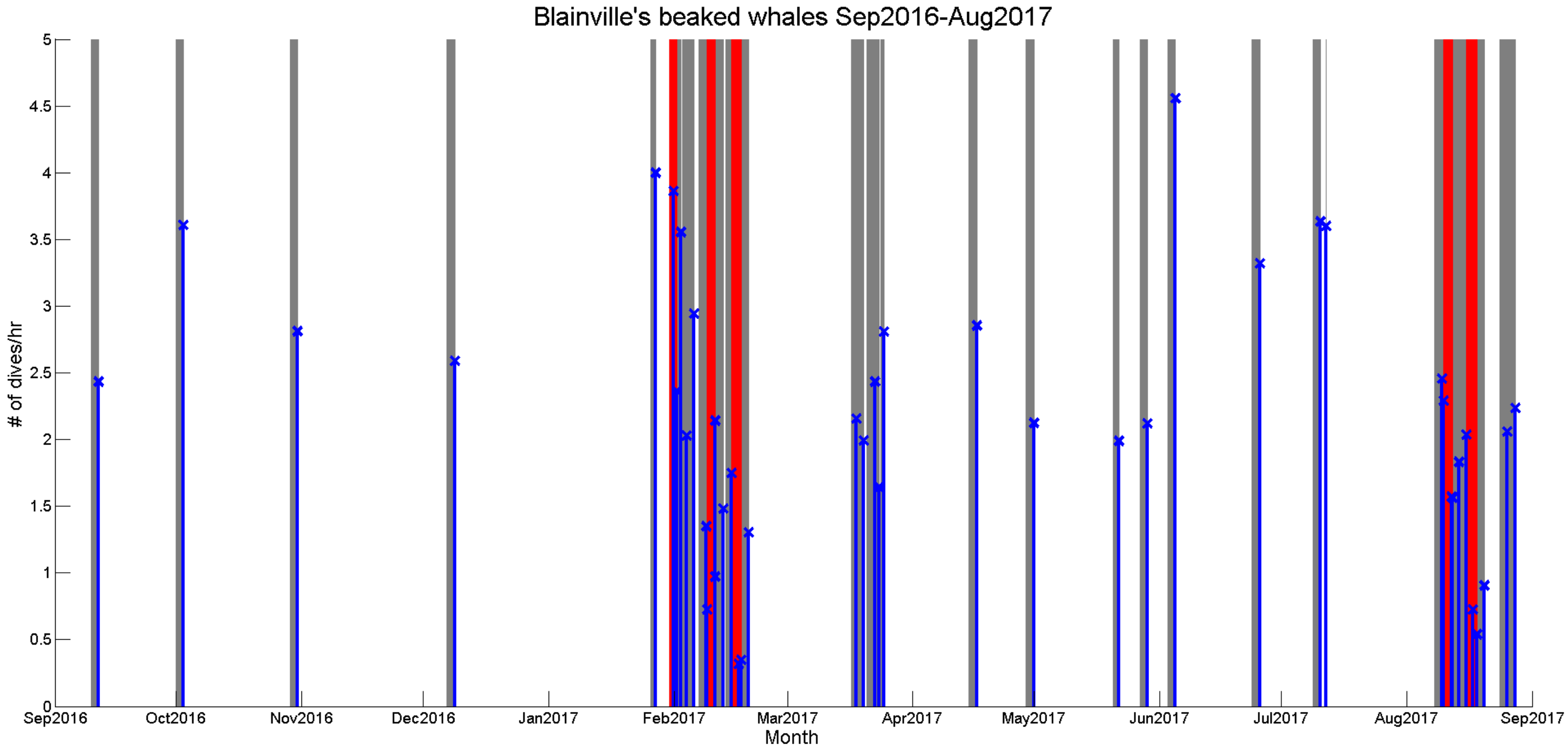


Figure 8: Results of the number of automatically grouped and manually sorted Blainville's beaked whale group foraging dives per hour Sep 2016 to Aug 2017. Gray shaded regions indicate availability of full bandwidth data (dark gray). Decimated data collections are not shown due to insufficient bandwidth for processing beaked whale clicks. White indicates periods of time when no full bandwidth data were collected. Red shaded regions indicate when classified full bandwidth data were collected, typically during the Feb and Aug SCC training event, and highlights abundance during known training activity. The red bar at the end of Jan 2017 indicates a classified data collection during a separate training event. The first red bar in each pair in Feb and Aug corresponds to the first phase of the SCC that does not utilize hull mounted MFAS, while the second red bar corresponds to the second phase of the SCC that does utilize hull mounted MFAS. The time between the first and second phase of the SCC are separated by an unclassified data collection that typically corresponds to a weekend. Regions that are shaded gray or red, but do not have blue bars, indicate that zero whales were tracked during that time.

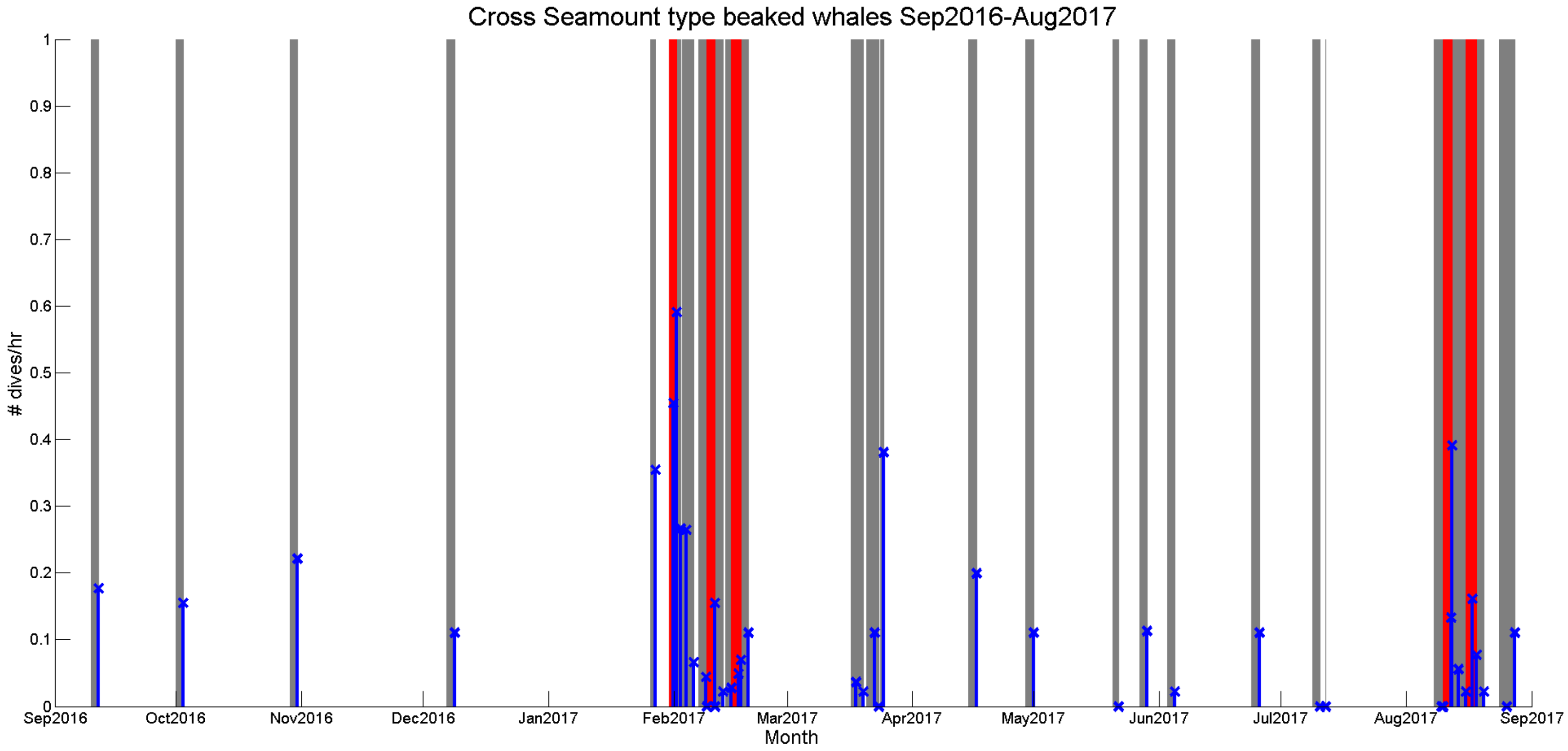


Figure 9: Results of the number of validated and grouped Cross Seamount-type beaked whale dives per hour Sep 2016 to Aug 2017. Gray shaded regions indicate availability of full bandwidth data (dark gray). Decimated data collections are not shown due to insufficient bandwidth for processing beaked whale clicks. White indicates periods of time when no full bandwidth data were collected. Red shaded regions indicate when classified full bandwidth data were collected, typically during the Feb and Aug SCC training event, and highlights abundance during known training activity. The red bar at the end of Jan 2017 indicates a classified data collection during a separate training event. The first red bar in each pair in Feb and Aug corresponds to the first phase of the SCC that does not utilize hull mounted MFAS, while the second red bar corresponds to the second phase of the SCC that does utilize hull mounted MFAS. The time between the first and second phase of the SCC are separated by an unclassified data collection that typically corresponds to a weekend. Regions that are shaded gray or red, but do not have blue bars, indicate that zero whales were tracked during that time.

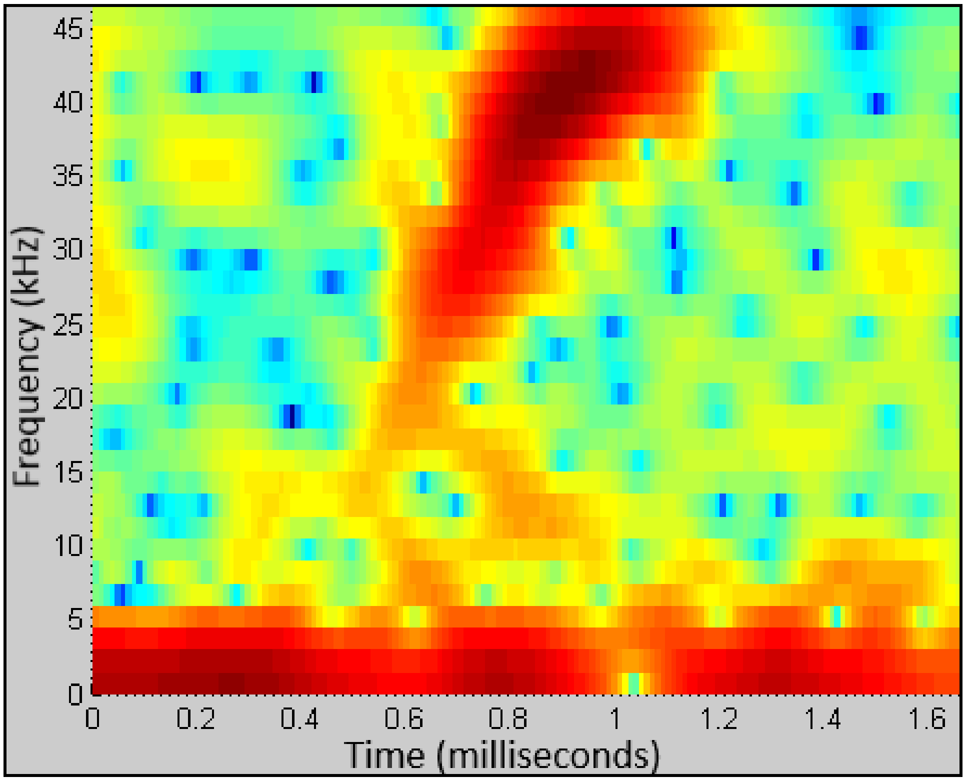


Figure 10: Spectrogram of an example CSM click. Energy from the FM sweep starts at ~17 kHz and extends beyond 48 kHz. The duration of the data displayed is approximately 1.6 milliseconds.

5.4 Long Term Abundance Results

Long term abundance estimates based on automated analyses of data collected between March 9, 2007 and the end of December 2010 are provided using the new metric of numbers of individual whales present in each 10 minute snapshot for minke (Figure 11) and humpback whales (Figure 12). Due to the frequency response of the hydrophones utilized during this time, calls under 100 Hz from fin/sei/Bryde's whales were not detectable prior to 2011.

Long term abundance estimates are provided for the first time for sperm whales (in localizations per hour) and killer whales (in groups per hour) between March 2007 and August 2017. During MFAS training these detectors have false positives which currently require manual verification efforts significantly more onerous compared to baseline periods, and are not presented herein. Detectors for the other blackfish have not yet been developed; those results will be presented as new detection and classification algorithms are developed. It is important to note that the results for the 11-year analyses of sperm whale localizations and killer whale groups are not directly comparable across the whole time span, largely due to varying hydrophone locations, specifications, and array configurations (e.g. Section 4.1). Data collected between March 9, 2007 and January 11, 2011 used the old array of 18 broadband hydrophones in two lines (A-B strings), data collected between January 20, 2011 and August 18, 2012 did not use the 18 A-B string hydrophones and were collected on 18 broadband BSURE replacement hydrophones with a broader frequency response. Data collected from August 22, 2012 to present utilized an additional 23 broadband BSURE replacement hydrophones (41 broadband BSURE replacement hydrophones total) and allow for better localization since they have closer spacing. These 41 BSURE replacement hydrophones can be directly compared to the 18 BSURE replacement hydrophones by only utilizing those hydrophones at the expense of spatial coverage and/or localization accuracy. In addition, data collected during these three different hydrophone configuration periods also recorded on the same additional 7 high-pass (3 on the Shallow Water Training Range [SWTR] and 4 on BARSTUR) and 6 broadband hydrophones (BARSTUR). This information regarding hydrophone configurations with additional detail was originally provided in Martin et al., 2017, and is reiterated here for clarification when interpreting the results from Figure 11 through Figure 15. An increase in effort from February to April in 2009 and 2010 corresponds to when personnel from SCC Pacific were at PMRF directing a sailboat to sight animals that were acoustically localized on a previous ONR project (Norris, 2010).

The number of Blainville's beaked whale automatically grouped dives per hour remains the metric for presenting beaked whale abundance; since this was presented in the FY16 annual report (Martin et al., 2017) and has not changed, it is not presented again. A Cuvier's beaked whale detector was in development at the end of FY17 but was not ready for automated processing; this detector will be tested in FY18. Similarly, the new beaked whale classification algorithms will be applied to the 2007-2016 data for both Blainville's and CSM whales in FY18.

Finally, in FY18, the newer data (January 2011 onward) will be re-processed for all available species with only the older 18 hydrophones (or with hydrophones in similar locations) to make historical data (2007-2011) more comparable to the newer data for further long-term analyses. As previously mentioned, for the baleen whales this is only possible for minke and humpback whales, since there was no capability to detect fin/sei/Bryde's calls under 100 Hz prior to January 2011. In addition, given different spatial locations of hydrophones and different equipment capabilities, extrapolation is expected to be necessary rather than direct comparisons.

5.4.1 Baleen Whale Long-Term Abundance (2007-2010)

Minke whale presence and relative abundance from 2007-2010 (indicated by blue vertical bars in Figure 11) continued to exhibit the same fairly consistent and clear seasonal presence in the late fall/winter and early to mid-spring as was observed in FY17. Minke whales appeared to reliably arrive at PMRF in late November or early December, and similarly depart in late April or early

May. While the number of minke whales on the range at any given time varies between 1 and 10 animals, they were detected on every recording during that time period.

