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FY20 Annual Report on Pacific Missile Range Facility Marine Mammal Monitoring

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14. ABSTRACT

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1. Raw acoustic data from 62 bottom-mounted hydrophones at PMRF were recorded at the full bandwidth sample rate of 96 kHz and at a decimated sample rate of 6 kHz. This report updates last year's report with inclusion of 2,972.2 hours of new data collected from September 7, 2019 to September 2, 2020. Additional decimated data were recorded in the spring of 2020 to capture acoustic conditions and whale presence at the beginning of the COVID-19 pandemic.
2. Abundance results for baleen whales from September 7, 2019 to September 2, 2020 indicated that a maximum of four minke whales were detected in a 10-minute snapshot period in February 2020, while a maximum of three humpback whales were detected in March 2020. Similarly, there was a maximum of three tracks from the low-frequency baleen whale group that occurred in 10-minute snapshot periods in January and February 2020. Spectral correlation call templates were utilized to attribute calls from acoustic tracks to fin, Bryde's, and a 40 Hz down sweep call type (potentially from fin and/or sei whales).
3. For the first time, all available data collected on hydrophones with sufficient frequency response to detect low-frequency baleen whales (January 11, 2011 to September 2, 2020) were processed and all tracks were fully manually

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4. Abundance results for odontocetes from September 7, 2019 to September 2, 2020 included Blainville's, Cross Seamount (CSM), and Cuvier's beaked whales, sperm whales, and killer whales. The number of FY20 Blainville's beaked whale dives were corrected based on sample validation of four FY20 baseline recordings (96% true positive rate and 4% false positive rate) and there was a monthly maximum of 4.44 dives per hour (October 2019). The number of fully validated FY20 CSM beaked whale dives had a strong diel trend at night and occurred far less frequently than Blainville's beaked whale dives, resulting in a monthly maximum of 0.45 dives per hour (July 2020). The number of fully validated FY20 Cuvier's beaked whale dives had a slightly lower number of group foraging dives per hour than CSM beaked whales, with a monthly maximum of 0.19 dives per hour (May 2020). Killer whale high-frequency modulated (HFM) call groups were not detected in any FY20 recordings. There was a maximum of four sperm whale tracks detected in a 10-minute snapshot period in April 2020.

5. Killer whale HFM call groups detected since 2002 were analyzed for a possible diurnal trend that was noticed in Martin et al. (2020). Seventy-seven percent of HFM call groups (37 of 48) began during daylight hours while the remaining 13% of HFM call groups were detected when the moon was over three-quarters full, indicating a very strong trend that is not just diurnal, but potentially dependent on illumination.

6. Longman's beaked whale frequency modulated (FM) clicks were documented on the September 7, 2019 recording. Future efforts will focus on tuning the beaked whale classifier to both identify the Longman's beaked whale FM click and improve the false negative rates of the Cuvier's and CSM beaked whale classifiers.

7. Disturbance analyses were conducted at PMRF for minke whales and Blainville's beaked whales during the February and August 2020 Submarine Command Course (SCC) training events.

a. The three minke whale tracks that overlapped with the February 2020 SCC were investigated. The first minke whale was not exposed to mid-frequency active sonar (MFAS) and may have demonstrated a behavioral reaction by briefly changing its call rate when the closest non-active ship was 11.9 km away and the animal was in the starboard beam sector. The second minke whale was only exposed to MFAS in in the first 5-minute bin of the track. The cumulative sound exposure level (cSEL) for the first bin, and therefore the entire track, was 157 dB cSEL re: 1μPa2s. Later in the track the second minke whale may have demonstrated a behavioral response by making an apparent heading change when the distance to the closest ship not transmitting sonar decreased from 22 km to 8.1 km. The third minke whale track had a minimum distance of 896 m to the closest ship not transmitting sonar, which is the shortest distance that we have ever reported for PMRF. Despite this very close encounter, the third minke whale did not exhibit an apparent change in heading or call rate.

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8. Under a related effort, improved disturbance analysis methods were developed for estimating the received levels (RL) on tagged marine mammals. A continuous-time correlated random walk model was fitted to the tag positions using the R package crawl (Johnson and London, 2018) and estimated position errors were used to calculate whale location error ellipses. Combined with measured and modeled whale depths, RLs can be characterized for a 3D sound field. These improved methods are summarized in this report, and full methods and results are reported separately by Henderson et al. (2021).

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a. Following the effort that investigated the Lombard effect in minke whales (Helble et al. 2020a), the Lombard effect in humpback whales was investigated and results were published by Guazzo et al. (2020). Source level (SL) and noise level (NL) were measured over the 150–1000 Hz band and humpback whale song units had a median SL of 173 dB re 1 μPa at 1 m, and SLs increased by 0.53 dB/1 dB increase in background NLs.

b. One second power spectral density levels were integrated over the minke whale detection band (1320 to 1440 Hz) every minute and peaks in NL during the SCC were documented for the first time. In addition, daily peaks in noise in the 1400 to 1800 Hz band were discovered in recordings and the source is hypothesized to be from species (micronekton and/or fish) of the vertical migration in Hawaii. These peaks in noise levels from anthropogenic and natural sources have not been documented previously and further investigation is important to understanding how these types of increases in NL can impact the detection/classification and localization of whale calls.

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EXECUTIVE SUMMARY

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ACRONYMS

A2D	Analog-to-Digital
BREVE	Behavioral Response Evaluation
BRS	Behavioral Response Study
COMPACFLT	Commander, Pacific Fleet
crawl	Continuous-time correlated random walk model R package *crawl* (Johnson and London, 2018)
CREEM	the Centre for Research into Ecological and Environmental Modeling
CRW	Correlated Random Walk
cSEL	Cumulative Sound Exposure Level
CSM	Cross Seamount Beaked Whale
CY	Calendar Year
DCL	Detection Classification Localization
E-BREVE	Environmentally-influenced Behavioral Response Evaluations
FM	Frequency Modulated
FY	Fiscal Year
GMT	Greenwich Mean Time
GPL	Generalized Power Law
HFM	High Frequency Modulated
HST	Hawaii Standard Time
ICI	Inter-Call-Interval
INI	Inter-Note-Interval
LMR	Living Marne Resources Program
M3R	Marine Mammal Monitoring on Navy Ranges
MFAS	Mid-Frequency Active Sonar
NARWHAL	Navy Acoustic Range Whale Algorithms
NIWC Pacific	Naval Information Warfare Center Pacific
NL	Noise Level
NOAA	National Oceanic and Atmospheric Administration
NUWC Newport	Naval Undersea Warfare Center Newport
ONR	Office of Naval Research
PAM	Passive Acoustic Monitoring
PMRF	Pacific Missile Range Facility
PSD	Power Spectral Density
RL	Received Level
SCC	Submarine Command Course
SL	Source Level
WARP	Whale Acoustic Reconnaissance Project

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1. Introduction

In fiscal year (FY) 2020 the Naval Information Warfare Center (NIWC) Pacific Whale Acoustic Reconnaissance Project (WARP) Laboratory (San Diego, California) utilized passive acoustic data recordings from bottom mounted range hydrophones at the Pacific Missile Range Facility (PMRF), Kauai, Hawaii to monitor vocalizing marine mammals both during baseline periods and during U.S. Navy training activities.

The overall FY20 goals of this ongoing effort were 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 (DCL) algorithms;

2) Understand short-term and long-term baseline occurrence patterns and quantify abundance for multiple marine mammal species;

3) Estimate sound levels that marine mammals are exposed to during U.S. Navy training with hull-mounted mid-frequency active sonar (MFAS), and investigate behavioral responses;

4) Test and evaluate concurrent data recordings collected on NIWC Pacific's legacy PC recorder, and the Marine Mammal Monitoring on Navy Ranges (M3R) packet recorder. As discussed in Section 4.1, the Living Marine Resources (LMR) Program funded an effort in late FY20 to upgrade the NIWC Pacific legacy PC recorder, and development and testing of the new NIWC Pacific recorder is currently underway.

5) Collaborate with researchers conducting other monitoring efforts (e.g. MFAS exposure and response to tagged animals), along with other U.S. Navy laboratories, academic institutions, and research organizations, to fill data gaps and provide a more complete monitoring data product.

Overall, this report highlights multiple areas where progress was made in FY20. Fin whale song patterns were analyzed over time utilizing baseline data recorded from 2011 to 2017. Calls were classified by using spectral correlation call templates and tracks were manually validated using tools described in Section 3.1.4. Data recorded from 2011 to 2020 were analyzed and manually validated tracks for Bryde's, fin, and a 40 Hz downsweep call type (potentially from fin and/or sei whales) are presented in Section 4.2.3.1.

Under a related effort, the methods for estimating received levels (RLs) on whales exposed to MFAS during U.S. Navy training at PMRF were improved in FY20 in multiple ways, including fitting a continuous-time correlated random walk model to the tag positions using the R package *crawl* (Johnson and London, 2018) to estimate position errors, then utilizing the resulting whale location error ellipse information to represent the RLs as 3D sound fields. These improvements were developed to analyze exposures on tagged whales and are summarized in Section 4.3.1 and are reported separately by Henderson et al. (2021).

An investigation of the integrated power spectral density levels over the minke whale boing detection band (1320 Hz to 1440 Hz) was done using baseline data and classified data collected during the February 2014, 2015, and 2017 Submarine Command Course (SCC) training events. In addition, daily peaks in noise in the 1400 to 1800 Hz band were discovered in recordings and the source is hypothesized to be from species (micronekton and/or fish) of the vertical migration in Hawaii. This analysis was performed to obtain insight into how variable the various sounds in a species' detection band behave and are presented in Section 4.4.2

2. Methods

2.1 PMRF RANGE DATA

Passive acoustic monitoring (PAM) data were recorded for 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) has been provided in prior reports (Martin et al. 2017, Martin et al. 2018).

In FY20, three types of acoustic recordings were obtained:

1) Standard full-bandwidth recordings at the 96 kHz native sample rate (frequency response up to approximately 45 kHz) were recorded during two separate periods of time (for a minimum of 24 hours and up to a maximum of 45 hours) a month for 62 hydrophones.
2) Decimated data recordings at the reduced sample rate of 6 kHz provide 3 kHz of bandwidth for longer duration baseline sampling of both baleen whale vocalizations and lower frequency noise conditions. Additional decimated recordings were made in the spring of 2020 to capture acoustic conditions and whale presence at the beginning of the COVID-19 pandemic.
3) Select full-bandwidth data were concurrently collected using the NIWC Pacific legacy PC recorder and the M3R packet recorder developed by NIWC Pacific and Naval Undersea Warfare Center (NUWC) Newport to evaluate the performance of the M3R packet recorder. Full bandwidth data collected on the M3R packet recorder utilized the same 62 hydrophones, and an additional 39 high-pass hydrophones for a total of 101 channels recorded.

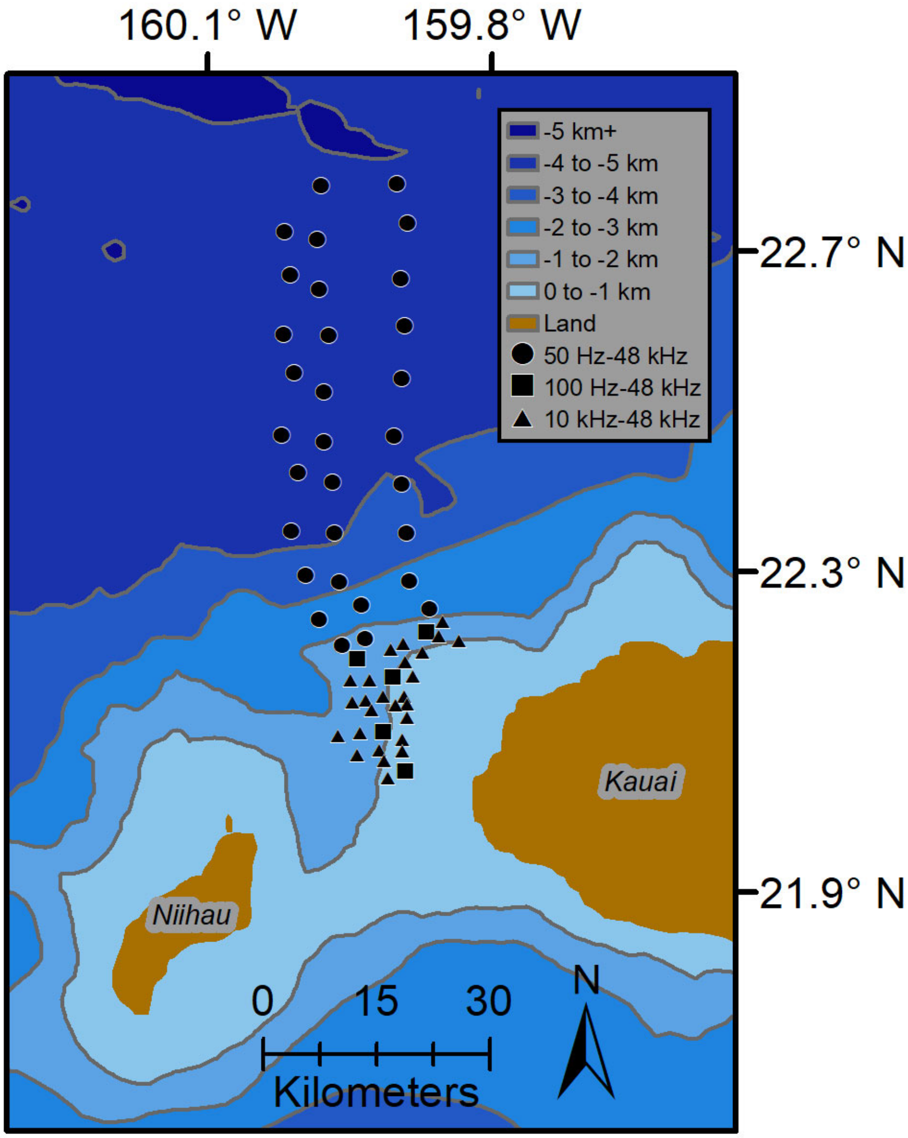

Figure 1: Hydrophone array configuration at PMRF's instrumented range. Symbols indicate the approximate location of the 62 hydrophones recorded in FY20 and their frequency response range.

3. Navy Acoustic Range Whale Analysis (NARWHAL) Algorithm Suite

3.1 AUTOMATED DETECTION, CLASSIFICATION, AND LOCALIZATION ALGORITHMS

Multiple algorithms are utilized to process PMRF recorded data to detect a variety of marine mammal vocalizations and to localize and track individuals when possible. A custom C++ detection algorithm automatically processes detections of beaked whales (Blainville's, Cross Seamount [CSM], and Cuvier's), killer whales, sperm whales, baleen whales (minke whales, and the low-frequency baleen group of whales not identified to specific species [Bryde's, fin, sei, and blue whales]), and MFAS transmissions. When post-processing recorded data, different operating points (i.e. algorithm versions and parameters) can be utilized, and the data are available for 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 five times faster than real-time.

A custom Matlab Generalized Power Law (GPL) algorithm separately processes detections and localizations for humpback whale song, blue whales, fin whale song, Bryde's whales, possible sei whales, and the 40 Hz downsweep call type (potentially from fin and/or sei whales). Classification of fin whale song, Bryde's whales, possible sei whales, and the 40 Hz downsweep call type requires additional steps. This includes semi-automated tracking so only calls that form tracks are further analyzed, automatic classification of tracked localizations utilizing call templates, and manual investigation to validate automatic classification results. These algorithms have been discussed in detail in peer-reviewed journal publications and reports (Helble et al. 2012, Helble et al. 2015, Helble et al. 2016, Henderson et al. 2016, Henderson et al. 2018, Manzano-Roth et al. 2016, Martin et al. 2015, Martin et al. 2016, Martin et al. 2017, Martin et al. 2018, Martin et al. 2019, Helble et al. 2020b).

3.1.1 Tracking for Annual and Long-Term Abundance

The existing semi-automated Matlab localization association tracker was previously described in Martin et al. (2018), and was utilized to track automated localizations from baleen and sperm whales. Advancements to sperm whale processing which enabled tracking, and development of new parameters for sperm whale tracking were presented by Alongi et al. (2019) and were previously reported in Martin et al. (2019) and Martin et al. (2020). Tracks of individual whales continue to be analyzed via systematic snapshots for 10-minute periods where a whale is counted as present if a tracked call occurs in a 10-minute period. This allows a census-type abundance estimate of whale counts in the study area.

The number of tracks represented by the snapshot results is a stable metric; whale tracks that occur over the PMRF hydrophone array are assumed to have: a probability of detecting a calling whale equal or very close to 1.0; a high probability of localizing all calls within a track; and improved localization accuracy as compared to tracks outside the array. As one extends the study area beyond the hydrophone array, both localization accuracy and the probability of detecting whale tracks decreases. For individual whale track results presented in Section 4.2 a smaller study area of ~1,200 km^2 (22.8° to 22.275° N-S and -159.85° to -160.05° E-W), which encompasses the hydrophone array, was utilized for tracking. Low-frequency baleen whale tracks in Section 4.2.3.1 utilized a larger study area of ~12,500 km^2 (23.1° to 22.0° N-S and -159.5° to -160.5° E-W) centered on the hydrophone array. At some point outside of the hydrophone array the assumption of direct path propagation becomes invalid. We are currently working towards automatically identifying indirect path calls and potentially in the future will be able to utilize indirect path propagation for localizing calls. Although the low-frequency baleen whale tracks in Section 4.2.3.1 could potentially occur far outside of the hydrophone array, and tracked localizations could include indirect path detections and have high positional error, the calls in these tracks have been fully validated and there is high confidence in classification of the results.

The species that are not able to be localized and individually tracked include Blainville's, CSM, and Cuvier's beaked whales, killer whales, and sometimes sperm whales when multiple whales form close foraging groups and click rates increase. The calls detected from the beaked whale species and killer whales occur when multiple individual whales are within close proximity and emitting similar calls, such as the case when beaked whales emit echolocation clicks during a group foraging dive, and dive count is the metric used to quantify abundance for that species.

The number of tracks and group dives can be used to estimate abundances but are limited to the number of animals vocalizing and are often related to behavioral state. Overall, these numbers represent a minimum number of calling whales and can be converted to a minimum density of animals on the range. To extend PAM analyses to include all members of a baleen whale species requires additional information relating the proportion of calling whales (e.g. males) to all whales (i.e. females, calves, and juveniles), which is currently unknown. For some odontocete species (e.g. beaked whales) the group foraging dives can be converted to a minimum density of animals by employing an average group size.

3.1.2 Disturbance Analysis

Disturbance analysis is the process of investigating whether whale presence overlaps with and is affected by anthropogenic activities such as MFAS transmissions and close proximity of ships (even when not transmitting MFAS), thereby conducting an opportunistic, passive acoustic behavioral response study (BRS). When overlap occurs, a variety of metrics are calculated/estimated such as whale orientations (i.e. moving towards or away), ship orientations relative to the whale, and distances relative to all ships. When ships are transmitting sonar (i.e. during SCC exercises as determined by PAM analysis of MFAS localizations), complex propagation modeling is conducted to calculate sound levels that an animal may have received from multiple ships over the duration it was acoustically present.

The NIWC WARP Laboratory is working collaboratively with Cascadia Research Collective (Dr. Robin Baird and Michaela Kratofil) and Southall Environmental Associates Inc. (Dr. Brandon Southall) in a systematic analysis of available satellite tagged odontocetes (short-finned pilot whales, rough-toothed dolphins, and bottlenose dolphins) between 2011 and 2020. New methods are under investigation to estimate the RL; one approach uses a similar approach to Shick et. al (2019) using imputed whale locations, while a new approach uses systematic azimuthal slices that intersect with the 95% confidence interval of the whale location error ellipse. A summary of the improved disturbance analysis methods applied to tag data are presented in Section 4.3.1. These recently developed improvements are reported as a separate and concurrent/related effort (Henderson et al. 2021) and the improved processes will be carried over to the disturbance analysis process for PAM animal tracks in FY21.

The NIWC WARP laboratory is also working collaboratively with the Centre for Research into Ecological and Environmental Modellng (CREEM) at the University of St. Andrews (Dr. C. Harris, Dr. I. Durbach, and Dr. L. Thomas) to quantify behavioral responses of baleen whales to MFAS. Prior efforts have shown that boing calling minke whales' spatial distributions are different using a before, during and after paradigm (Harris et al. 2019). More recent efforts have shown whales increase their speed and have more directional movement during periods of MFAS activity, and that the movement can be attributed to MFAS ships (Durbauch et al. 2021).

3.1.3 Noise Analysis

The primary goals of conducting noise analyses on PMRF acoustic data are to better understand how PAM processing results are affected by noise levels, and to assess vocal behavioral changes relative to environmental noise levels. The noise analyses characterize noise in relevant frequency bands of interest to look for changes in noise over a wide variety of spatial and temporal scales, and to assess any impact these changes may have on detecting and localizing marine mammal vocalizations. Results from noise analyses are also utilized for internal purposes, summarized in Martin et al. (2020), to identify data dropouts or suspicious “unnatural” noise readings that could affect recording effort. The noise results are also used to look for long-term trends in changes in ambient noise.