The plot for humpback whale abundance from 2007-2010 (indicated by purple vertical bars in Figure 12) highlights the species' late fall/winter and mid to late spring presence at PMRF, again similar to that observed in FY17. The humpback whales do not arrive in the winter off Kauai as consistently as the minke whales appear to do; in these data there is one arrival in October of 2009 but in the rest of the data the whales do not appear until January. They are also less consistently recorded on the range than the minke whales, with several spring recordings having no localizations of humpback whales. Humpback whales may be nearshore during these times but are not monitored because 1) there are fewer broadband hydrophones nearshore which are necessary for detecting humpback whale calls, and 2) higher noise levels in the nearshore environment makes detecting the same call on multiple hydrophones difficult. Humpback whales may arrive at different Hawaiian islands at different times or they may vary their migratory timing based on prey availability on their summering grounds and temperatures on both their wintering and summering grounds (e.g. Johnston et al. 2007; Rasmussen et al. 2007) in addition to their reproductive status, age, and sex (Craig et al. 2003). The variability seen here may be linked to differing arrival times to Kauai, possibly related to changes in temperature across years. Compared to the number of minke whales tracked during this time (Figure 11) it is apparent that calling humpback whales have a lower relative abundance and occurrence in the offshore area monitored at PMRF, while as mentioned previously, humpbacks preferentially occur in nearshore, shallow waters (Frankel et al. 1995; Pack et al. 2017). For example, there was a maximum of 10 minke whales in one snapshot in December 2007 compared to 2 humpback whales in March 2010. We do not know if this represents a true higher abundance of minke whales in Hawaii, or if this just an indication that minke whales vocalize more consistently or frequently than humpback whales in waters offshore of PMRF.

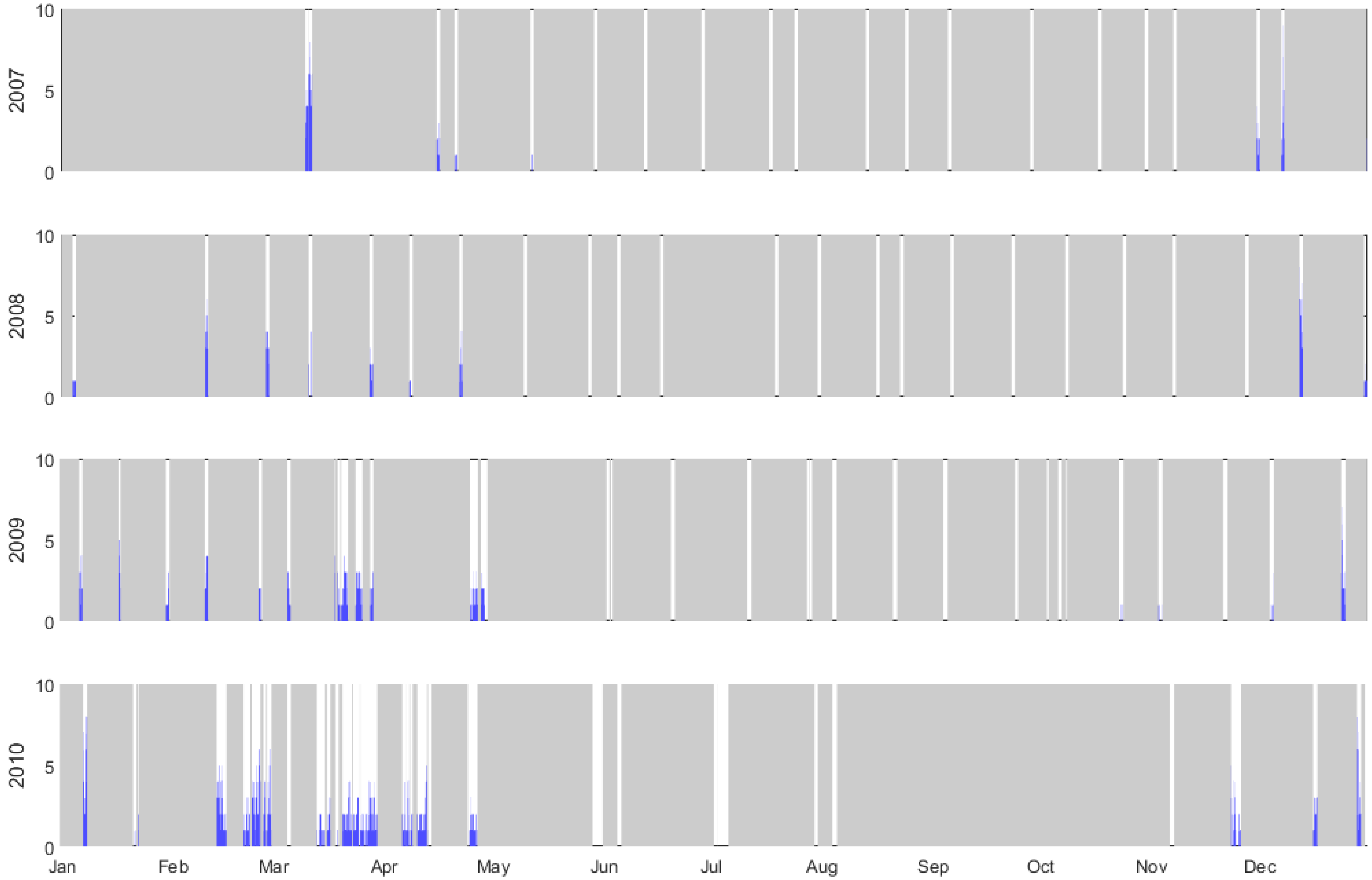


Figure 11: The number of automatically tracked individual calling minke whales in snapshots taken every 10 min in 2007 to 2011 (blue vertical bars). White vertical bars indicate availability of full bandwidth data. Gray shaded space indicates periods of time when no data were collected. Regions that are shaded white but do not have blue bars indicate zero whales. The following values are the maximum number of whale tracks for each year presented above: 2007 (10 tracks); 2008 (8 tracks); 2009 (7 tracks); 2010 (9 tracks).

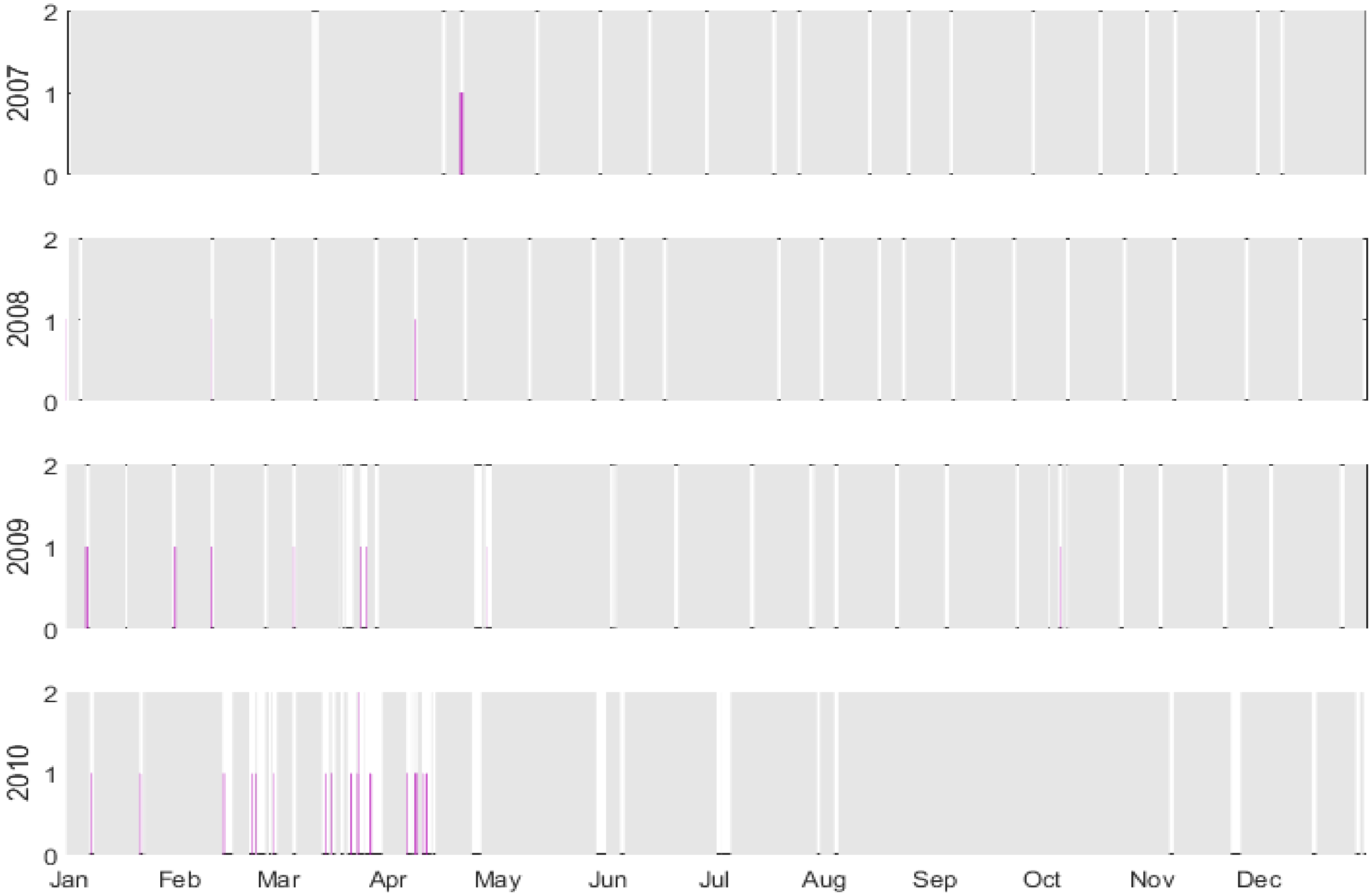


Figure 12: Results of the number of automatically tracked individual singing humpback whales in snapshots taken every 10 min in 2007 to 2011 (purple vertical bars). White shaded regions indicate availability of full bandwidth data. Gray shaded space indicates periods of time when no data were collected. Regions that are shaded white but do not have purple bars indicate zero whales. The following values are the maximum number of whale tracks for each year presented above: 2007 (1 track); 2008 (1 track); 2009 (1 track); 2010 (2 tracks).

5.4.2 Sperm Whale Long Term Abundance (2007-2017)

Figure 13 provides the number of sperm whale localizations per hour between 2007 and 2017 (indicated by black vertical bars). Notice this is the number of un-validated localizations per hour, rather than the number of tracked individuals as is the case for baleen whales. Also, given the high variability in the sperm whale localizations per hour, the vertical axis of Figure 13 is presented on a log scale going from 1 to 100. The higher number of localizations per hour (well over 100 localizations per hour) from 2012 to present are likely due to recording twice as many hydrophones compared to 2007 to 2012, which had detections on the order of tens of localizations per hour. The high variability of sperm whale localizations per hour is shown for March 2008 and 2009 with similar efforts and large differences in localizations per hour. Since sperm whale results from this project’s monitoring efforts have not been presented before, all available results from 2007-2017 are presented.

Sperm whale localizations are present year-round as would be expected from this species; however, there are appreciable false positives from other broadband sources. Efforts are planned in FY18 to refine sperm whale processing to reduce false positives and better characterize the detector. Tracking of sperm whale slow clicks has been previously demonstrated using PMRF data (Tiemann et al., 2006) where the slow clicking suggested a small number (2 in that case) of large bulls traveling. Slow clicks appear to be produced by male sperm whales for breeding purposes and a review of some datasets with a few number of sperm whales producing slow clicks has shown that their localized clicks could be tracked when viewed in an interactive situational display (i.e. C3D). However, when a larger number of sperm whales are aggregating in a foraging group and producing regular echolocation clicks, it may be necessary to report the number of groups (similar to beaked whales) due to difficulties attributing clicks to individuals and tracking individuals when in a group. Dependent on the calling behavior a sperm whale is engaged in, future results could potentially be a combined metric of tracked localizations (similar to baleen whales), and as calling groups (similar to beaked whales and killer whales). However, at this time only a generalized number of localizations per hour is presented, until the detector is improved and these combined metrics can be further explored.

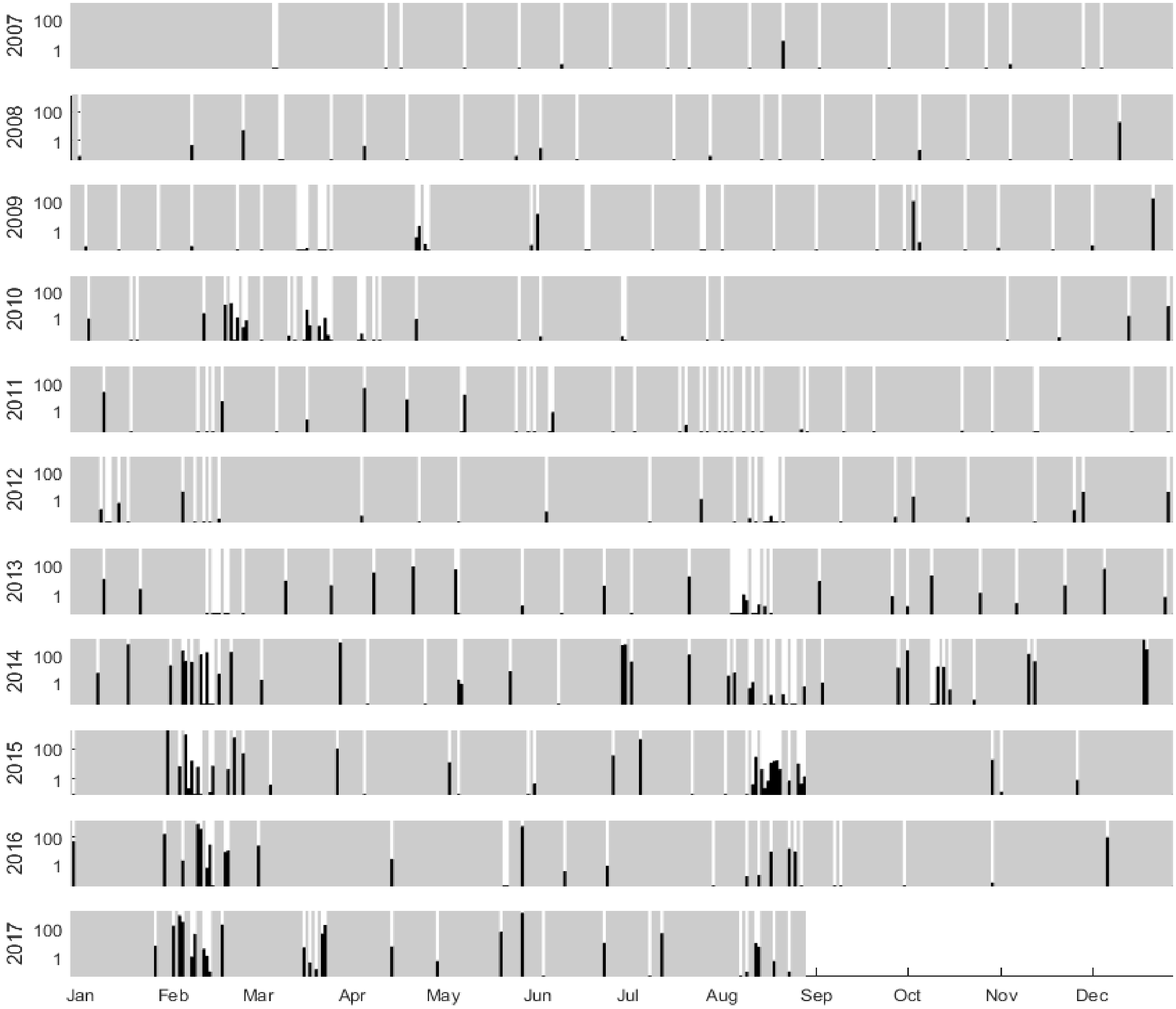


Figure 13: Results of the number of un-validated (i.e. contain false positives) sperm whale localizations per hour from 2007 to 2017 (black vertical bars). White shaded regions indicate availability of full bandwidth data. Gray shaded space indicates periods of time when no data were collected. Regions that are shaded white but do not have black bars, indicates zero localizations per hour. Note that the x-axis in these plots are on a log scale, as the localizations in the earlier data are far fewer than in later data. The following values are the maximum number of localizations per hour for each year presented above: 2007 (3.7 locs/hr); 2008 (18.9 locs/hr); 2009 (174.6 locs/hr); 2010 (13 locs/hr); 2011 (43.14 locs/hr); 2012 (3.8 locs/hr); 2013 (88.4 locs/hr); 2014 (868.2 locs/hr); 2015 (1,587.6 locs/hr); 2016 (903.8 locs/hr); 2017 (1,168.2 locs/hr).

5.4.3 Killer Whale Long Term Abundance (2007-2017)

Figure 15 provides the number of manually verified killer whale HFM calling groups (similar metric as beaked whales) detected from 2007-2017 (indicated by red vertical bars). The results presented here are only for full bandwidth 96 kHz data since the decimated data do not have sufficient bandwidth for the detectable portion of killer whale HFM calls (10-35 kHz). Due to relatively low levels of abundance and occurrence, all automatically grouped killer whale calls were manually verified to contain killer whale HFM calls (Figure 14). Killer whale groups were detected year round, although there may be an increase in occurrence and abundance during the fall and winter months (Figure 15). Since this overlaps in time with migratory baleen whale seasonal presence, it may indicate that killer whales are more active when there is an increase in the supply of a food source. Since killer whales also feed on other odontocetes (e.g. dolphins) that are present year round, this may explain why HFM groups were detected year round, with lower occurrence in the summer months (Baird et al., 2006).

Only a few sightings of killer whales on the PMRF instrumented range have been documented and none have been tagged. A verified HFM call group was acoustically detected on February 10, 2016 (Figure 15). Subsequently, on 14 February 2016 local fishermen reported to R. Baird that they sighted (and provided a photograph) of a single adult killer whale off the east side of Niihau that afternoon (pers. comm. R. Baird). On 7 August 2017, killer whales were acoustically detected just prior to the cessation of calling of a large number of rough-toothed dolphins that had been spread across the range and were acoustically active for several days prior to this. Just after the killer whales were detected, the rough toothed dolphin vocalizations narrowed to a tight cluster, went silent within a few minutes, and then remained quiet for at least a half an hour. The killer whales were acoustically detected again the following day on the northern edge of the range, and then were not detected again during that SCC (Jarvis et al, submitted).

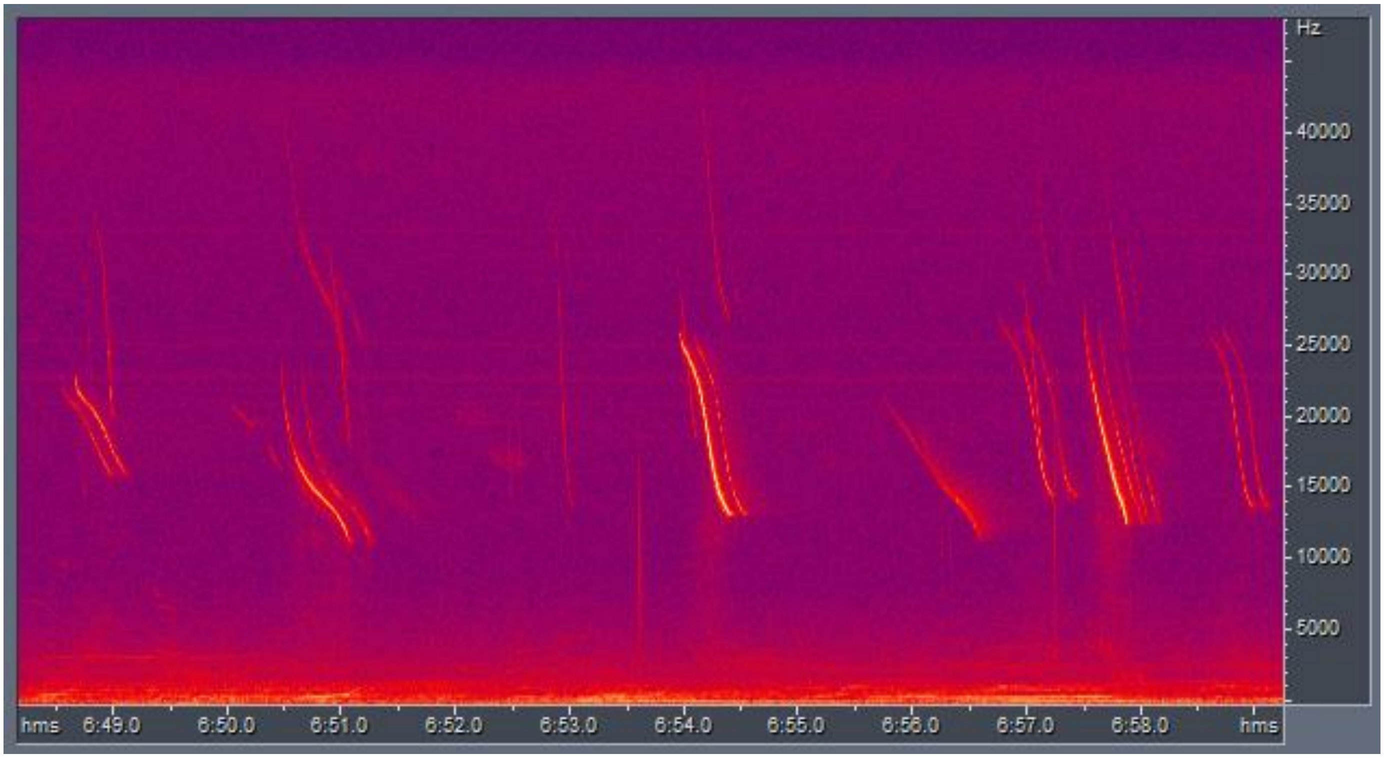


Figure 14: Spectrogram of example killer whale HFM calls in the 10-35 kHz band that are automatically detected and grouped. The duration of the data displayed is approximately 11 seconds.

Figure 15: Results of the number of killer whale call groups from 2007 to 2017 (red vertical bars). White shaded regions indicate availability of full bandwidth data. Gray shaded space indicates periods of time when no data were collected. Regions that are shaded white but do not have red bars, indicates zero groups. The following values are the maximum number of localized killer whale groups each year presented above: 2007 (1 group); 2008 (0 groups); 2009 (0 groups); 2010 (4 groups); 2011 (2 groups); 2012 (1 group); 2013 (0 groups); 2014 (1 group); 2015 (2 groups); 2016 (1 group); 2017 (2 groups).

5.5 Disturbance Analysis of Minke Whales Results

This effort utilized tools jointly developed with the ONR BREVE project to semi-automatically process the February 2017 SCC data to generate the disturbance data set. Results shown here are from processed disturbance data for un-validated minke whale tracks for a large study area that extends well past the hydrophone array in all directions. The large study area was utilized in an attempt to help track individuals as they depart and enter the range. Localization accuracy is best on the range and the probability of localizing a call within the hydrophone array is estimated to be near 1.0, however localization accuracy and the probability of localizing a call decreases the further a call occurs outside of the hydrophone array. Validating tracks on, or close to, the hydrophone array consists of inspecting the call intervals and estimated velocities for consistency with known minke whale characteristics, as well as visually examining some of the vocalizations from the track. Validation is more difficult when using the large study area since some tracks may be entirely outside of the hydrophone array and the surrounding perimeter and are composed of relatively fewer calls (e.g. fewer than 30) with variable call intervals. For abundance estimation purposes and to facilitate track validation efforts in the future, it is recommended to use a study area smaller than the one used in this report, such that it encompasses the hydrophone array and only the immediate nearby extent.

5.5.1 Overall Changes in Track Abundance

Overall, there appeared to be a notable decline in minke whale abundance at the onset of the second phase of the SCC in February 2017. Figure 16 depicts a zoomed in look of the entire second phase of the February 2017 SCC depicted in Figure 5. It includes time leading up to the start of the MFAS; periods of time when ships repositioned (typically lasting a few hours) between training events and are not transmitting MFAS (white space); and periods of time when transmissions from hull mounted MFAS, sonobuoys, and helicopter dipping sonar were localized (red vertical bars). This provides an overarching preliminary look and possible insight into minke whale abundance during periods of time when MFAS was transmitted. The overall trend is variable, however, during the reposition at the early part of the second phase of the SCC around 15 February 2017 ~ 1500-1900 GMT (when hull mounted sonar was not transmitted) there appeared to be a step-wise increase in minke whale abundance (from 2 to 7 whales) possibly suggesting recovery of abundance which later declined when MFAS training resumed. Given these tracks have not been manually corrected for duplicates (i.e. tracking one whale as multiple whales) or combined tracks (one track for multiple whales), the numbers are preliminary at this point. This unexpected increase is being investigated and could be at least partly to tracking what appears to be one rapid boing calling minke whales as four whales during the time of the increase from 2 to 7 whales. This highlights the importance of validation of automatically generated tracks when interpreting potential impacts.

Due to the low abundance of humpback (Figure 6) and low-frequency baleen (Figure 7) whales, it is difficult to discern based solely on abundance whether animals are responding to hull mounted MFAS by ceasing to call; additional metrics such as call rate, call source level, cumulative sound exposure level, and kinematics (e.g. swim speed and turn rate) would need to be considered along with the increased noise levels associated with training.

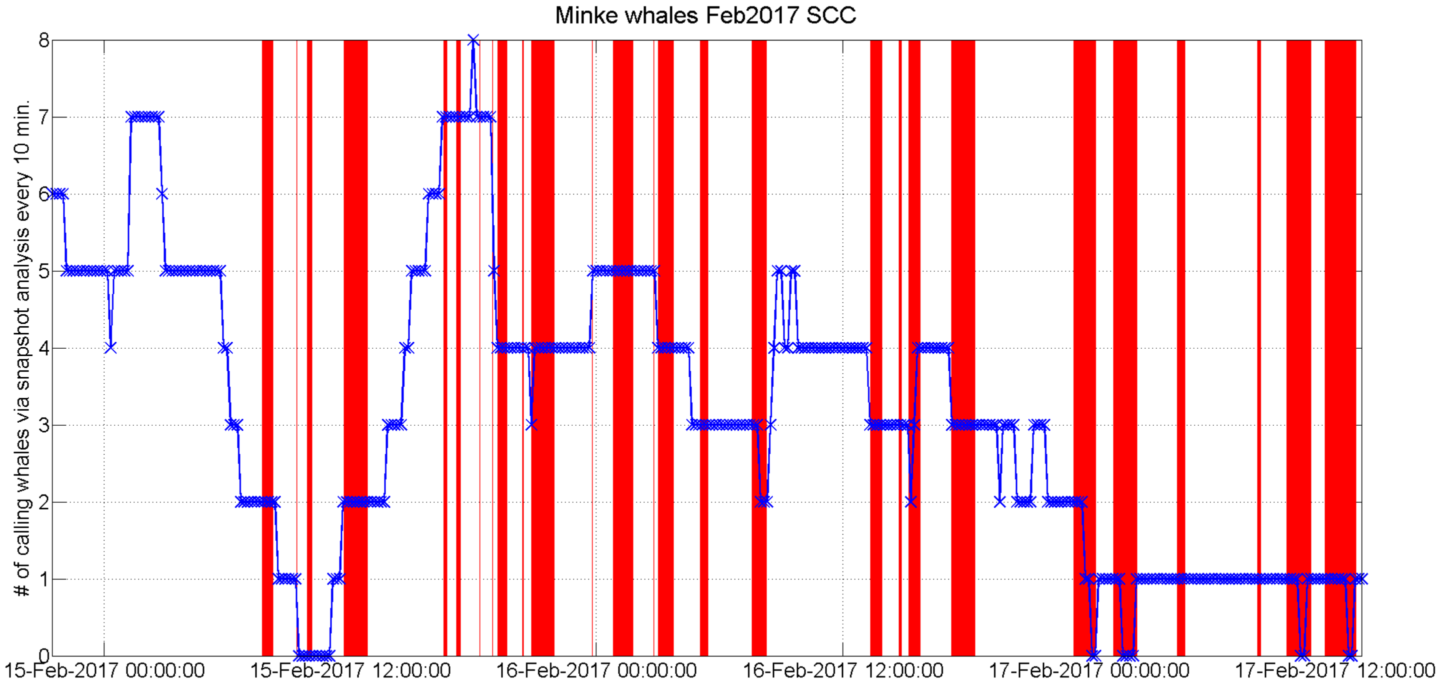


Figure 16: Detailed view of un-validated calling minke whale counts taken every 10 min (blue markers connected with blue lines) during the second phase of the February 2017 SCC which is during training with hull mounted MFAS. Data at the full 96 kHz sample rate were recorded for the entire time displayed. Red vertical bars indicate periods of time when transmissions from hull mounted MFAS, sonobuoys, and helicopter dipping sonar were localized.

5.5.2 Analyses of Disturbance on Individual Whales

An example of an application of semi-automated determination of behavioral disturbances, both from proximity of ships as well as MFAS exposures, on marine mammals is as follows. The onset of the February 2017 SCC hull mounted MFAS training occurred at 0741 on 15 February 2017 GMT and ended at 1300 on 17 February 2017 (53 hours of SCC MFAS training activities).

Minke whale tracks from the semi-automated Matlab tracking algorithm for data beginning on 14 Feb 2017 21:39 through 17 Feb 14:08 (~64.5 hr) are provided in Figure 17.