In FY20, the noise results were utilized to investigate the Lombard effect in minke and humpback whales and were published in Helble et al. (2020a) and Guazzo et al. (2020), respectively. A summary of the findings from these publications are presented in Section 4.4.1. Noise results were also utilized to investigate integrated power spectral density levels over the minke whale boing detection band (1320 Hz to 1440 Hz) during baseline conditions and multiple SCC training events, and is summarized in Section 4.4.2.

3.1.4 Additional Tools

To classify tracks of baleen whales vocalizing between 10-50 Hz, we developed a tool to allow us to manually inspect the track and categorize it. This tool displayed a map of each track, two plots showing inter-call intervals for the vocalizations detected for that track, and images of the call templates extracted by the Matlab GPL algorithms. An analyst looked at all of this information and classified each track into one of the following categories: (1) likely fin whale, (2) Bryde’s whale, (3) sei whale, (4) 40 Hz downsweep calls (potentially from fin and/or sei whales), or (5) none of these. Calls that we think can be likely attributed to sei whales are downswept from 80-100+ Hz to 30-50 Hz, and are comparable to recordings collected by Rankin and Barlow (2007). These calls are hard to classify looking only at 10-50 Hz data, so they are most likely grouped into category 4 above. Sei whales are also reported to produce calls that are very similar to fin whale B calls (Rankin and Barlow 2007), which is why category 1 is described as “likely” fin whale. We believe category 1 is fin whale, because these tracks often consist of both A and B notes (sei whales are not known to produce vocalizations similar to the fin whale A note) and occur in regular, repeated patterns, which have not been observed in sei whales in the North Pacific (see Helble et al. 2020b for more details). Category 5 contains both sounds from higher frequency whales (likely humpback) which extended into the 10-50 Hz band or false detections that are not believed to be from whales.

An additional tool was also developed to more easily view the raw acoustic data associated with the Matlab GPL detection and localization outputs. Down-sampled 4-channel acoustic data from each of the 4 array center hydrophones can now be saved automatically as .wav files during the GPL processing stage, and Raven selection tables compatible with the Raven Pro software package 2019 can also be generated. Viewing the raw acoustic data and the associated detections and/or localizations with Raven Pro allows the user to determine if any calls were missed during the localization process, in which case they can be manually added to the track. This process is especially important when cue rate is being calculated, as any missed calls in the automatic detection/localization process would result in an undercount of the acoustic cue rate. Examining the detections in relation to the raw acoustic record also gives better situational awareness for detector performance and for observing other interesting events or signal types that may have been missed by the automated processing algorithms.

We also developed a tool for measuring the inter-note interval (INI) between subsequent notes in fin whale song. This automated process also determined whether the INI pattern was a singlet (constant INI) or doublet (alternating between two different INIs) pattern. The process is described in detail and the code is provided in Helble et al. (2020b), but we will discuss it briefly here. The INI for each note type pairing (A-A, A-B, B-A, B-B) was calculated by measuring the time between the start of the first note and the start of the subsequent note. Intervals between subsequent notes were only counted as INIs if the value was less than or equal to 60 seconds. The peak INIs for each of the note pairings within a track were determined by fitting a Gaussian model to the distribution of INIs, in 1 second bins. The Gaussian model was either a single-term model for a single INI peak or a two-term model for two INI peaks. The model with the least uncertainty was selected. This method resulted in smoothed curves that matched the distribution of the observed INIs (Figure 2). The spread of the INIs was quantified by measuring the width of each INI peak at half of its height. Peak INIs were only calculated for tracks that had at least 20 instances of that note type pairing. The one- and two-term models allowed for an automatic and consistent way of determining if a track contained singlet (single peak) or doublet (two peak) singing patterns for each note pairing.

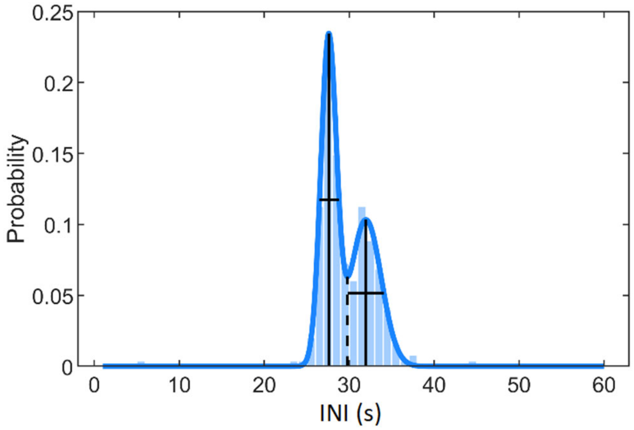

Figure 2: Distribution of inter-note intervals for an example A-A doublet track from February 9, 2015. The true distribution of INIs is plotted in the background and the two-term Gaussian model that was fit to this distribution is plotted as the curved blue line. The INI peaks are shown as solid vertical lines and have values of 28 and 32 seconds. The spread of the distributions is shown as solid horizontal lines at y-values of half the peak height and have values of 2.3 and 4.3 seconds. The dashed vertical line at the local minimum of the fitted curve divides the two peaks.

4. Results and Discussion

4.1 PMRF RANGE DATA COLLECTION RESULTS

The FY20 data utilized for this report spanned September 7, 2019 to September 2, 2020 with the exception of Bryde's, fin, and sei whale results in Section 4.2.3.1, since those results have not been previously provided. The previous annual report (Martin et al. 2020) utilized data between August 18, 2018 and August 25, 2019. The total hours of recording effort for full bandwidth and decimated data collections, and the percentage of total time recorded are shown in Table 1. Overall, full bandwidth and decimated data collections recorded 32.7% of the total time between September 7, 2019 and September 2, 2020. Four recordings in January 2020 were concurrently collected on NIWC Pacific's legacy PC recorder and the M3R packet recorder. Review of the M3R packet recorder data revealed the analog-to-digital (A2D) boards used by the M3R recorder had missing codes in the transfer function (i.e. there are missing A2D output codes for some input voltages). This error was unable to be corrected with firmware updates and was due to a manufacturer issue specific to their 64 channel 16-bit A2D boards, and to correct this issue requires replacing the A2D boards used by the M3R packet recorder. In late FY20 the LMR Program funded an effort to upgrade the NIWC Pacific legacy PC recorder, which is currently underway. NIWC Pacific is also working collaboratively with NUWC Newport to upgrade their M3R packet recorder.

Table 1: Total hours of recording effort for full bandwidth and decimated data collections between September 2019 and September 2020. The percentage of total time recorded is the ratio of hours of recording effort to hours of total time between the start of recording effort on September 7, 2019 and the end of recording effort on September 2, 2020.

Data type (recorder)	Hydrophones	Hours	Percentage of total time recorded
96 kHz full bandwidth (NIWC Pacific Legacy PC)	62	1760.2	20.3%
6 kHz decimated (NIWC Pacific Legacy PC)	37	1080.0	12.4%
96 kHz full bandwidth (M3R packet recorder)	62/101	132.0	1.5%

4.2 ABUNDANCE AND DISTRIBUTION

4.2.1 Minke Whales

The maximum numbers of automatically-tracked, individual calling minke whales in a 10-minute snapshot period for each hour of the day from recordings made between September 2019 and September 2020 are shown in Figure 3. These results utilized the smaller study area focused on the hydrophone array and included all decimated and full bandwidth data, including classified full bandwidth data recorded during the February and August SCCs. Minke whale seasonal presence at PMRF is captured in Figure 3, with hourly maximums from one to two individual whales detected starting in November 2019, down to one individual whale present per hour in May 2020, and no minke whales detected in the rest of the year of data. The maximum number of minke whales detected in a one-hour bin from September 2019 to September 2020 occurred on February 2, 2020, when four whales were present from the 09:00 to 12:00 Hawaii Standard

Time (HST) hour bins (dark red). While there is a strong seasonal pattern, minke whale tracks occurred with no apparent diel pattern (Figure 3). For comparison, Martin et al. (2020) utilized the same tracking parameters and from August 2018 to August 2019 there was also a maximum of four minke whales detected in two consecutive one-hour bins that occurred in December 2018.

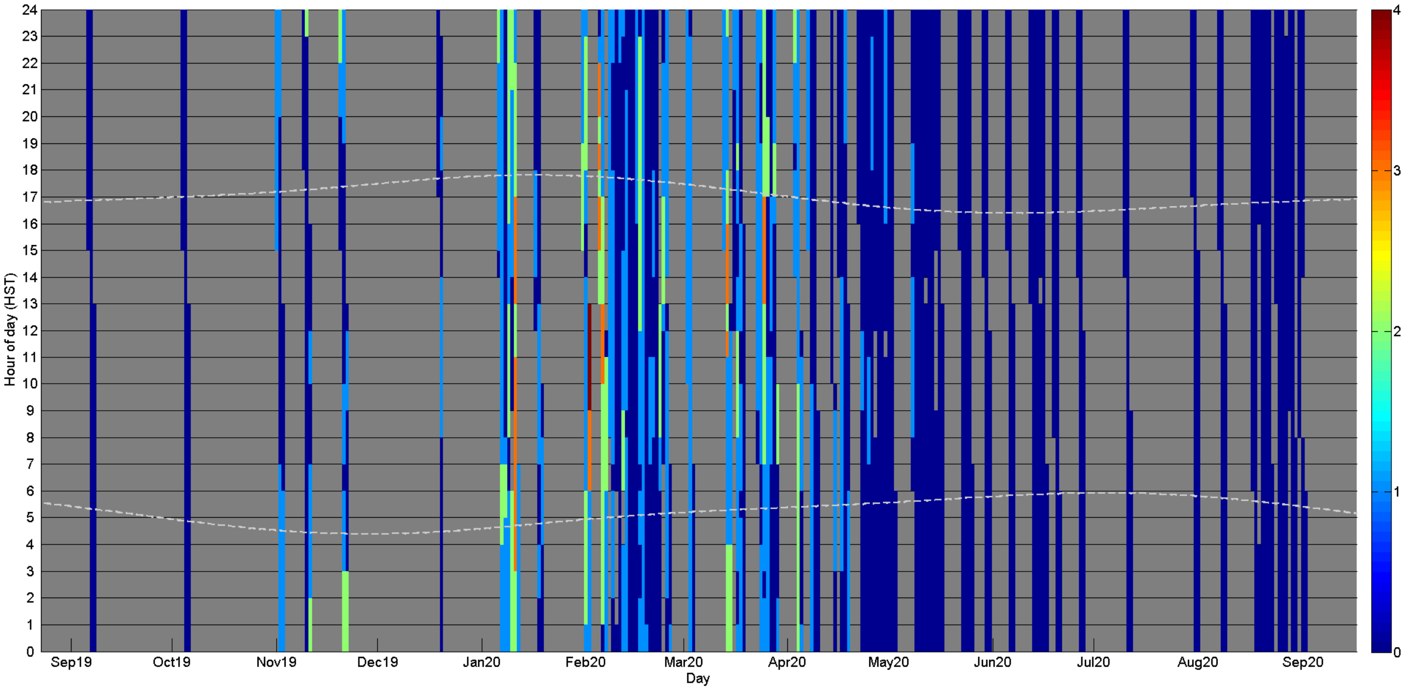

Figure 3: The maximum number of minke whales detected in a 10-minute snapshot period for each hour of the day from September 2019 to September 2020 ranged from one (light blue) to four (dark red). Dark blue regions indicate periods of effort when acoustic recordings were collected and zero whale tracks were present. Results are from decimated and full bandwidth data collections, including data collected during the February and August SCCs. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