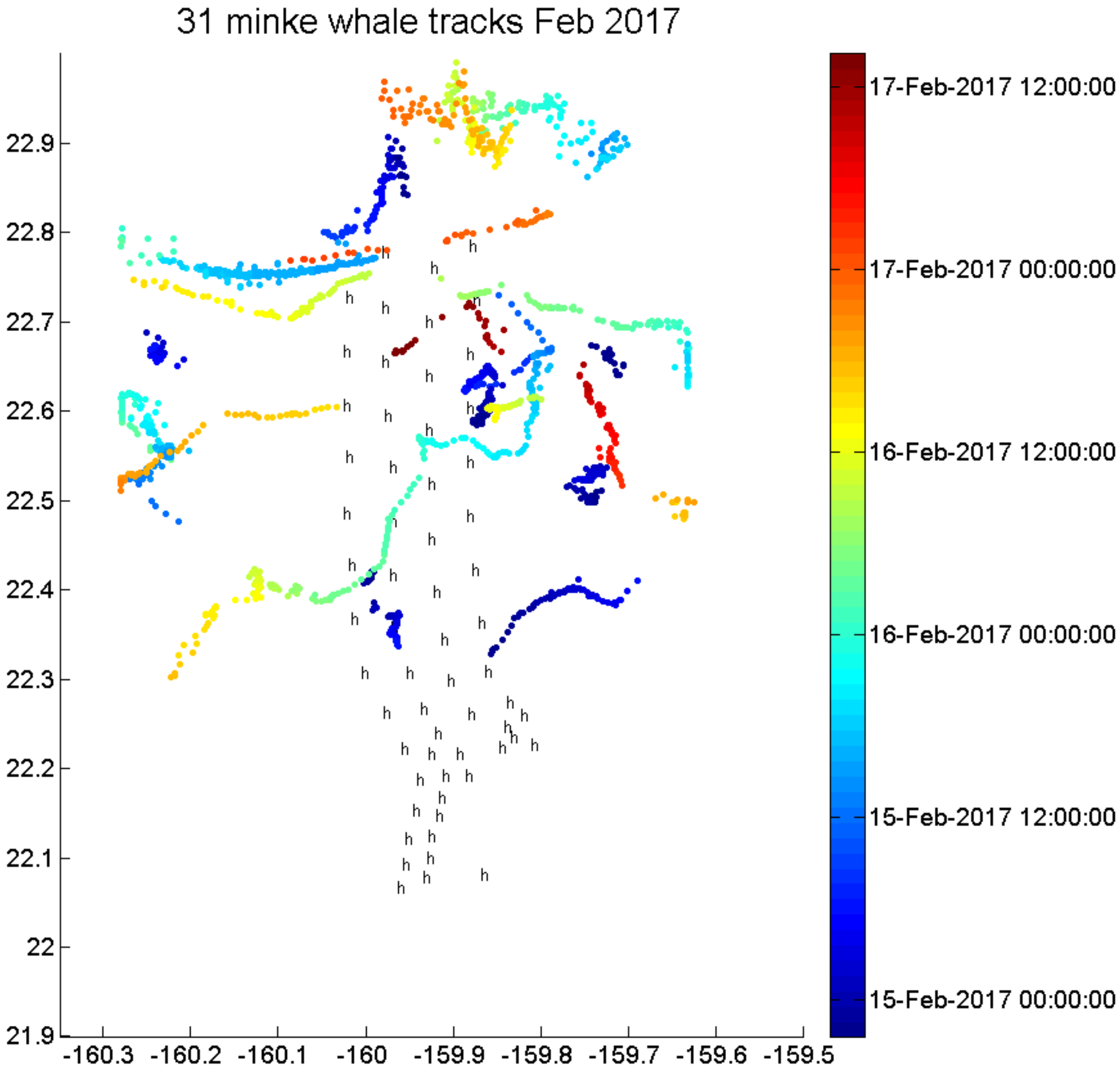
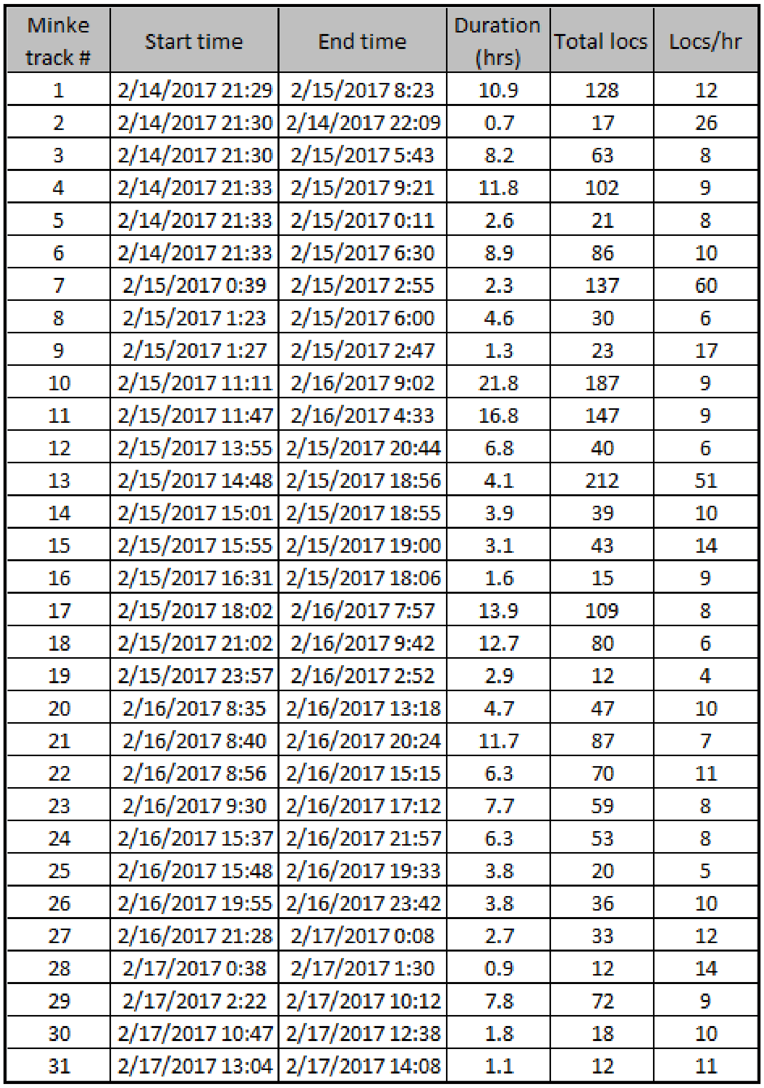


Figure 17: Color indicates time of the 31 minke whale tracks latitude vs. longitude prior to and during the February 2017 SCC.

The start and end times for the 31 minke whale tracks before and during the February 2017 SCC are provided in Table 3**.** Notice that only 23 whale tracks overlapped temporally with ship positions (also indicated by tracks in Figure 17 that ended before 15 Feb 2017 0741). The 23 minke whale tracks that overlapped with ship positions were analyzed for disturbances from both ships' proximities and MFAS exposures from hull-mounted sonars (Table 4). The total number of localizations that comprised a track and the metric of localizations per hour are also included in Table 3. Although the specific inter-call-interval between each localization in a track was calculated, the localizations per hour metric in Table 3 was intended to give an approximate indication if a minke whale was vocalizing at the nominal rate of 1 call every 5 or 6 minutes (10 to 12 calls in 1 hour), the rapid call rate of 1 call approximately every 30 seconds (120 calls in 1 hour), or a combination of both call types. It is important to consider that when the localizations were tracked, a 2,400 second coast time was allowed to elapse between calls and before a track was ended to account for an animal skipping several calls, or some calls not being localized properly. Track 13 is a rapid calling minke whale with 51 localizations per hour (Table 3). Tracks 14, 15 and 16 all occur at the same time and near the same locations and are suspected to be duplicates of Track 13. This requires further investigation to understand and perform improvements on the tracking processes.

Table 3: Minke whale track start and end times and track durations. Locs=localizations



Minke track #	Start time	End time	Duration (hrs)	Total locs	Locs/hr
1	2/14/2017 21:29	2/15/2017 8:23	10.9	128	12
2	2/14/2017 21:30	2/14/2017 22:09	0.7	17	26
3	2/14/2017 21:30	2/15/2017 5:43	8.2	63	8
4	2/14/2017 21:33	2/15/2017 9:21	11.8	102	9
5	2/14/2017 21:33	2/15/2017 0:11	2.6	21	8
6	2/14/2017 21:33	2/15/2017 6:30	8.9	86	10
7	2/15/2017 0:39	2/15/2017 2:55	2.3	137	60
8	2/15/2017 1:23	2/15/2017 6:00	4.6	30	6
9	2/15/2017 1:27	2/15/2017 2:47	1.3	23	17
10	2/15/2017 11:11	2/16/2017 9:02	21.8	187	9
11	2/15/2017 11:47	2/16/2017 4:33	16.8	147	9
12	2/15/2017 13:55	2/15/2017 20:44	6.8	40	6
13	2/15/2017 14:48	2/15/2017 18:56	4.1	212	51
14	2/15/2017 15:01	2/15/2017 18:55	3.9	39	10
15	2/15/2017 15:55	2/15/2017 19:00	3.1	43	14
16	2/15/2017 16:31	2/15/2017 18:06	1.6	15	9
17	2/15/2017 18:02	2/16/2017 7:57	13.9	109	8
18	2/15/2017 21:02	2/16/2017 9:42	12.7	80	6
19	2/15/2017 23:57	2/16/2017 2:52	2.9	12	4
20	2/16/2017 8:35	2/16/2017 13:18	4.7	47	10
21	2/16/2017 8:40	2/16/2017 20:24	11.7	87	7
22	2/16/2017 8:56	2/16/2017 15:15	6.3	70	11
23	2/16/2017 9:30	2/16/2017 17:12	7.7	59	8
24	2/16/2017 15:37	2/16/2017 21:57	6.3	53	8
25	2/16/2017 15:48	2/16/2017 19:33	3.8	20	5
26	2/16/2017 19:55	2/16/2017 23:42	3.8	36	10
27	2/16/2017 21:28	2/17/2017 0:08	2.7	33	12
28	2/17/2017 0:38	2/17/2017 1:30	0.9	12	14
29	2/17/2017 2:22	2/17/2017 10:12	7.8	72	9
30	2/17/2017 10:47	2/17/2017 12:38	1.8	18	10
31	2/17/2017 13:04	2/17/2017 14:08	1.1	12	11

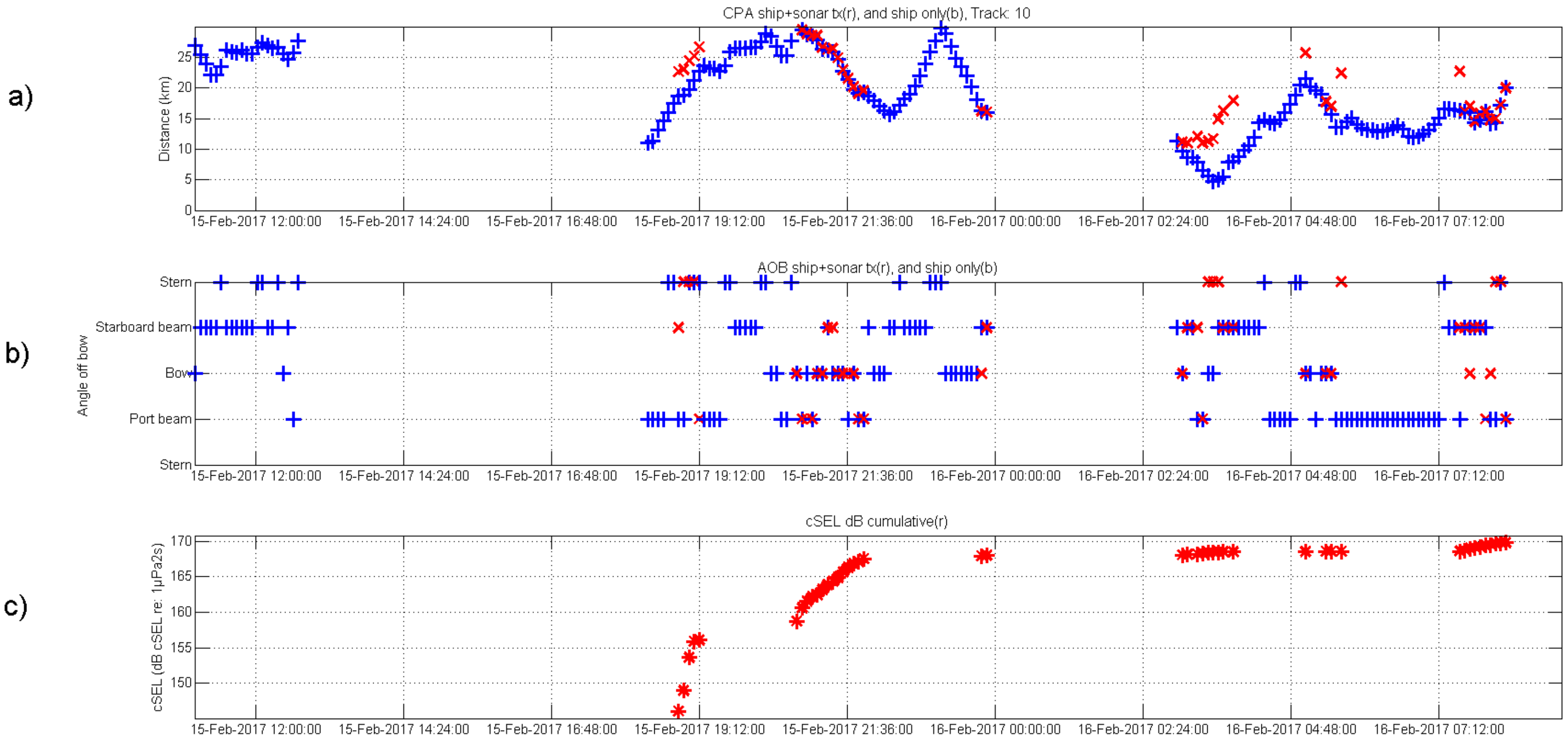


Figure 18: Overview of ship-whale geometries and cumulative received levels for minke whale track 10 during the February 2017 SCC on a 5 min binned basis. The time axis on all three plots is scaled for the start and end time of track 10 and includes 10 minutes before and after the start and end times of the track. Plot a) shows the distance from the closest ship transmitting sonar (red markers) and the closest ship not transmitting sonar (blue markers). Plot b) shows the orientation of the animal relative to the closest ship transmitting sonar (red markers) and the closest ship not transmitting sonar (blue markers). Plot c) depicts the cumulative sound exposure level the animal received over the duration it was tracked, energy was only accumulated during times of MFAS training when transmissions were localized. Minke whale track 10 had the minimum closest point of approach to a ship not transmitting sonar, and the highest cumulative sound exposure level out of all 31 minke whales tracked during the February 2017 SCC.

A visual summary of the disturbance analysis for minke whale track 10 on a 5-minute binning basis is provided in Figure 18. Although the times of each localization comprising track 10 are not depicted, the time axis on all three plots is scaled for the start and end time of track 10 (Table 3). Also note that there are periods when ship positional data were not available (e.g., when ships were repositioning on the range between training events); there are no markers on Figure 18 at these times.

Disturbance analysis plots (such as Figure 18) are only included here for track 10, although they were generated for all animal tracks that overlapped with ship or hull mounted sonar activity. Minke whale track 10 is depicted relative to generalized tracks of multiple ships transmitting MFAS (as indicated by the gray shaded regions as actual ship positions are sensitive data) in Figure 19. There are several points of interest to highlight, with some potential behavioral responses observed. First, the yellow star in Figure 19 indicates the closest point of approach (CPA) of a ship transmitting MFAS to minke whale track 10. At this CPA the whale is within the port aspect of the ship (Table 4). However, considering succeeding ship positions (not depicted), overall the ship traveled approximately perpendicular and away from the whale's track. In the overlapping 5 minute bin at this point, the ship and animal were 11 km distant, with a cumulative received level of 168.3 dB cSEL re: 1µPa^{2}s. At this CPA to a ship transmitting MFAS, minke whale track 10 exhibited a reduction in call rate (reduction of 1 call every 5 minutes nominally to 1 call every 10 minutes). Second, the black star in Figure 19 indicates the CPA of a ship not transmitting MFAS to minke whale track 10. At this position, the animal was off the bow and the ship and animal were 4.8 km distant. At the CPA of a ship without sonar, minke whale track 10 again had a reduction in call rate (1 call every 10 minutes) for two call intervals before returning to the nominal rate of 1 call every 5 to 6 minutes. It is worth pointing out that the animal may have responded in the same way (a reduction in call rate) to the CPAs of both ships, regardless of the presence of sonar. It is also interesting to note that the minke whale associated with track 10 continued to call at the nominal call rate (emitting 7 calls) for 41 minutes after the training event ended, particularly considering it received the highest cumulative sound exposure level (169.8 dB cSEL re: 1µPa^{2}s) out of all animals tracked during the portion of the February 2017 SCC training event that utilized hull mounted MFAS. This minke whale did not cease calling during the period of training that utilized MFAS, but rather ceased calling well after the training event ended. This animal also did not cease calling in direct response to proximity or exposure to ships maneuvering during MFAS training or MFAS transmissions, but did exhibit a reduction in call rate when closest in distance to a ship transmitting sonar and a ship not transmitting sonar.

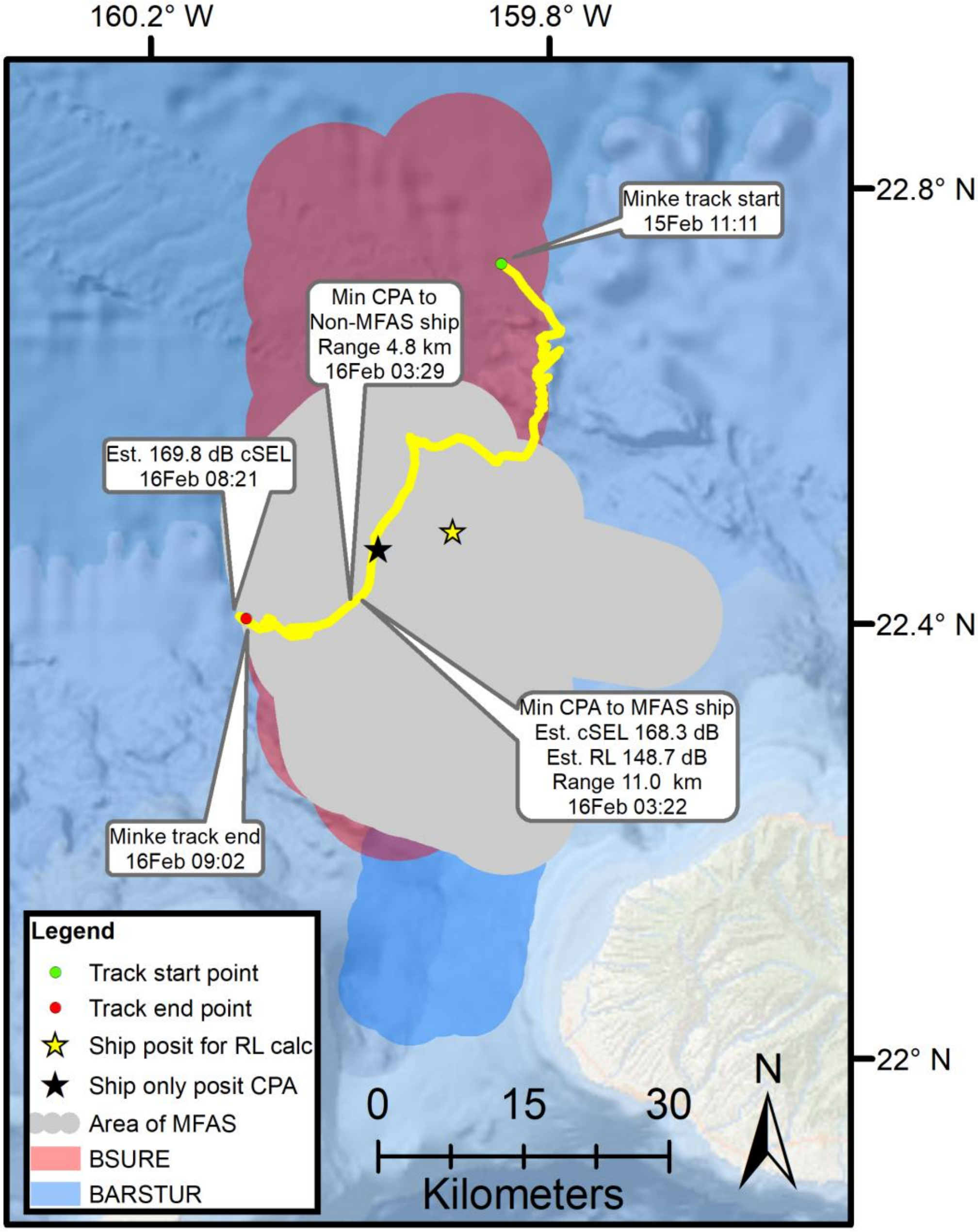


Figure 19: Situational plot for minke whale track 10. The callout labels point to the animal's precise position along the center of its track (yellow line) when the animal was closest to a ship not transmitting sonar (black star), closest to a ship transmitting MFAS (yellow star), at the start of the animal's track (green dot), at the end of the animal's track (red dot), and when the animal received the highest cumulative sound exposure level (31 minutes before the animal's track ended and when MFAS transmissions ceased)

Table 4: Overview of fundamental statistics for the 31 minke whales tracked during the February 2017 SCC. Notice that minke whale tracks 2, 3, 5-9, and 16 did not overlap with any ship tracks. Max cSEL=maximum cumulative sound exposure level, max RL=maximum received level, max RL st dev=maximum received level standard deviation, CPA=closest point of approach, AOB=angle off bow, MFA=mid-frequency active [sonar].

Trk	Max cSEL (dB)	Max RL (dB)	Max RL st. dev.	CPA ship only (km)	AOB quadrant ship only	CPA ship w/MFA (km)	AOB quadrant ship w/MFA
1	151.0	148.2	0.7	15.9	90	31.7	90.0
2	No ship/sonar overlap with animal track						
3							
4	147.5	143.2	0.2	39.2	180	50.7	90.0
5	No ship/sonar overlap with animal track						
6							
7							
8							
9							
10	169.8	152.3	0.6	4.8	0	11.0	-90.0
11	163.1	147.1	0.1	15.1	90	31.9	0.0
12	138.2	129.2	0.1	40.9	180	54.7	90.0
13	144.0	140.7	0.1	31.6	180	46.2	0.0
14	142.7	138.8	0.0	31.9	180	47.5	0.0
15	148.6	143.3	0.1	30.0	180	42.6	0.0
16	No ship/sonar overlap with animal track						
17	167.1	150.7	0.1	20.1	-90	22.3	90.0
18	160.5	147.6	0.3	41.0	180	41.9	180.0
19	150.7	143.3	0.1	51.4	0	53.3	0.0
20	155.0	152.2	0.3	25.8	0	27.6	90.0
21	163.0	149.5	0.3	22.2	90	29.9	180.0
22	155.3	147.2	0.3	35.4	90	35.5	90.0
23	162.5	150.9	0.8	22.4	-90	25.5	0.0
24	168.6	150.4	0.0	9.9	-90	10.1	180.0
25	167.5	152.2	0.9	10.5	180	27.0	-90.0
26	157.4	150.0	0.6	49.7	-90	49.8	-90.0
27	162.8	150.8	0.2	38.1	0	38.1	-90.0
28	155.7	145.2	0.1	35.2	90	45.4	0.0
29	158.9	146.4	0.0	11.3	90	43.4	-90.0
30	162.7	150.3	0.3	27.1	90	32.2	180.0
31	157.0	148.9	0.3	29.7	-90	30.3	0.0

5.6 Noise Analysis Results

An initial noise analysis revealed occasional high-noise conditions that were previously undocumented. Upon further inspection, the DCLTDE laboratory discovered that high-noise conditions appeared to be attributed to electrical noise during periods when the range equipment feeding the recorder were shut off. Although instances such as this are detectable by performing noise analyses, it is a different issue than considering the impact of noise levels on detector performance since this instance resulted in a complete loss of hydrophone data. Standardized analysis for dataset noise levels is a new emergent capability, which was just recently identified and is actively being worked on to account for potential issues with the recorded data.

6 Concurrent and Related Efforts

The ONR BREVE project (PI: S. Martin) is a joint effort involving the National Marine Mammal Foundation, the Centre for Research into Ecological Environmental Modelling (CREEM) at St. Andrew's University, and SSC Pacific. The primary goal is to develop and apply methods to determine if baleen whale species' behavioral responses to actual Navy training can be determined statistically using existing large data sets of PAM data from PMRF. A robust understanding of baseline behaviors for multiple baleen species (minke, fin, humpback, Bryde's, sei, and blue whales) will need to be established for comparison with behavioral observations during Navy training. Statistical methods developed to quantify behavioral responses to short-term controlled exposure experiments will be extended to long-term and larger-scale passive acoustic data to develop metrics of response and behavioral state estimates for baseline and exposure conditions. Semi-automated disturbance analysis generates animal kinematics (e.g. speed and heading), call intervals, geometries between both non-transmitting ships and ships transmitting MFAS, and cumulative sound exposure levels animals receive. The framework to perform the disturbance analysis was developed by the BREVE project and the FY17 PACFLT effort streamlined the processing stages. This illustrates the utility of processes developed by the BREVE project for PACFLT efforts. A project funded by the LMR program (PI: T. Helble) related to the BREVE project involves developing tools to help semi-automate processes involved in determining baseline marine mammal behaviors and behavioral reactions to ship-animal encounters. Some tools have been applied from PACFLT funding and combined with new tools being developed at SSC Pacific to help aid the significant manual effort that is required to fully investigate individual ship-animal encounters. Additional tools will be created in this project to help automatically classify low-frequency baleen whale tracks to the species level. This project is directly applicable to the BREVE project and exposure analyses conducted in SSC Pacific's DCLTDE laboratory, but can be leveraged in the future to use on PACFLT monitoring data. These tools will enhance data analysis efficiency and repeatability and help eliminate subjectivity, which is inherent to human analysis when analyzing marine mammal behavior that is highly variable.

A current internal SSC Pacific Science and Technology effort (PI: E. Henderson) has the goal of attaching acoustic pingers to humpback whales, supplemented by satellite tags, to demonstrate that they can be tracked by pinger emissions using the bottom mounted range hydrophones at PMRF. This would provide indisputable confirmation of species, animal locations when they are not actively vocalizing, and evaluation of automated tracking accuracy, as well as some initial cue rate information (to help inform long term abundance and density estimates) and evidence for the amount of time individual whales spend on PMRF. If the tags can be successfully tracked, longer duration attachments may allow an estimation of behavioral responses to Navy training activity as well. In FY17, seven satellite tags were deployed but no pinger tags were deployed due to a permitting issue. All seven tagged humpback whales continued to travel west/northwest after being tagged, with only one whale returning briefly to the PMRF range area (Henderson et al. 2017; attached as an Appendix). These results may indicate that humpback whales generally spend little time on or near the range, which would minimize their likelihood of exposure to ship movement or MFAS. However, the effort will be repeated in FY18 with the inclusion of the pinger tags, and will be conducted just prior to an SCC training event. This will help determine if the behavior from 2017 is consistent across years, and may lead to some opportunistic observations of behavioral responses to Navy training activity. This effort was largely supported through SSC Pacific funding, but a portion of the work was funded by PACFLT as well.

7 FY17 Reports and Presentations

7.1 Reports and Publications

Guazzo, R.A., Hildebrand, **Helble, T.A.,** J.A., Wiggins, S.M., D'Spain, G.L. and Weller, D.W., 2016. The correlation between the local environment and gray whale behavior as tracked using a sparse hydrophone array in Monterey Bay National Marine Sanctuary. The Journal of the Acoustical Society of America, 140(4), pp.3360-3360.

Helble, T. A., Henderson, E. E., Ierley, G. R., & **Martin, S. W**. (2016). Swim track kinematics and calling behavior attributed to Bryde's whales on the Navy's Pacific Missile Range Facility. *The Journal of the Acoustical Society of America*, *140*(6), 4170-4177.

Henderson, E. E., Martin, S. W., Manzano-Roth, R.A., and B. Matsuyama. 2016. Occurrence and habitat use of foraging Blainville’s beaked whales (Mesoplodon densirostris) in Hawaii. Aquatic Mammals 42(4).

Henderson, E. E., J. Aschettino, M. Deakos, G. Alongi, and T. Leota. 2017. Satellite Tracking of Migrating Humpback Whales in Hawaii. SSC Pacific Technical Report 18-017-TR.

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7.2 Presentations

Baird, R.W., **Martin, S.W., Manzano-Roth**, R., Webster, D.L., Southall, B.L. (2017) Assessing exposure and response of satellite-tagged odontocetes to MFA sonar during Submarine Commanders Courses at PMRF. Navy Marine Mammal Monitoring Meeting, Seattle. April 2017.

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Satellite Tracking of Migrating Humpback Whales in Hawaii

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To better understand the behavior of humpback whales (*Megaptera novaeangliae*) in the deeper waters of their Hawaiian breeding grounds west of Kauai, seven presumed males were satellite tagged using LIMPET-configured SPLASH tags in late March 2017. All tagged whales were traveling away from Kauai when encountered, heading west towards the island of Niihau, which they circled for 1.0 – 7.9 days. Five whales continued to travel west/northwest, with directed travel over deep water while milling over shallow seamounts and near islands, including Ka'ula Rock, Middle Bank, and Nihoa. Four of the tags stopped transmitting while the whales were at or near these seamounts. Only one whale traveled directly north from Niihau rather than following the Hawaiian archipelago to the northwest. Tags remained attached for 1.6 – 12.3 days, and total distances traveled ranged between 143.5 and 826.4 km, although straight-line distances traveled were far shorter (19.8 – 548.8 km). The median travel speed while near islands or seamounts was 1.1 km/hr, while the median intermediary speed approaching or leaving these areas was 3.0 km/hr, and the median directed travel speed over open water was 5.5 km/hr. Mean dive depth was 33.4 m, while maximum dive depths reached 395.5 m. Dive depths correlated with seafloor depths, with dives over shallow seamounts often using the full extent of the water column, while the deepest dives occurred over open water and usually at night. These results begin to provide insight into the offshore and migratory behavior of humpback whales in Hawaii, and build a baseline of behavior against which to compare potential responses to Navy training activity in this area.

Introduction

Humpback whales (*Megaptera novaeangliae*) migrate long distances between summer feeding grounds in high latitudes and winter breeding grounds at lower latitudes (Calambokidis *et al.* 2001, Stevick *et al.* 2003, Rasmussen *et al.* 2007, Burns *et al.* 2014). In the North Pacific, there are five main feeding grounds between the Aleutian Islands and western Gulf of Alaska and the Farallon Islands, and three main breeding areas, the largest of which is located around the Hawaiian Islands in the central Pacific (Darling & McSweeney 1985, Baker 1986, Craig & Herman 1997, Calambokidis *et al.* 2001). Whales from the Hawaiian Islands breeding ground migrate most frequently to southeastern Alaskan waters and the Gulf of Alaska, but have been observed as far to the southeast as California and to the northwest as the Aleutian Islands (Calambokidis *et al.* 2001).

Humpback whales largely arrive in Hawaiian waters starting in December (Lammers *et al.* 2011, Henderson *et al.* 2018), and most leave by April or May (Baker & Herman 1981, Mobley Jr & Herman 1985), although whales have been visually or acoustically detected as early as November (Barlow 2006) and as late as June (Henderson *et al.* 2018). The peak in abundance is generally in February or March, varying from year to year (Baker & Herman 1981, Mobley *et al.* 1999, Au *et al.* 2000), and may be related to oceanographic parameters on both the feeding grounds and breeding grounds (e.g., Johnston *et al.* 2007, Rasmussen *et al.* 2007). The timing of arrival for individual whales is a function of sex, age, and reproductive status (Craig *et al.* 2003). While the breeding season itself lasts four to six months, individual whales may only stay in Hawaii for a few weeks (e.g., Herman *et al.* 2011), with females with calves staying the longest, up to five weeks (Mobley & Herman 1985, Craig & Herman 1997). The majority of humpback whales in Hawaii, particularly mothers with calves, seem to preferentially occur in shallow water less than 200 m deep (Smultea 1994, Craig & Herman 2000, Johnston *et al.* 2007). Earlier studies found higher abundances of humpback whales in the Four Island Region (Maui, Molokai, Kahoolawe and Lanai) and on Penguin Bank off Molokai (Baker & Herman 1981), while later studies found more animals in the Kauai/Niihau region as well, which may have been a result of an overall increase in abundance as the population recovered from whaling impacts (Mobley *et al.* 1999, Mobley *et al.* 2001). Sightings and acoustic detections have also occurred in the northwestern Hawaiian Islands, suggesting that region may also be a part of the wintering grounds (Johnston *et al.* 2007, Lammers *et al.* 2011).

While there is some movement between islands within a breeding season (Cerchio 1998, Cerchio *et al.* 1998, Mate *et al.* 1998, Calambokidis *et al.* 2001), animals are more likely to be observed off a different island in subsequent years rather than within a season (Calambokidis *et al.* 2001), although there may be some site fidelity to specific island regions across years (Cerchio *et al.* 1998). Baker and Herman (1981) suggested whales might be taking advantage of a clockwise gyre current north of Oahu and Kauai, and therefore move northwesterly through the islands to save energy; however, Cerchio et al. (1998) found no tendency for movement across the islands in either direction. Migrations between the Hawaiian Islands and Alaskan feeding grounds were at one time estimated to take three months (Baker *et al.* 1985), although they have been more recently recorded to be as short as 36 (Calambokidis *et al.* 2001) and 39 (Gabriele *et al.* 1996) days. The few studies that have tracked migrating humpback whales between their feeding and breeding grounds through telemetry tags have found animal movement when leaving Hawaii to be fairly directed to the north and northeast (Abileah *et al.* 1996, Mate *et al.* 1998, Norris *et al.* 1999). Other tagging studies along migratory routes have also found highly directed travel between low latitude breeding grounds and high latitude feeding grounds (Lagerquist *et al.* 2008, Gales *et al.* 2009, Horton *et al.* 2011, Kennedy *et al.* 2014). However, there may be some transition in behavior before humpback whales begin their directed migration. For example, one study found several humpback whales spending time at shallow seamounts near a breeding ground in New Caledonia before beginning directed travel (Garrigue *et al.* 2010), and another found humpback whales from the Revillagigedo Archipelago breeding ground visited other wintering areas in Mexico before heading northwest (Lagerquist *et al.* 2008).

While on their breeding grounds, males engage in a variety of behavioral roles. These may include escorting a female with or without calf as the main (primary) escort, or competing for the primary escort position with one or more males (termed secondary escort), affiliating with one or more males in a group without a female, or found alone. Singing can occasionally occur while escorting a female but is conducted most often when alone (Tyack & Whitehead 1983, Baker & Herman 1984, Mobley Jr & Herman 1985, Helweg & Herman 1994, Darling & Bérubé 2001, Darling *et al.* 2006, Herman *et al.* 2011, Herman *et al.* 2013). Males can switch behavioral roles frequently within or across years regardless of age or size (Baker & Herman 1984, Herman *et al.* 2011). Females may be found alone or with a calf; however, they are most often sighted with at least one escort or within a competitive pod (Mobley & Herman 1985, Clapham 1996).