4.2.2 Humpback Whales

The maximum number of automatically-tracked, individual calling humpback whales detected in a 10-minute snapshot period for each hour of the day from recordings made between September 2019 and September 2020 are shown in Figure 4. These results utilized a small study area focused on the hydrophone array and include all decimated and full bandwidth data, not including classified full bandwidth data recorded during the February and August SCCs since humpback whale tracks that occur during training events need to be fully validated to ensure they are not false positive tracks of vessels or other anthropogenic sources. Humpback whale seasonal presence occurred from January to May 2020 and typically a maximum of one acoustic humpback track (based on song) was detected in a one-hour bin (Figure 4). There was a maximum of three acoustic humpback tracks detected in the 11:00 HST hour bin on March 24, 2020. Compared to the winters of 2015 to 2018 (Martin et al. 2019) and 2019 (Martin et al. 2020), when humpback presence started as early as September and lasted until

April/May, this is a relatively late arrival for the humpback whales to Kauai. However, in the winters of 2002-2014 (Martin et al. 2019), humpback presence typically occurred from January to April/May, which was more comparable to this year. The early years of those data had low data collection effort, and didn't include decimated data, which were recorded starting in August 2014. However, since the level of occurrence of offshore humpback tracks is relatively low compared to minke whales, and relatively fewer hours of data were recorded from September to December 2019 compared to recent years, it is possible that the start of offshore humpback whale presence wasn't captured in the available data and occurred earlier than January 2020.

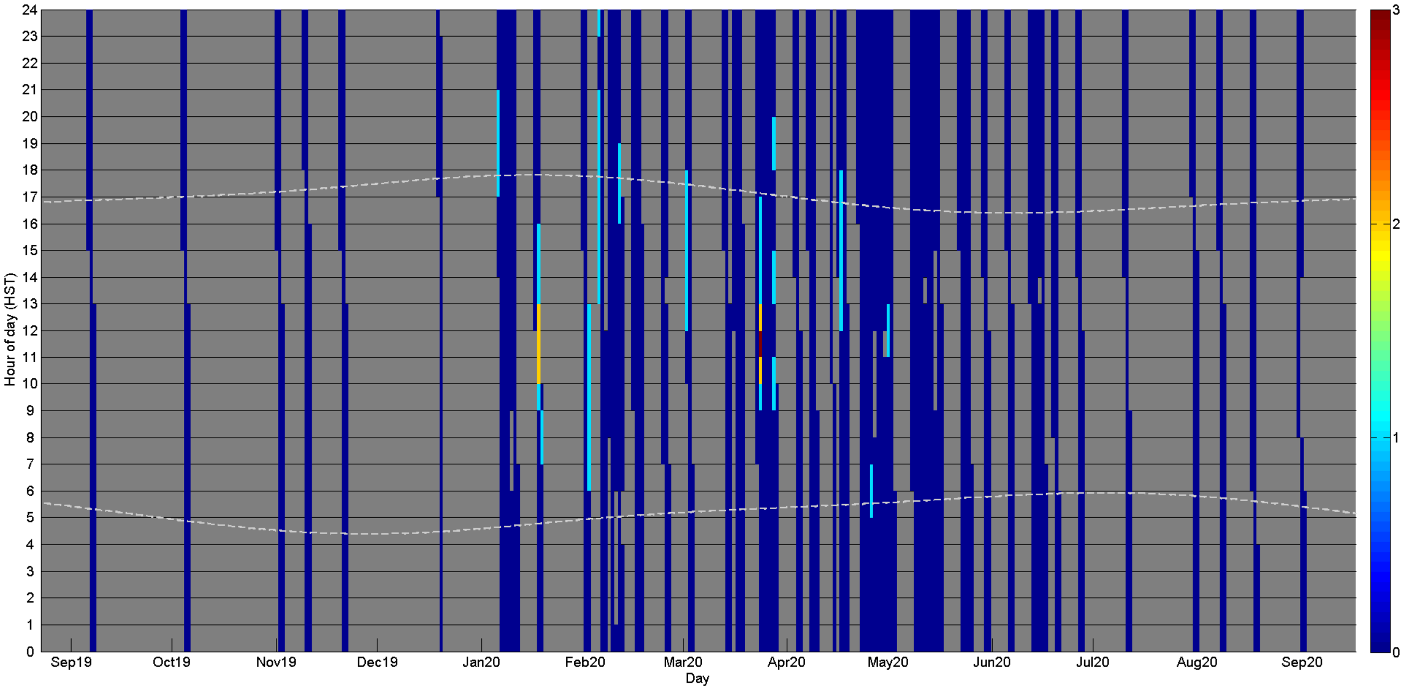

Figure 4: The maximum number of humpback whales detected in a 10-minute snapshot period for each hour of the day from September 2019 to September 2020 ranged from one (light blue) to three (dark red). Dark blue regions indicate periods of effort when acoustic recordings were collected and zero whale tracks were present. Results are from decimated and full bandwidth data collections only. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

4.2.3 Low-Frequency Baleen Whales

The maximum number of automatically tracked individual calling low-frequency baleen whales (e.g. fin, sei, Bryde's, and blue whales) detected in a 10-minute snapshot period for each hour of the day from September 2019 to September 2020 are shown in Figure 5. These results utilized the smaller study area focused on the hydrophone array and include all decimated and full bandwidth data, including classified full bandwidth data recorded during the February and August SCCs. It is important to make the distinction that the track results in Figure 5 are from the C++ detection and localization algorithm described in Section 3.1 and the output from this process have been presented in prior annual reports. Tracks separated by individual species are discussed below in Section 4.2.3.1. The maximum number of low-frequency baleen whales present in a one-hour bin ranged from one to three whales between November 2019 and April 2020, with no apparent presence outside of this season, which had occurred in previous years and was attributed to Bryde's whales (Martin and Matsuyama 2014, Helble et al. 2016, and Martin et al. 2019; Figure 5). A maximum of three low-frequency baleen whales were detected in a one-hour bin on January 19, 2020 in the 6:00 HST hour bin and on February 13, 2020 in the 17:00 HST hour bin.

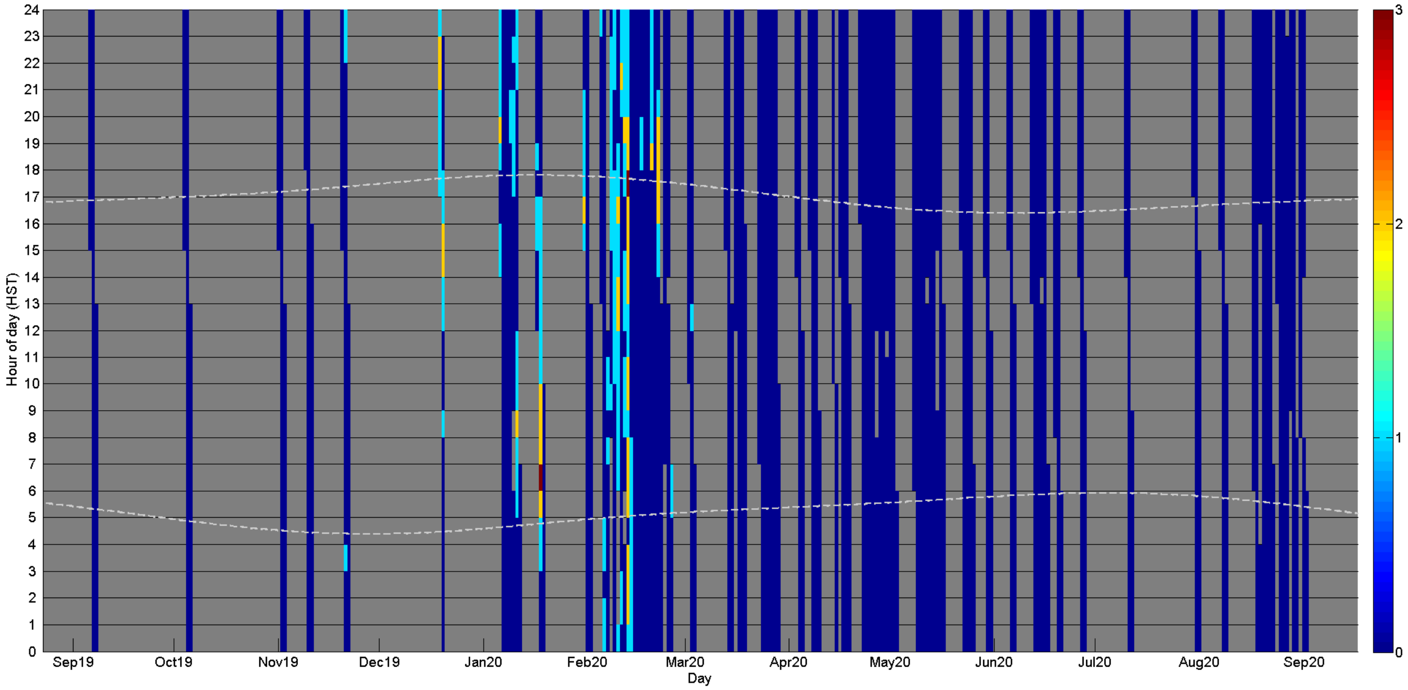

Figure 5: The maximum number of low-frequency baleen whales detected in a 10-minute snapshot period for each hour of the day from September 2019 to September 2020 ranged from one (light blue) to three (dark red). Dark blue regions indicate periods of effort when acoustic recordings were collected and no whale tracks were present. Results are from decimated and full bandwidth data collections, including data collected during the February and August SCCs. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

4.2.3.1 Classification of Bryde's, Fin, and Sei Whales

The results in Section 4.2.3.1 and 4.2.3.2 utilized custom Matlab GPL algorithms to automatically process recorded decimated data and full bandwidth data downsampled to 6 kHz. Only the results in Section 4.2.3.1 and 4.2.3.2 utilized full bandwidth data downsampled to 6 kHz. These results were also tracked utilizing the larger study area centered on the hydrophone array, and all tracks were fully manually validated by systematically investigating spectrograms and inter-call intervals as described in Section 3.1.4. Figure 6 to Figure 8 utilized all decimated and full bandwidth data from January 2011 to September 2020, including classified data collected during SCC training events. As a note, the baseline decimated and full bandwidth data in Figure 6 are a superset of the results in Helble et al. (2020b) that are summarized in Section 4.2.3.2. Tracked calls were classified using the following call type templates: 1) fin whale song 2) Bryde's whales' 33Hz calls and 3) 40 Hz downsweep calls (potentially from fin and/or sei whales).