The US Navy’s Pacific Missile Range Facility (PMRF) underwater hydrophone array is located in the offshore waters northwest of Kauai, and has been used to conduct testing and training events in the area since the late 1960’s (Navy 2011). The baseline behavior of animals on a Navy instrumented range can be used to evaluate potential behavioral responses to Navy activity, and quantifying the temporal and spatial use of the area allows researchers to assess the likelihood that a response may occur. Therefore, the goals of this study were to photo-identify, satellite tag, and track humpback whales in the offshore waters of Kauai, in particular near PMRF, in order to catalog their behavior and habitat use in these waters. A secondary goal was to determine if animals found on or near the range spend extended periods of time or if they are heading north on their migration and only passing through the area. An additional goal of this study, to track the whales on PMRF using separate high-frequency pinger tags, was not accomplished due to permitting issues, but is planned to be added to this study in 2018.

Methods

Vessel-based satellite tagging and photo-identification were conducted March 17 – 24, 2017 in the offshore (>3 nm) waters between Kauai and Niihau, the northwestern-most islands of the main Hawaiian Islands. When a humpback whale(s) was sighted, the boat followed the whale while maintaining a distance of at least 100 m from the individual or group. Sighting data was entered into an electronic application, COMPASS (Richlen *et al.* 2017) as well as hand written datasheets. Data collected included sighting location and time, whale behavior, individual behavioral roles, group size, and identification photos of the left and right side dorsal fin and tail fluke when possible. Based on the whale's behavior, a decision was made on whether to attempt to approach a whale for satellite tagging. Photos were taken using one of three digital SLR cameras (Canon 50D, 7D, or 7D Mark II) with 100 – 400 mm zoom lens. Following the field effort, individual identification photos were compiled and compared across individuals to identify whales encountered more than once.

If a group or individual was determined to be a good candidate for tagging, they were approached within 100m in a steady and safe manner. No individual was approached within 15 m for tagging attempts more than three times; in two cases multiple animals in the same group were approached but tagging approaches were made for different individuals. Location-dive tags (Wildlife Computers Mk10A) in the Low-Impact Minimally Percutaneous External electronics Tag (LIMPET) configuration were used for tagging, and were attached with two titanium darts with backward-facing petals to the dorsal fin. Tags were remotely deployed with a DanInject JM Special 33 pneumatic projector (DanInject ApS, Børkop, Denmark) from a 6.7 m rigid-hulled inflatable boat. Tags were programmed to transmit 21 hours per day (based on availability of satellites in the area) with up to 750 transmissions per day and record dive start and end times, maximum depth, and dive durations for dives greater than 5 m in depth or 30 sec in length in 75 sec bins. The tagged whale was monitored for any response to the tagging event immediately after they were tagged; in addition, the group was followed until photographs had been obtained of all individual dorsal fins and flukes, particularly the tagged whale's dorsal fin with the tag.

Track positions were estimated using the Argos Data Collection and Location System with a Kalman filtering algorithm and further screened using the Douglas-Argos Filter version 8.50 (Douglas *et al.* 2012) available in Movebank (Movebank.org). Additional manual filtering was conducted to remove erroneous locations appearing on land or resulting in unrealistic humpback whale travel speeds of greater than 15 km/h (Noad & Cato 2007). All locations were utilized for analysis regardless of location class (based on estimated error and number of messages received), unless they were removed during the filtering process. Original filtered location positions were used to estimate travel speeds, and a Directivity Index was calculated for all tracks, which is the straight-line distance divided by the cumulative distance. This Index provides a measure of track linearity with lower values indicating many changes in direction and higher values (close to 1) indicating linear movement.

In addition, track data were time-interpolated in 20 min intervals and analyzed using the R package adehabitatLT (Calenge 2006, Calenge 2015), designed for the analysis of animal trajectories based on telemetry data. This analysis was conducted order to identify different behavioral states (e.g. milling, traveling, foraging) along each humpback whale track. To do this, tracks were assessed for different Markovian behavioral states (i.e., track segments with homogenous properties) using the interpolated data, and segmented into these state-specific periods using a Bayesian partitioning method developed by Gueguen (2001, 2009). This analysis used the distance traveled between the interpolated positions to determine the states. The distances corresponding to each state were determined *a priori* by combining the distance data from all seven tracks and finding the top three modes and standard deviation. First the probability density that a given step between segments was generated by the a priori model was estimated, then the optimal number of segments for each track was determined using the log-likelihood for each number of segments.

Dive data were analyzed using the R package diveMove (Luque 2007) to obtain the total number of dives, dive depths, dive durations, and descent and ascent rates. Track analyses included fitting the interpolated tracks to seafloor depth using the ETOPO1 1-arc global relief data (https://www.ngdc.noaa.gov/mgg/global/) that were gridded using the R package sp (Pebesma & Bivand 2005, Bivand *et al.* 2013). In order to assess potential relationships between dive depths and bathymetry, Pearson's correlation analyses using Student's t-distribution were conducted between dive depths and bathymetry using these fitted tracks. A correlation analysis was also conducted between dive depths and time of day to look for diurnal patterns in dive data.

Results

A total of eight days of survey effort were conducted in the channel between Kauai and Niihau (Figure 1), resulting in 60 groups that ranged in size from one to six animals (mean 2.3). From those groups, at least 85 individual humpback whales were encountered based on dorsal fin identification, and seven unique individuals were successfully tagged (Table 1). The majority of groups encountered were traveling from east to west across the channel. Fluke photographs were collected from 58 humpback whales (e.g., Figure 2), with two individuals resighted on a different day. The first resighted individual was observed in a group of three sub-adults that approached the boat, then again four days later as a surface active solitary animal that was briefly joined by a second animal. The second resighted individual was observed on the second day as a secondary escort in a competitive pod, and was encountered in the same role again four days later when it was tagged.

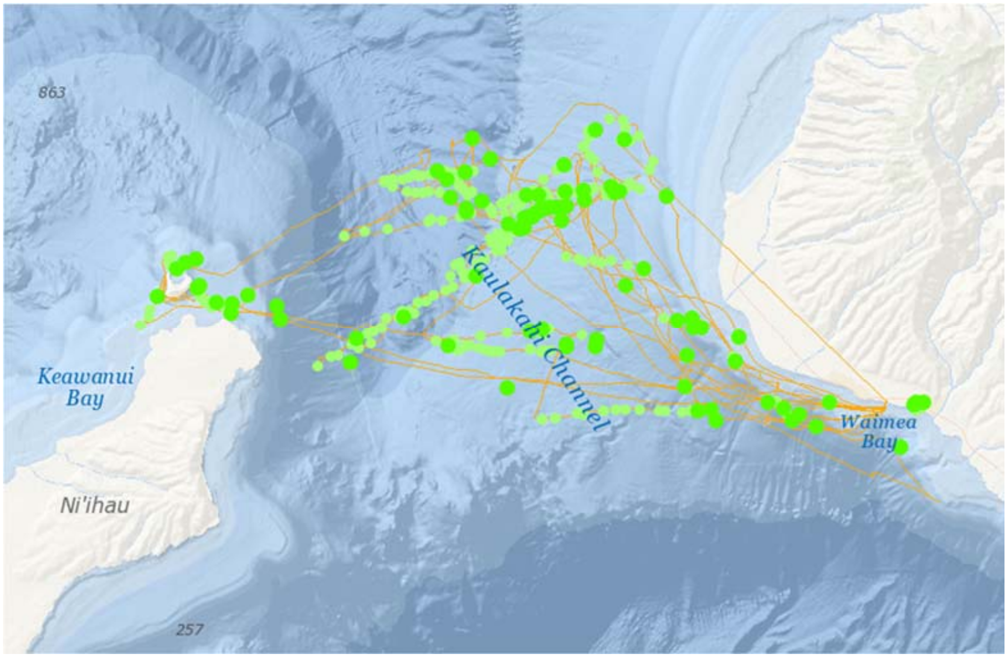

Figure 1: Map of survey area in the Kaulakahi Channel between the islands of Kauai and Niihau. Daily effort tracklines shown in orange, with initial group sightings as dark green circles and resighted positions of the tracked groups in light green.

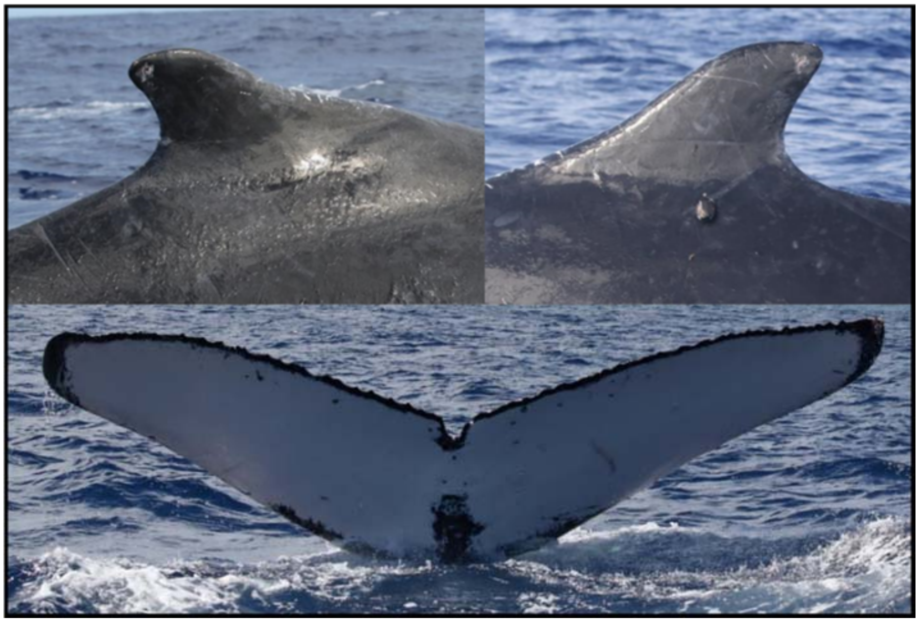

Figure 2: Examples of photographs of the left and right sides of the dorsal fin (top) and the tail fluke (bottom) for one of the satellite-tagged animals. All photographs taken under National Marine Fisheries Permit #16239.

All seven of the tagged whales were probable males judging by their behavior. All animals looked healthy (e.g., none of the whales appeared to be thin or malnourished). Two were secondary escorts in the same competitive pod, two were in adult dyads (likely male-male), two were in sub-adult dyads (also likely male-male), and one sub-adult was encountered alone. One of the dyads joined a competitive pod just after being tagged. The only reactions observed to the tagging was a peduncle swish by one individual and an accelerated dive by another. Both of these individuals returned to their original behavior immediately following these responses. Among the five other humpback whales, no reaction was observed. In addition, two of the whales successfully took over the primary escort position in their respective pods for a period of time after being tagged.

Table 1: Summary of satellite tagging effort of humpback whales off Kauai, HI.

Tag ID	Time Deployed (HST)	Age-class	Group Information
158569	3/19/17 10:45	adult	Pair adult males
158570	3/20/17 9:29	sub-adult	Pair subadult males
158571	3/22/17 9:02	sub-adult	Single animal
164790	3/22/17 15:47	adult	Competitive pod of five animals
164791	3/21/17 11:26	sub-adult	Pair subadult males
164792	3/22/17 16:41	adult	Competitive pod of five animals
164793	3/24/17 8:27	adult	Pair adult males, joined with competitive pod of five animals

Distance travelled and rate of travel for all seven tracks are summarized in Table 2. The tags transmitted between 1.6 and 12.3 days with an average of 5.1 days (Figure 3). The short attachment durations were likely due to the competitive pod activity; in fact, the longest two tag durations were from two sub-adult males not encountered in competitive pods. The whales traveled daily distances of 62.8 – 142.5 km, with cumulative distances between 143.5 and 816.2 km. However, since all seven animals spent 1.0 – 7.9 days (mean = 2.45 days) in proximity to Niihau, and five of the animals spent additional time near other islands or seamounts (Figure 3), the cumulative distance traveled exceeded the straight-line distance traveled by as much as 8 times (Table 2). This led to generally low Directivity Indices, as low as 0.12. However, the two animals that had the longest tag attachments, 158671 and 164791, had higher Directivity Indices (0.66 and 0.71, respectively), and had fairly long straight-line distances as well (548.8 and 582.5 km, respectively). Tagged animal 158671 followed the Hawaiian archipelago to the northwest for several days, stopping at multiple seamounts, before beginning to increase travel speed and head directly northwest (Figure 3). In contrast, animal 164791 headed north after spending 7.9

days near the island of Niihau, increasing travel speed and moving in in a fairly directed manner (Figures 3 and 4). Median travel speeds for all whales were estimated between 1.96 and 4.04 km/hr, with a high degree of variability. Median speeds were used as the mean values were skewed slightly higher by some periods where speed approached 15 km/hr, the maximum allowed speed before a position was removed from analyses. These higher speeds could still indicate the presence of erroneous positions, but could also represent real bursts of speed, such as during competitive pod activity.

Table 2: Summary of humpback whale satellite track data from Kauai, HI.

Tag ID	**# Days transmitted**	**Median ± SD Speed (km/h)**	**Cumulative Distance (km)**	**Straight-line Distance (km)**	**Mean Daily Distance (km/day)**	**Directivity Index**
158569	2.3	2.84 ± 3.5	143.5	46.4	63.5	0.32
158570	6.0	2.37 ± 4.5	379.2	166.9	62.8	0.44
158571	8.1	3.61 ± 3.2	826.4	548.8	102.5	0.66
164790	3.0	4.04 ± 6.3	295.9	156.0	100.3	0.53
164791	12.3	1.96 ± 2.7	816.2	582.5	66.6	0.71
164792	2.3	3.27 ± 2.6	166.0	19.8	73.1	0.12
164793	1.6	3.67 ± 3.0	226.6	113.0	142.5	0.50

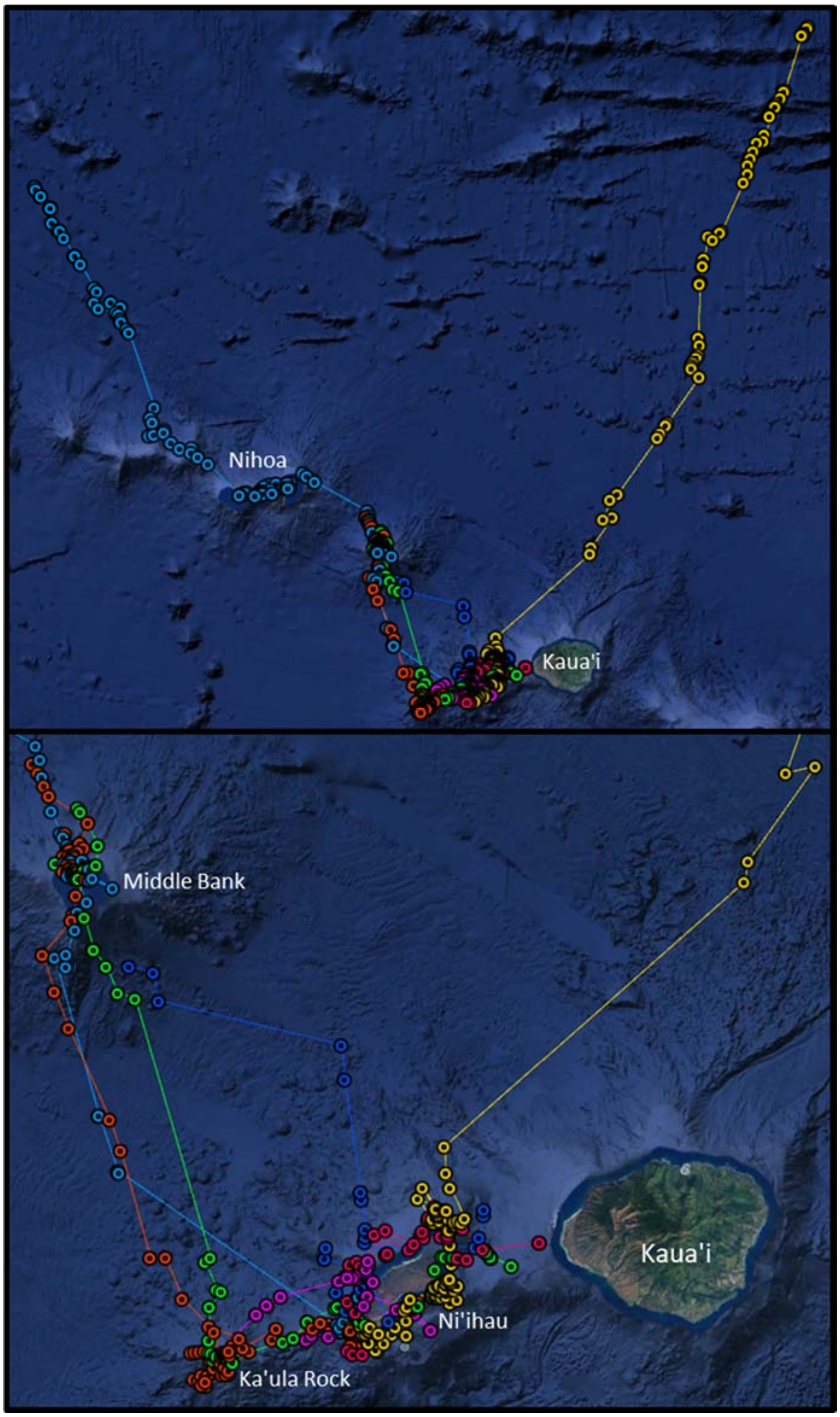

Figure 3: Satellite-derived filtered location positions and tracks of all seven tagged humpback whales (top); same tracks zoomed in (bottom) to see movement around the island of Niihau. 158569 is in purple; 158570 is in red; 158571 is in light blue; 164790 is in green; 164791 is in yellow; 164792 is in magenta; 164793 is in dark blue. See Appendix A for additional location figures.