Fin whale results (Figure 6) show a clear seasonal pattern, with fin whale presence as early as October (2016), and as late as April (2015, 2019, and 2020). Peak annual presence typically occurs in December and/or January, with the exception being 2019 when peak presence occurred in April. This may be due to relatively low recording effort in December 2019 and January 2020. Typically, two individual animal tracks occurred in a 10-minute snapshot period, and a maximum of four tracks were detected in December 2018 and April 2019. These results are very similar to the C++ algorithm results shown in Figure 5, but provide species level separation when possible.

Improved low-frequency baleen whale classification methods have enabled Bryde's whales to be more easily classified, revealing that between January 2011 and September 2020, a maximum of four tracks were detected in a 10-minute snapshot period occurred in February 2017 before the SCC. Bryde's whale results in Figure 7 depict the year-round presence that has been previously documented in August-October 2014 (Martin and Matsuyama 2014, Helble et al. 2016), and June 2018 (Martin et al. 2019). Figure 7 illustrates that the maximum number of Bryde's whale tracks detected in a month varies from zero to 4. Of the 114 months of data represented in Figure 7, 87 months had no Bryde's whale tracks, 17 months had a maximum of one track detected, 8 months with a maximum of 2 tracks detected, and one month each with a maximum of 3 and 4 Brydes' whales tracks detected. It is interesting that over the most recent 24 months of data, Bryde's whale tracks have occurred in only two months; it is unclear if this is related to limited statistical sampling or reflects a true decline in the number of calling Bryde's whales in the area. Fewer recordings were made in the fall and early winter of 2019 than in February through April and August of 2019 and January and February of 2020; this made have led to missed opportunities for detection. Future analyses efforts will be focused on Bryde's whale calls, and so a more thorough examination of the data will be conducted to look for missed detections, and Bryde's whale presence will be modeled against environmental data to look for trends in occurrence patterns. Bryde's whales have been previously detected and localized by the C++ low-frequency baleen whale group detector but were only easily classified if tracks occurred outside of the seasonal presence of other low-frequency baleen whales (e.g fin and sei).

The presence of tracks composed of the 40 Hz downsweep call is depicted in Figure 8. Based on current literature and classification methods, tracks attributed to this call type may be produced by fin and/or sei whales. A maximum of one to two tracks were detected in a 10-minute snapshot period per month, typically between November and April. Tracks only occurred once outside of this period in May 2011, with a maximum of two tracks detected. Although tracks attributed to the 40 Hz downsweep call type are not currently classified to a species, these tracks are available for potential reclassification in the future pending new literature and additional manual investigation. In addition to capturing the calls centered at 40 Hz, the 40 Hz downsweep category also occasionally captures calls that start at higher frequencies (from 80-100+ Hz) and sweep as low as 30-50 Hz. Based on recordings collected by Rankin and Barlow (2007), these calls can likely be attributed to sei whales. An example of these call types can be seen in Figure 9, occurring at the same time as fin whale "B" calls, but from a different location on the range.

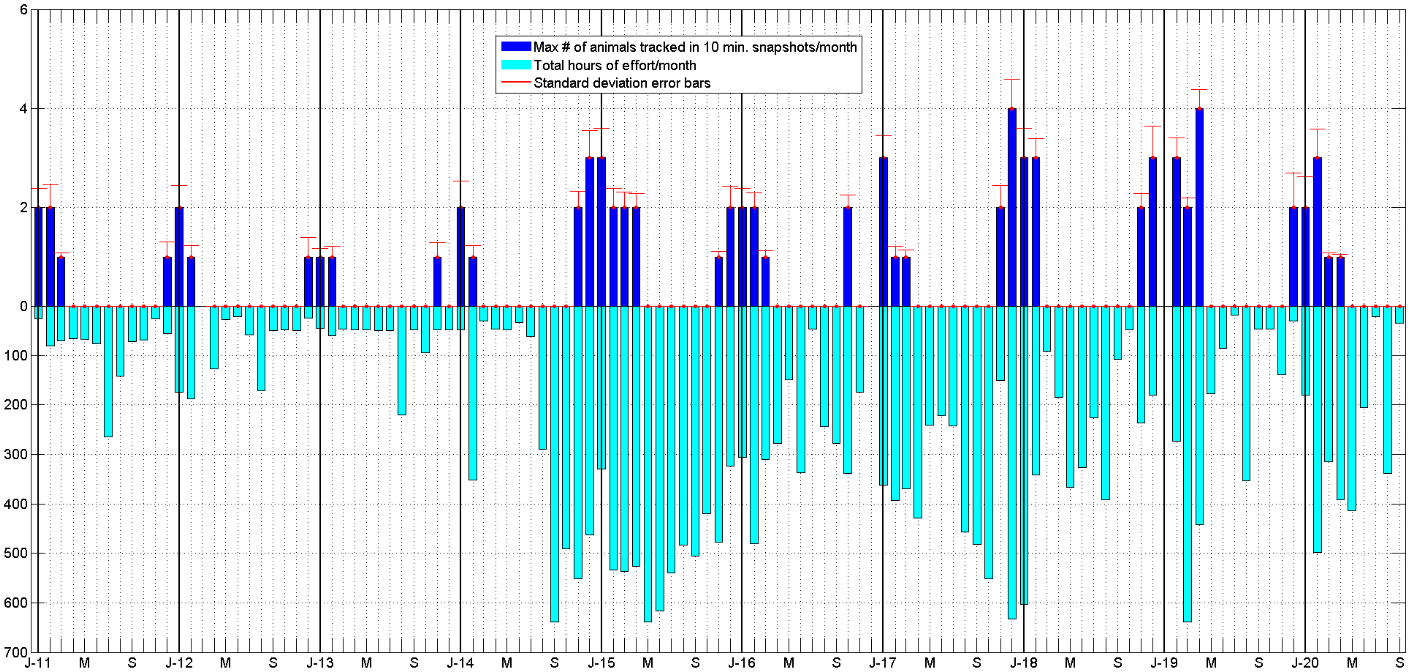

Figure 6: The maximum number of fully manually validated fin whale tracks that were detected in a 10-minute snapshot period per month from January 2011 to September 2020. If cyan bars are not present then data were not recorded for that month.

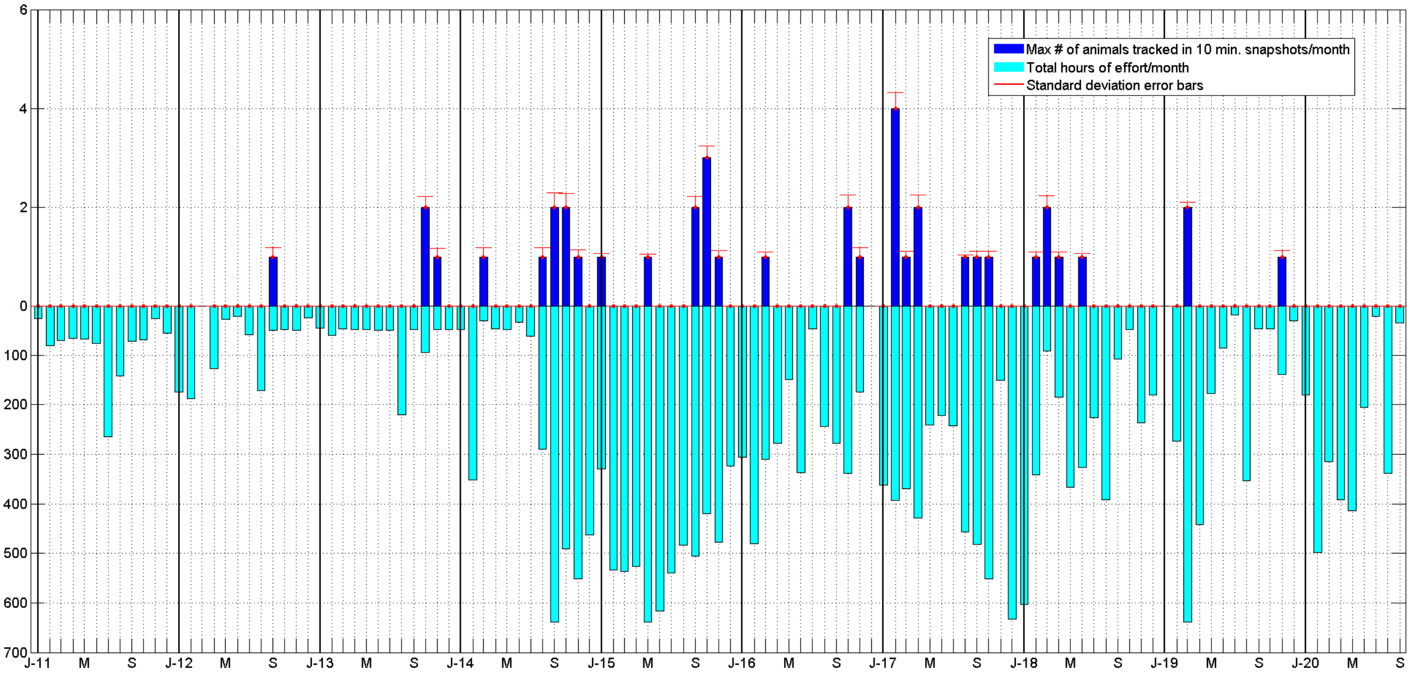

Figure 7: The maximum number of fully manually validated Bryde's whale tracks that were detected in a 10-minute snapshot period per month from January 2011 to September 2020. If cyan bars are not present then data were not recorded for that month.

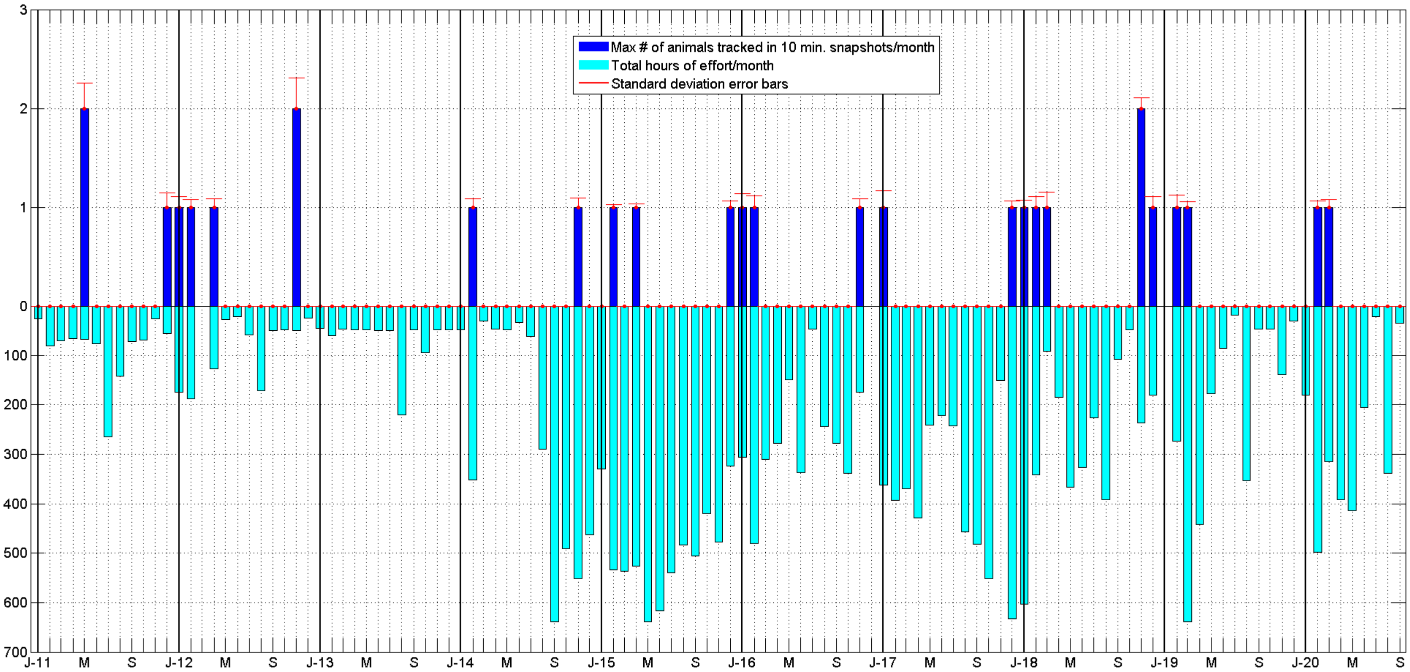

Figure 8: The maximum number of fully manually validated whale tracks composed of the 40 Hz down sweep call type that were detected in a 10-minute snapshot period per month from January 2011 to September 2020. If cyan bars are not present then data were not recorded for that month.

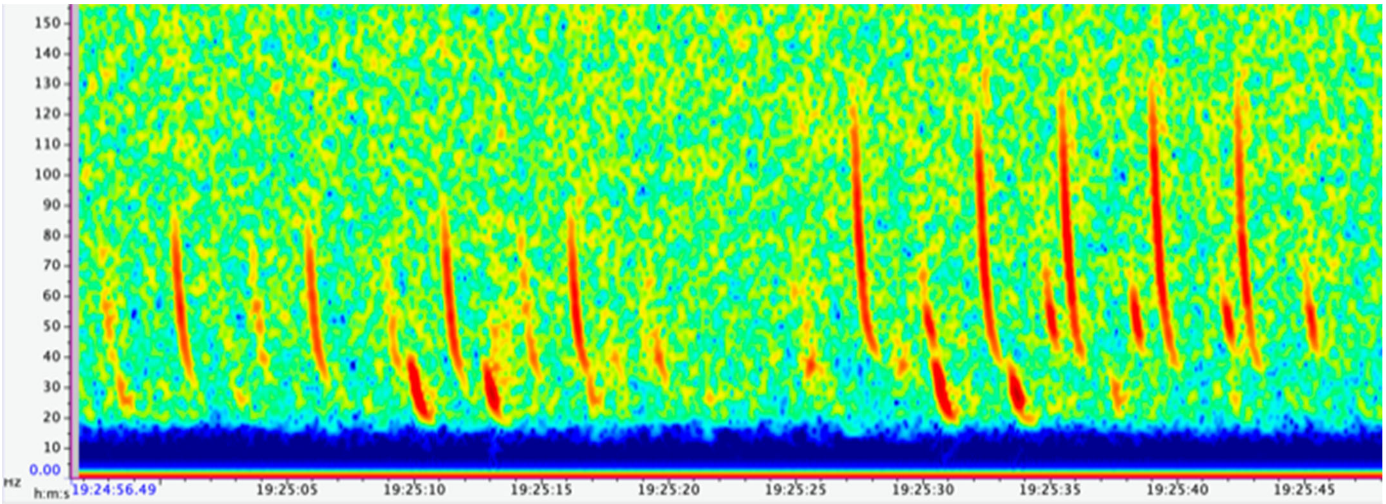

Figure 9: Example spectrogram of unknown call types (likely sei whale) that can sometimes trigger classification in the 40 Hz downsweep category. Fin whale 20 Hz "B" type calls can also be seen in the spectrogram but occur from a separate location on the range than the higher frequency calls.

4.2.3.2 Fin Whale Song Patterns

Male fin whales sing by producing 20-Hz pulses in regular patterns of inter-note intervals. While singing, fin whales may also alternate the frequency ranges of their notes. Different song patterns have been observed in different regions of the world's oceans. New song patterns suddenly emerging in an area have been hypothesized to either be indicators of new groups of whales in the area or signs of cultural transmission between groups (Weirathmueller et al. 2017). Since the status of fin whales around Hawaii is unknown and visual surveys are expensive and difficult to conduct in offshore areas, passive acoustic monitoring can be used as a way to monitor these whales.

We used passive acoustic recordings from an array of 14 hydrophones to analyze the song patterns of 115 fin whale encounters made up of 50,034 unique notes off Kauai, Hawaii from 2011–2017. Fin whale singing patterns were found to be more complicated than previously described. Fin whales off Hawaii sang in five different patterns made of two 20-Hz note types and both singlet and doublet INI patterns. We used "A" to refer to the lower-frequency, smaller-bandwidth note (which has sometimes been referred to as a "backbeat" in the past) and "B" to refer to the higher-frequency, larger-bandwidth note (which has sometimes been referred to as a "classic" note in the past). Song patterns are named according to the note pairing and inter-note interval pattern. The average inter-note intervals present in their song patterns were 28/33 s for the A-A doublet, 30 s for the A-A singlet, 17/24 s for the B-B doublet, 17 s for the B-B singlet, and 12/20 s for the A-B doublet (Figure 10). The average cue rate was 131 notes/hour, which increased over time as the dominant song pattern changed from A-A patterns to A-B doublet (Figure 11). Some of these song patterns were unique to these fin whales in Hawaiian waters, while others were similar to song patterns recorded from fin whales off the U.S. west coast. Individual fin whales often utilized several different song patterns within a single track, which suggests that multiple song patterns are not necessarily indicators of different individuals or groups (Figure 12, Figure 13). Cultural transmission may have occurred between fin whales in Hawaiian waters and off the U.S. west coast, which would result in similar songs being present at both locations but on lagged timescales. Alternatively, groups occupying the Hawaiian waters could shift over time resulting in different song patterns becoming dominant. This work has implications for the population structure and behavior of Hawaii fin whales (Helble et al. 2020b).

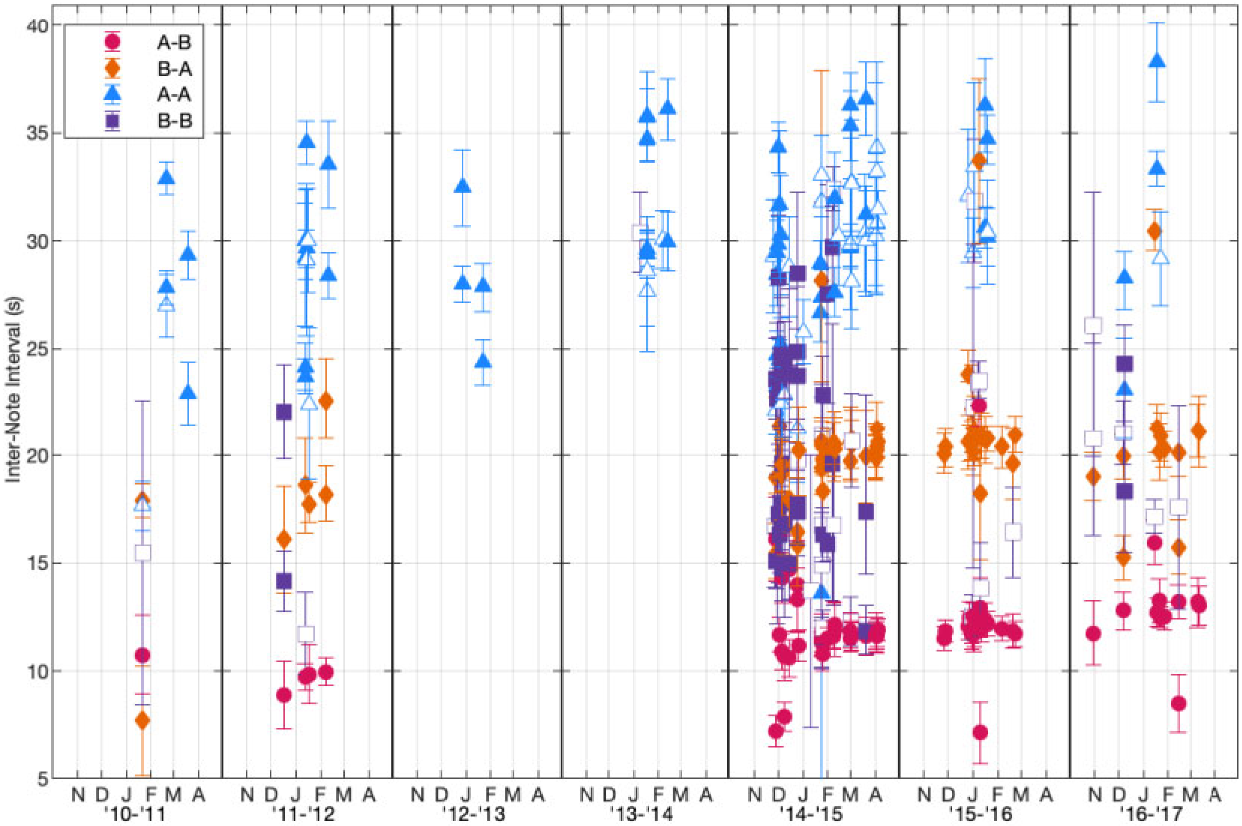

Figure 10. Peak inter-note interval (INI) values for each note pairing type in each track and error bars. Each season is plotted from October to May based on the earliest and latest fin whale tracks. The INI values are plotted as a function of when each track started. Points were only plotted if the track had at least 20 pairs of those note types in the song sequence. Filled-in markers indicate that the song pattern occurred as a doublet while open markers indicate that the song pattern occurred as a singlet. INIs less than 4 seconds and greater than 60 seconds were not included in these calculations. The y-axis was restricted based on the range of observable INIs. (Figure 6 in Helble et al. 2020b)