Patterns in speed and directivity are also reflected in the different behavioral state models (e.g., Figure 4); these behaviors were determined to be directed travel, milling or Area Restricted Search (ARS), and an intermediary behavior. During the *a priori* model assignment, three distance values (0.002, 0.01, and >0.02 degrees) were selected from a histogram of all distances across the 20 min interpolated bins for all seven whales, with an overall standard deviation of 0.012 degrees. These values were used to estimate the probability densities of each track step for each distance model; the optimal number of segments for each track was then calculated using the log-likelihood value. The number of segments per track, or the number of times the state switched from one behavior to another, ranged from 4 - 32, with a mean of 15.6. The shortest distance between points, indicative of low travel speeds and higher rates of turning, occurred in all tracks when the animals were in shallow water close to islands or over seamounts (Figure 4). Median swim speeds during this behavior were the slowest at 1.1 km/h. More directed travel seemed to occur at moderate speeds as the animals moved across open water (median speed = 5.5 km/hr), and there was an intermediate speed that occurs before and after the presumed milling which may correspond to animals slowing down or speeding up as they approach or leave shallower water or change behaviors (median speed = 3.0 km/hr).

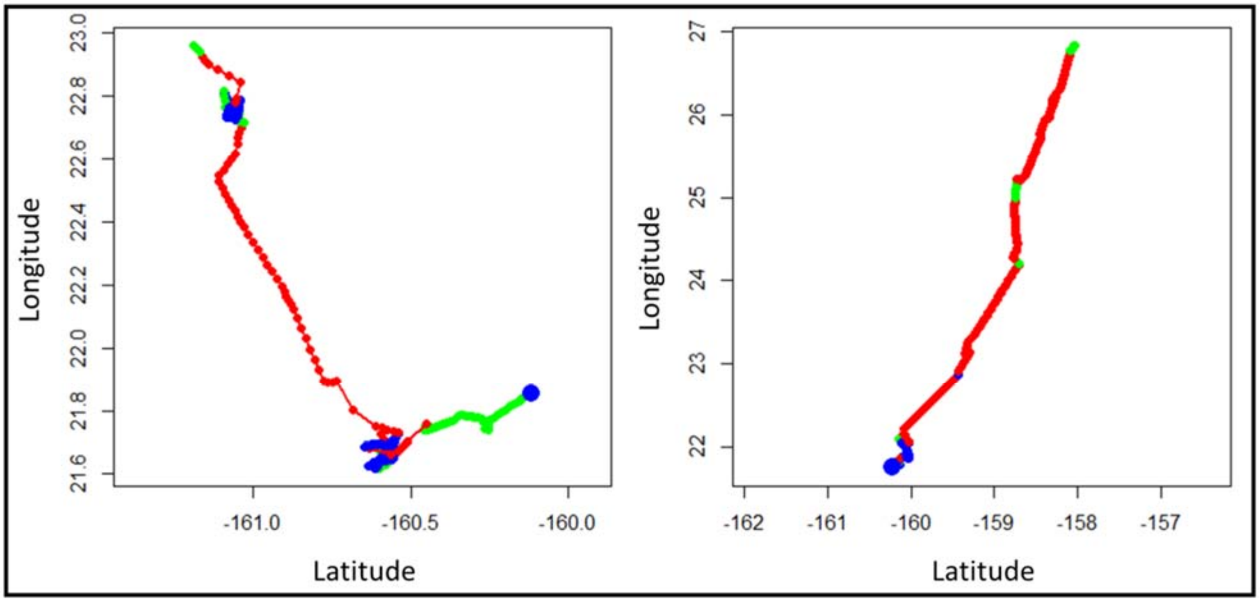

Figure 4: Track of tagged humpback whales 158670 (left) and 164791 (right) with Markovian behavioral states based on distance per 20 min interval shown with colors corresponding to different states (blue locations have a mean distance of 0.002 degrees, green tracks 0.01 degrees, and red tracks >0.02 degrees). The tracks were modeled with 14 and 16 segments, respectively, with shorter distances and slower speeds occurring when the whales are near islands or seamounts, and longer distances and faster speeds as the whales move across deeper water.

Dive data are summarized in Table 3. The number of dives recorded for each whale ranged from 77 to 370, with mean dive durations ranging from 7.6 to 29.6 min. Dive depths were on average 29.2 to 38.7 m (SD 7.2 to 10.6 m), with maximum depths reaching 172.0-395.5 m. Dive depths increased as the whales moved between islands and seamounts; in fact, dive depths were significantly correlated with seafloor depth such that dives remained shallow in shallower waters but then began to deepen when the whales moved into deeper waters (Rho = -0.14 to 0.35, p-value < 0.001 to 0.036; e.g., Figures 5 and 6). Daytime hours were considered to have occurred between 6:30 and 18:30 for this analysis based on approximate sunrise/sunset times. Generally, day and night were evenly sampled across all dive data, with daytime dives making up 42.3% - 52.8% of all dives (mean 48%); the exception was whale 164793, for which 70.4% of its dives occurred in the daytime. This, however, was the shortest duration tag and only sampled one nighttime period. Dive depths also correlated significantly with time of day, such that more deep dives occurred at night (Rho = -0.22 to 0.18, p-value < 0.001), with the exception of tagged whale 158670 (p-value = 0.27) who conducted a series of deep dives during the first tagged day (Figure 6), presumably in the channel between Kauai and Niihau although there were no satellite positions during that period. The seafloor depths for the interpolated locations were derived using gridded bathymetric data. However, the dive data was almost continuous, and so the same seafloor depth may have been applied across the entire 20 min period between surface positions even though the whale had actually moved into deeper or shallower water. Therefore, as evidenced in Figures 5 and 6, there are some dives that appear to occur at a greater depth than the seafloor, but in most cases the dive depths aligned well with the estimated seafloor depths.

Table 3: Summary of dive bin data.

Tag ID	**Number Dives**	**Mean Duration (min)**	**Mean ± SD Depth (m)**	**Max Depth (m)**	**% Daytime Dives**
158569	154	7.55	31.95 ± 8.9	358.5	42.3%
158570	280	9.74	34.77 ± 10.6	297.5	51.2%
158571	370	20.40	29.49 ± 7.36	238.5	50.7%
164790	264	11.68	29.23 ± 7.2	172.0	47.0%
164791	286	25.31	38.68 ± 8.89	395.5	44.0%
164792	80	29.55	37.94 ± 8.3	287.5	52.8%
164793	77	20.93	31.85 ± 8.8	238.5	70.3%

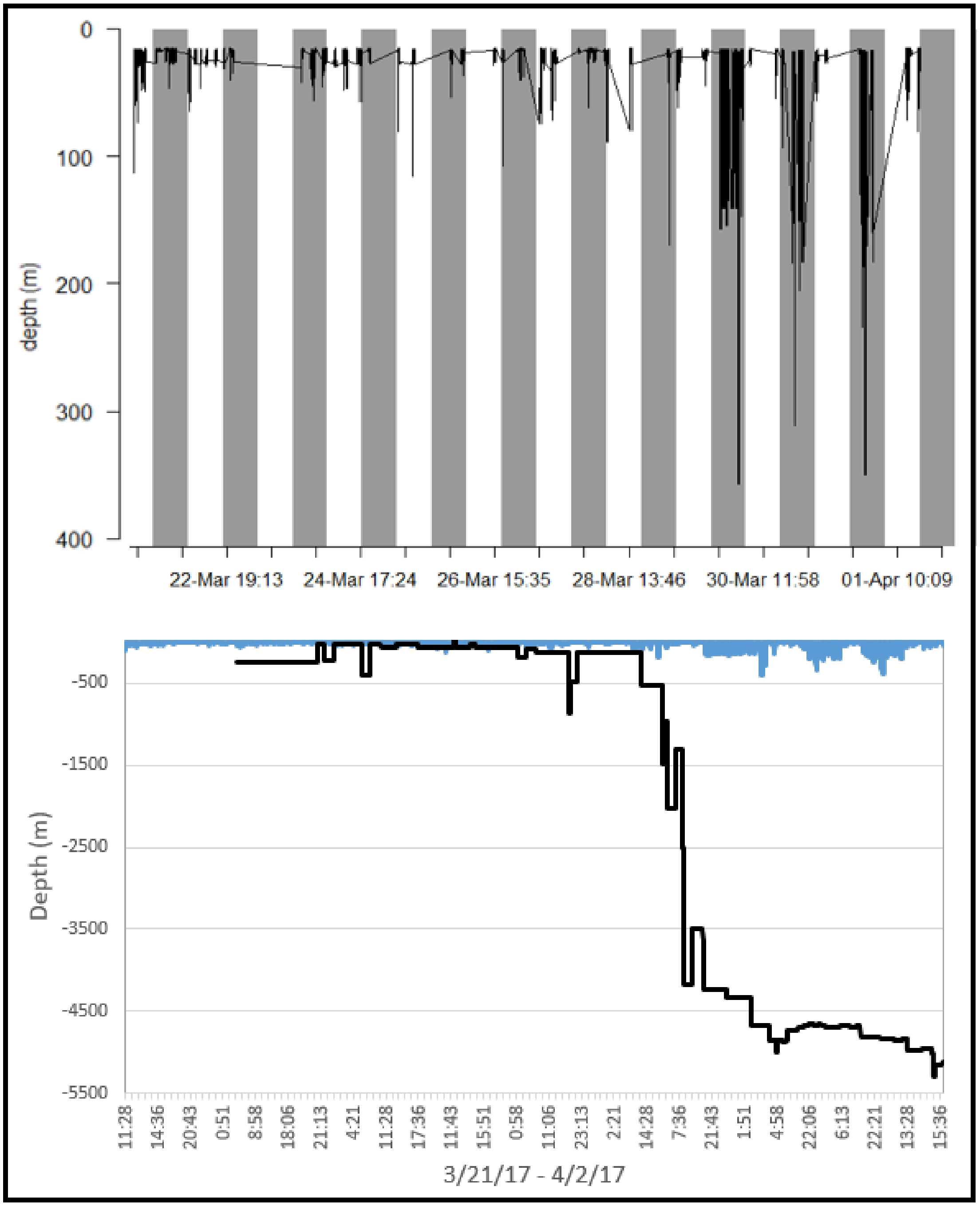

Figure 5: Dive profile for tagged humpback whale 164791. The top figure depicts the day hours with white bars and the night hours with gray bars, while the bottom figure shows the same dive profile in blue along with the concurrent seafloor depth in black. The longer, deeper dives begin once the whale has moved into the deeper waters; these dives also occur largely at night.

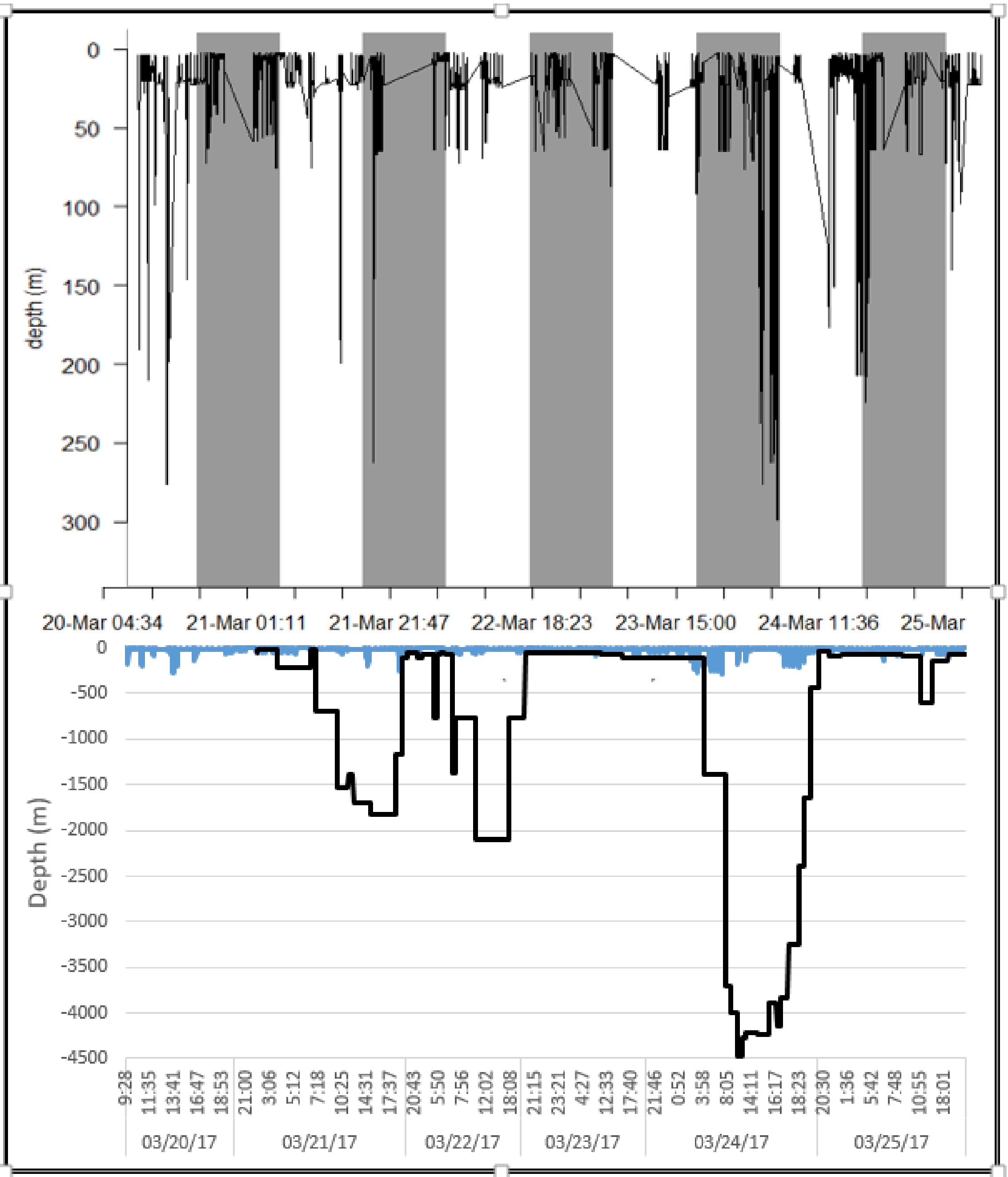

Figure 6: Dive profile for tagged humpback whale 158670. The top figure depicts the day hours with white bars and the night hours with gray bars, while the bottom figure shows the same dive profile in blue along with the concurrent seafloor depth in black. Again the pattern of longer, deeper dives over deeper waters with shallower dives near islands and on seamounts is evident, along with the deeper dives occurring largely at night (except for the initial dives on the first day).