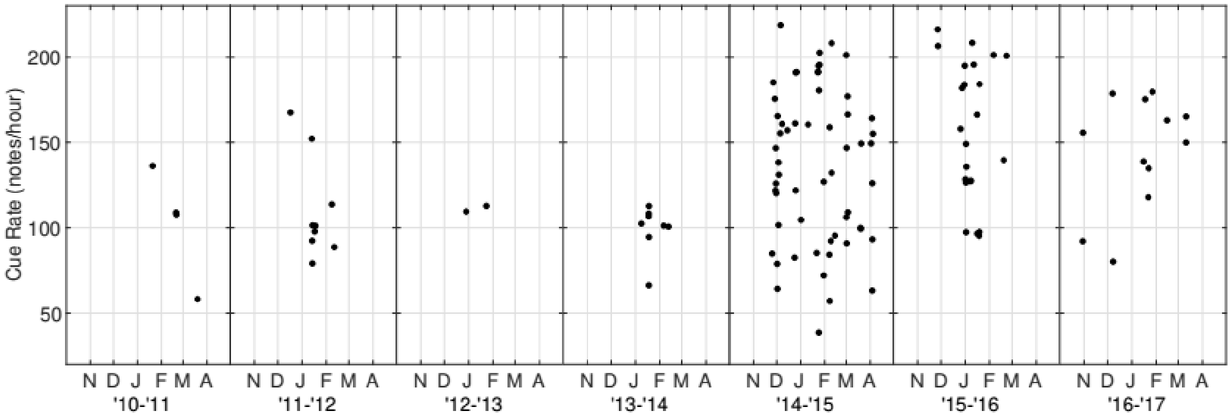

Figure 11. Along-track cue rate for fin whales at PMRF as a function of time. Cue rate was calculated as number of notes in a track divided by the total elapsed time of the track and is in units of notes/hour. Each season is plotted from Oct to May based on the earliest and latest fin whale detections. (Figure 9 in Helble et al. 2020b)

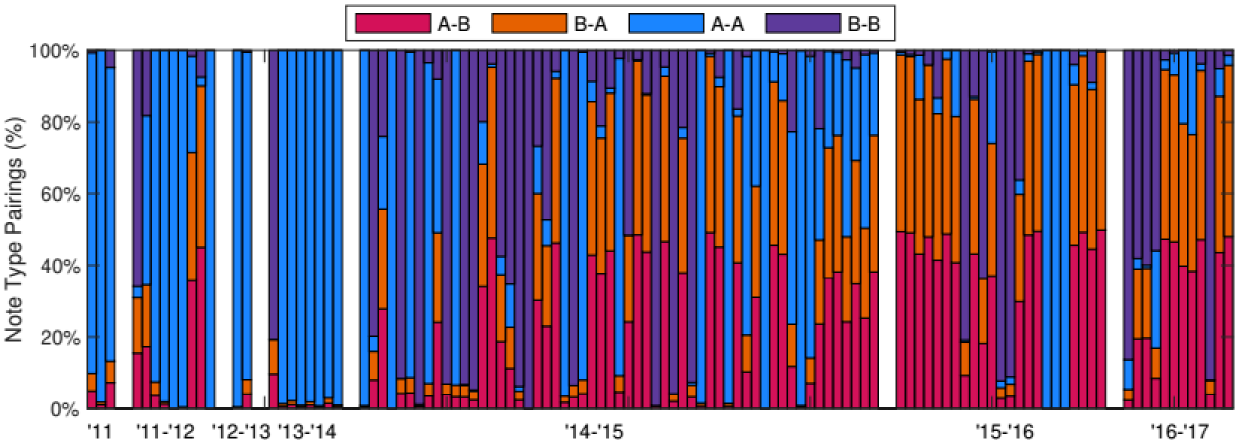

Figure 12. Percentage of different note pairings for each of the 115 fin whale tracks, spanning 2011–2017. Doublet and singlet songs are not differentiated in this plot. The tracks were seasonal and only occurred from October–April; white bars mark each of these seasons. (Figure 7 in Helble et al. 2020b)

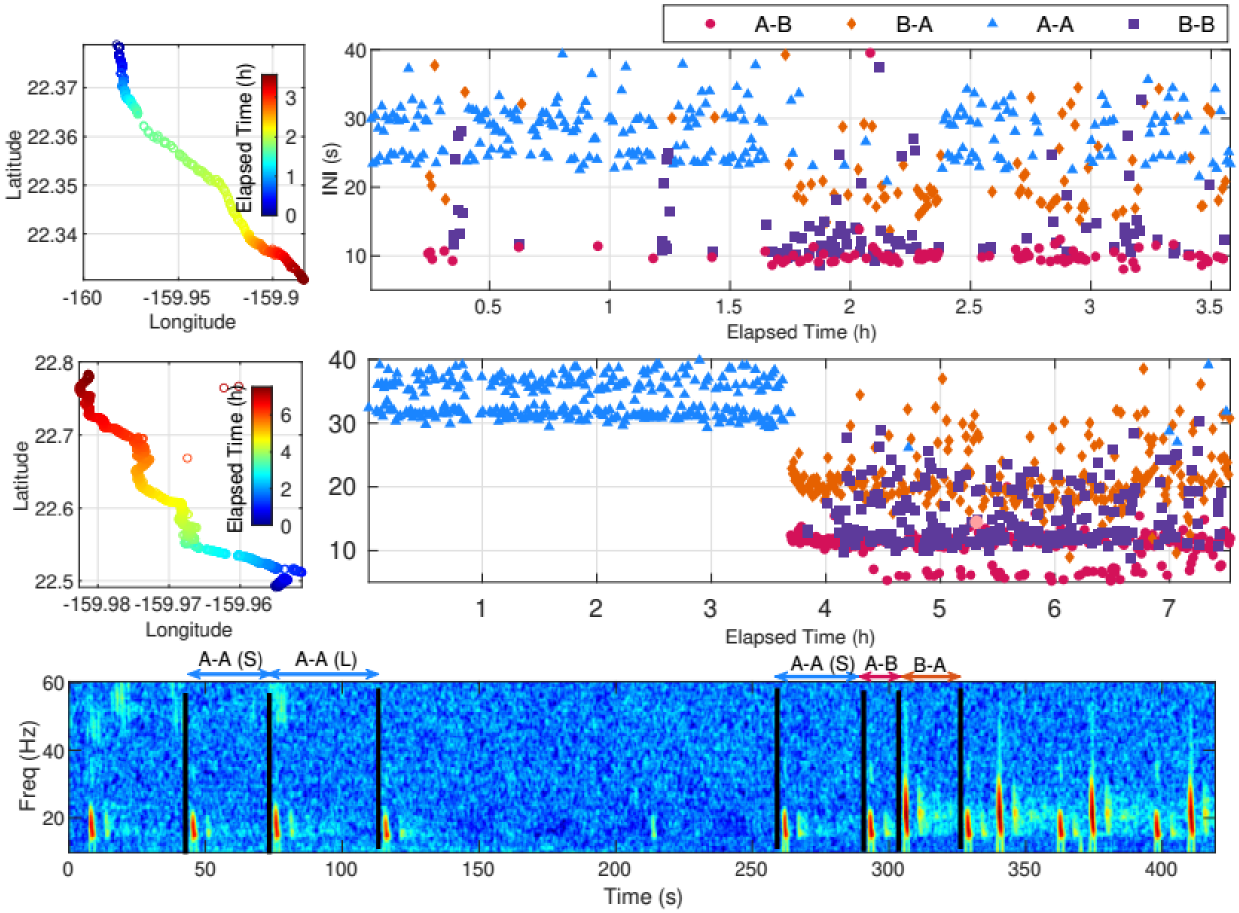

Figure 13. Two examples of fin whale tracks exhibiting a mixture of song patterns. The upper-left plot shows a fin whale transiting a distance of 11.5 km from north to south on January 13, 2012 at 07:11:20 Greenwich Mean Time (GMT). The middle-left plot shows a fin whale transiting a distance of 32.7 km from south to north on March 20, 2015 12:05:17 GMT. Neither of these tracks occurred at the same time as another fin whale singing on PMRF. The corresponding INIs are shown to the middle and right of each track, with each pairing type noted by color and shape. The spectrogram corresponds to the middle track and shows the transition period from A-A doublet song to A-B doublet song starting at 3.6 hours into the track. Example A-A INIs are labeled as (S) for short and (L) for long and A-B and B-A INIs are also labeled. The gap in the middle shows a presumed surfacing interval with a low signal-to-noise ratio A call at 215 seconds. (Figure 8 in Helble et al. 2020b)

4.2.3.3 Blue Whales

Following the same procedures as in Martin et al. (2020), blue whale calls were automatically processed using custom Matlab algorithms, and localizations were manually investigated if a recording contained 20 or more localizations. Blue whales have a low level of occurrence at PMRF and were only found in two FY20 recordings. The first recording was November 21, 2019 and had 31 northwestern Pacific call type localizations located northwest and outside of the hydrophone array. The second recording was February 5, 2020 and also had 24 northwestern Pacific call type localizations that occurred within the hydrophone array. The northwestern Pacific call type was described by Stafford et al. (2001); an example of this call in the data recorded at PMRF has a fundamental around 18 Hz and was presented in Martin et al.

(2020). Localization accuracy of blue whale calls suffer both from the long call duration with limited bandwidth along with in-direct path propagation well outside the array. Imprecise localizations also present a challenge for tracking and attributing calls to individual whales. In addition, based on current literature it is unclear if an individual whale can switch between the northeastern and northwestern Pacific call types. The northeastern Pacific call type did not occur in the FY20 recordings but they did co-occur in recordings between 2011 and 2019, which were analyzed in Martin et al. (2020).

4.2.4 Blainville's Beaked Whales

Four baseline FY20 recordings with Blainville's beaked whales group foraging dives were randomly selected for manual validation. Automatically detected and grouped clicks were manually validated by systematically reviewing click spectrograms, spectra, and inter-click interval (ICI) to be Blainville's beaked whale clicks. The four FY20 manually validated recordings contained 375 validated true positive dives (96% true positive rate) and 16 false positive dives (4% false positive rate). This high true positive rate and low false positive rate are due to the Blainville's beaked whale detector being more refined than other relatively newer beaked whale detectors (i.e. Cuvier's and CSM beaked whales). Due to high confidence in Blainville's beaked whale classification results and prior efforts that investigated Blainville's beaked whale dives during the SCCs (Manzano-Roth et al. 2016, Henderson et al. 2019), FY20 Blainville's beaked whale results during the SCC are included in this report. FY20 Blainville's beaked whale results discussed in this section and summarized in Figure 14 and Table 2 were adjusted by the true positive and false positive rates derived from manual sample validation of four baseline FY20 recordings.