Discussion

Seven presumably male humpback whales were satellite tagged in the waters of Kauai, Hawaii near the end of their breeding season. All seven continued moving west and spent some time around the island of Niihau. One whale began traveling north from there, while the other six whales continued moving west/northwest, appearing to follow seamounts along the Hawaiian archipelago. While close to the islands or over seamounts, the movement behavior of all seven animals demonstrated slower travel speeds and low directivity, similar to milling or area-restricted search (ARS) behavior (e.g., Bailey *et al.* 2009). When the whales were located in these shallower waters, their dives were also shallow, and often utilized the extent of the available water column. In contrast, when the animals traveled between these shallower areas, their speeds and directivity increased, and their dives began to deepen. The deepest dives largely occurred at night, but only when the whales were in deep offshore waters. The two whales with the longest attachment periods began to have longer stretches of faster, straighter travel as they began their migrations; we can only hypothesize that would have been true in all cases had the tags remained on longer, but cannot know for sure.

Mate et al. (1998) tagged six humpback whales off the southwest coast of Kauai in 1995, also in late March and early April. While they also found most animals moving from east to west across the channel between the islands, two of the whales ultimately traveled east to the other main Hawaiian Islands, while one remained near Kauai and then headed northeast, and two traveled almost due north towards Alaska. Only one of the whales went to Niihau briefly before moving north, in contrast to all seven whales in the present study spending 1.0 to 7.9 days around Niihau, and six of the whales continuing a northwest movement. The behavior in the present study was similar to that observed for humpback whales off New Caledonia and Socorro Island, Mexico, where the whales meandered near other islands and seamounts, or other wintering grounds, before beginning their directed migration travel (Lagerquist *et al.* 2008, Garrigue *et al.* 2010). The two whales with the longest tag attachments in the present study did begin more directed travel behavior once leaving the islands and seamounts, with travel speeds increasing from 1.1 – 3.0 km/hr to a fairly consistent 5.5 km/hr. Similarly, non-directed movement and slower swimming speeds of 1.2 – 3.3 km/hr have been observed while humpback whales are on their breeding grounds or nearby shallow areas (Mate *et al.* 1998, Lagerquist *et al.* 2008, Kennedy *et al.* 2014), while faster speeds of 2.8 – 6.5 km/hr have been recorded during the directed travel of migration (Mate *et al.* 1998, Noad *et al.* 2004, Lagerquist *et al.* 2008, Horton *et al.* 2011, Kennedy *et al.* 2014). These increased speeds, along with their track directivity and direction of travel, further supports the idea that at least two of the humpback whales in this study started migrating before the tags ceased transmitting.

The behavior observed while the animals were near islands or seamounts could be described as milling or ARS. While ARS is often linked with foraging, it could also indicate milling, resting, or breeding behavior. Bailey *et al.* (2009) observed ARS in blue whales (*Balaenoptera* *musculus*) in both January, at the end of their southbound migration, and in June and July, at the end of their northbound migration in the North Pacific; the latter time period is likely indicative of foraging, but the former may have indicated foraging as well as resting or breeding. Kennedy *et al.* (2014) observed very little ARS on the breeding grounds of humpback whales in the North Atlantic, but one of the whales began displaying ARS 200 km south of Kelvin Seamount near feeding grounds on the Gulf of Maine. While not designated as such, Garrigue *et al.* (2010) observed ARS-type behavior in the humpback whales that spent time near the island of New Caledonia or over nearby seamounts. In addition, Mate *et al.* (2007) tagged a humpback whale that may have been feeding near the Kermit-Roosevelt Seamount during its migration from Hawaii, and one of the humpback whales tagged near Socorro Island in Mexico spent nine days in an area frequented by foraging turtles and blue whales (Lagerquist *et al.* 2008) and may have also been foraging. Therefore it is possible that the ARS-like behavior in this study could correspond with some opportunistic foraging over shallow, productive seamounts before migrating.

This hypothesis may be supported by the diving behavior of the humpback whales. While in the shallow waters near Niihau and over the seamounts, many of the dives appeared to use the full extent of the water column. Humpback whales are known to forage near the seafloor, typically in shallow waters (e.g. 30 - 80 m; Parks *et al.* 2014); the depths of the seamounts here range from 20 – 70 m. In this study, once over open waters where depths were up to 4 km or more, the humpback whales conducted their deepest dives to 172 – 396 m, the majority of which were nocturnal. In previous studies, resting behavior occurred primarily in the morning, the surface activity of competitive pods (when dives might be expected to be shallower) tended to peak during the afternoon, and singing was recorded day and night with a possible increase at night (Baker & Herman 1981, Mobley & Herman 1985, Helweg & Herman 1994, Au *et al.* 2000). In addition, Henderson *et al.* (2018) used passive acoustic monitoring to localize singing humpback whales and found 200-300 m dives while milling (remaining in one localized area). Therefore, these deeper nighttime dives in open water could indicate singing, as singing has been recorded on the migration route (Norris *et al.* 1999) and on feeding grounds (McSweeney *et al.* 1989, Clark & Clapham 2004, Vu *et al.* 2012). Stimpert *et al.* (2012) recorded singing humpback whales on Antarctic feeding grounds diving over 100 m while singing, and recorded singing during feeding lunges. This behavioral plasticity of humpback whales could mean that the whales are opportunistically foraging before and during migration, or could simply be continuing their active competitive behavior and singing, or both. Additional tagging would further inform the potential implications of these results.

The use of distance between interpolated positions provided a simplistic but effective means of separating the track behavioral states into ARS, directed travel, and an intermediary state with moderate speeds and directivity. However, the inclusion of additional variables such as speed or turning angle could improve and refine the model even further. Furthermore, applying a similar analysis to the dive data may provide insight into diving behavior, such as has been conducted for sperm whales (*Physter macrocephalus*) in the Gulf of California (Irvine *et al.* 2017). Finally, the inclusion of environmental variables as predictors could further illuminate the movement and dive behavior of humpback whales as they begin their migration from Hawaii to Alaska.

None of the tagged whales spent time over the hydrophones at PMRF while tagged, although one animal (164792) was resighted twice near the range and was the only animal to return to the channel between Niihau and Kauai once tagged. However, the highly transitory behavior of all tagged and observed animals, with only two resighted animals and most animals moving from east to west, suggests that the channel between Kauai and Niihau is not a region regularly used by individuals for behavior other than transit. If that is the case, then the potential for behavioral impacts from Navy training activity on the range is low, as animals would likely be exposed only briefly to sonar and other related anthropogenic stressors as they move through the area, and would already be located south of the range and moving west, which could help reduce the exposure level. Additional observations are warranted, including continued tagging and photo-ID of individuals, to further determine the habitat use patterns of humpback whales in this area and if any animals demonstrate inter-annual site fidelity to the area. Observations conducted earlier in the breeding season may find different patterns of behavior and should also be conducted to investigate seasonal shifts in habitat use. Similarly, observations conducted within 3 nmi of the shore could also find animals in different behavioral states, as those encountered in offshore waters in this study may already have been in transit. A better understanding of humpback whale behavior in the offshore waters of an active Navy training and testing range will provide a baseline against which to compare behavior during training events to determine if a behavioral response may occur. This would be a complement to the ongoing passive acoustic monitoring of humpback whales and other cetacean species on PMRF (Martin *et al.* 2013, Helble *et al.* 2015, Henderson *et al.* 2016, Manzano-Roth *et al.* 2016, Henderson *et al.* 2018). Future efforts, including a field season in 2018, will also incorporate an active pinger tag for those animals encountered on the range, in order to track their movements with a finer resolution than can be done with a satellite tag. These tags could also provide behavioral response data if the animals are found on or near the range during a training event.

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Appendix A

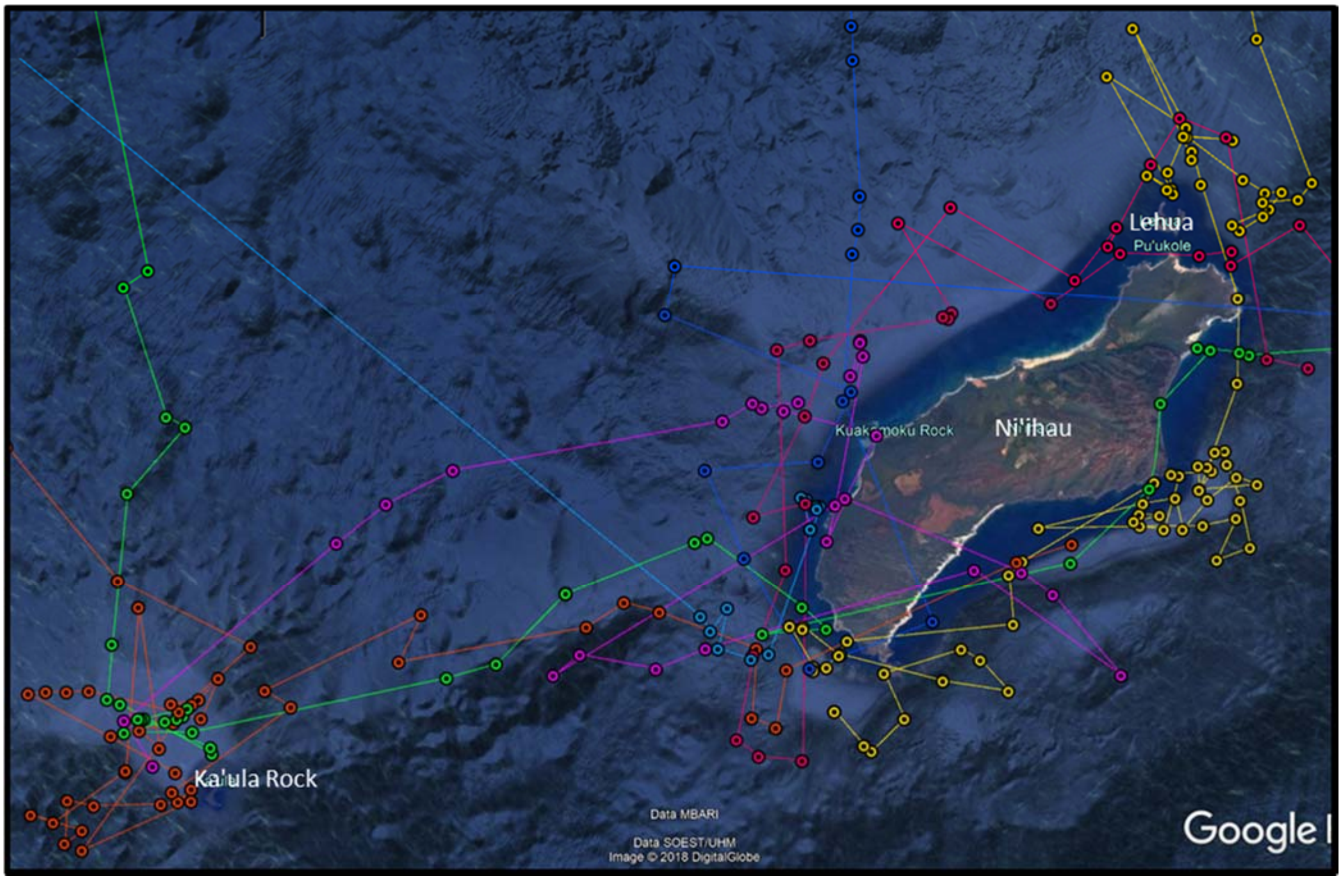

Figure A-1: Satellite-derived filtered location positions and tracks of all seven tagged humpback whales zoomed in to show the movement around Kaʻula Rock and Niʻihau.

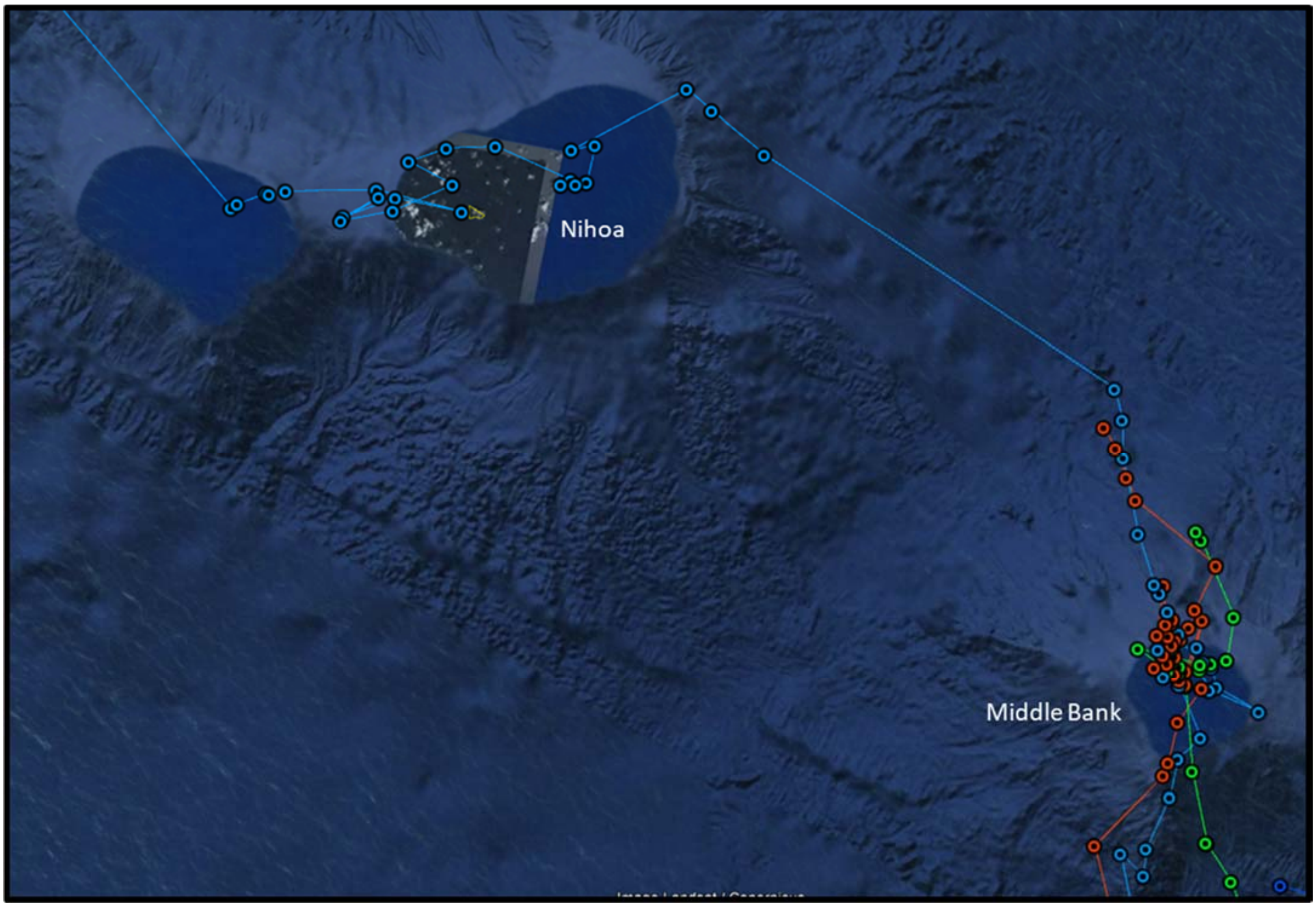

Figure A-2: Satellite-derived filtered location positions and tracks of four tagged humpback whales zoomed in to show the movement around Middle Bank and Nihoa.