There was a maximum of 6.2 group vocal dives (dark red) that were detected on October 5, 2019 in the 14:00 and 23:00 HST hour bins. The maximum number of dives reflects the number of dives that started in an hour bin and in this case, it is a fractional number since it was adjusted by the true positive and false positive rates. For dive data normalized by recording effort, the monthly number of dives per hour of effort ranged from 0.52 dives/hour in July 2020 to 4.44 dives/hour in October 2019 (Table 2). Between September 2019 and September 2020 there was an overall rate of 1.79 dives/hour. The monthly number of dives normalized by recording effort is the sum of dives that occurred in a month, divided by the sum of hours of recording effort for that month.

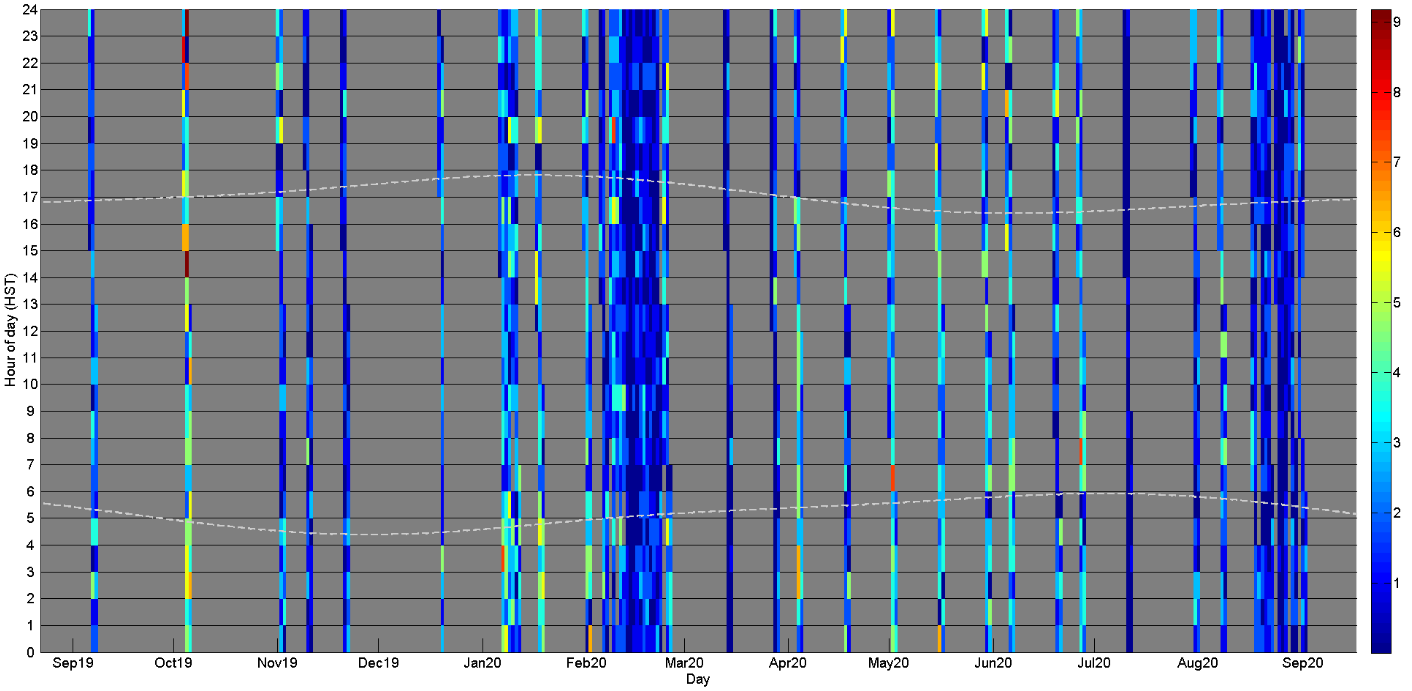

Figure 14: The total number of Blainville's beaked whale foraging dives per hour from September 2019 to September 2020 (corrected using sample validated dives). The total number of dives in a one-hour bin ranged from one (medium blue) to 9 (dark red). Results are from full bandwidth data collections, including data collected during the February and August SCCs. Gray areas indicate periods when full bandwidth data were not available. The gray dashed line indicates sunrise and sunset times.

Table 2: FY20 Blainville's beaked whale manually validated dive summary

Date	Sum of Dives	Hours of Effort	Dives/Hour
2019	**524.62**	**255.50**	**2.05**
Sep	83.44	45.33	1.84
Oct	201.41	45.33	4.44
Nov	182.23	136.00	1.34
Dec	57.54	28.83	2.00
2020	**2699.81**	**1550.00**	**1.74**
Jan	455.56	177.33	2.57
Feb	687.66	490.33	1.40
Mar	150.58	90.67	1.66
Apr	214.83	90.67	2.37
May	390.35	136.00	2.87
Jun	340.47	136.00	2.50
Jul	32.61	62.17	0.52
Aug	376.92	333.50	1.13
Sep	50.83	33.33	1.52

4.2.5 Cuvier's Beaked Whales

All automatically detected and grouped clicks that were classified as Cuvier's beaked whales were manually validated by systematically reviewing click spectrograms, spectra, and ICI. These results utilized all full bandwidth data, not including classified full bandwidth data recorded during the February and August SCCs since the version of the NARWHAL algorithms with updates for Cuvier's beaked whales has not yet been validated to assess potential false positives in those data. The FY20 recordings contained 116 validated true positive dives (49.2% true positive rate) and 120 validated false positive dives (50.8% false positive rate). This high false positive rate is due to misclassified group dives that were composed of clicks mostly from dolphins. The total number of Cuvier's beaked whale dives that occurred during an hour of full bandwidth data collection was typically one or fewer, with a maximum of two dives (dark red) that were detected in multiple one-hour bins in February, May, and June 2020 (Figure 15). The maximum number of dives reflects the number of dives that started in an hour bin.

The monthly number of manually validated dives per hour of recording effort ranged from zero dives/hour in December 2019 and July 2020, to 0.19 dives/hour in May 2020 (Table 3). Between September 2019 and September 2020 there was an overall rate of 0.08 dives/hour. The monthly number of dives normalized by recording effort is the sum of dives that occurred in a month, divided by the sum of hours of recording effort for that month. This species also occurred on the range throughout the year with no clear diel trend.

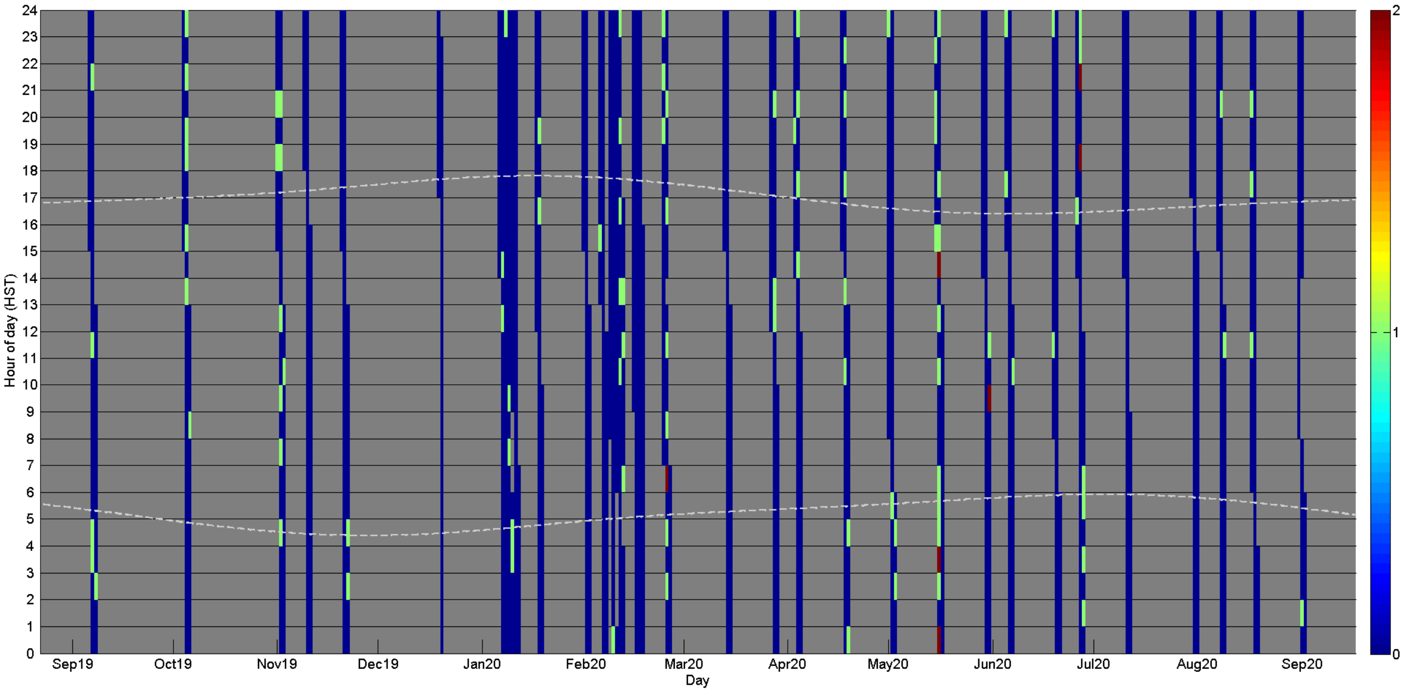

Figure 15: The total number of manually validated Cuvier's beaked whale foraging dives per hour from September 2019 to September 2020. Results are from full bandwidth data collections only. The total number of dives in a one-hour bin ranged from one (green) to two (dark red). Gray areas indicate periods when full bandwidth data were not available. The gray dashed line indicates sunrise and sunset times.

Table 3: FY20 Cuvier’s beaked whale manually validated dive summary

Date	Sum of Dives	Hours of Effort	Dives/Hour
2019	**23**	**255.50**	**0.09**
Sep	5	45.33	0.11
Oct	7	45.33	0.15
Nov	11	136.00	0.08
Dec	0	28.83	0.00
2020	**93**	**1156.33**	**0.08**
Jan	9	177.33	0.05
Feb	21	309.33	0.07
Mar	3	90.67	0.03
Apr	12	90.67	0.13
May	26	136.00	0.19
Jun	16	136.00	0.12
Jul	0	62.17	0.00
Aug	5	120.83	0.04
Sep	1	33.33	0.03

4.2.6 Cross-Seamount Beaked Whales

All automatically detected and grouped CSM clicks were manually validated by systematically reviewing click spectrograms, spectra, and ICI to be CSM beaked whale clicks. These results utilized all full bandwidth data, including classified full bandwidth data recorded during the February and August SCCs. The FY20 datasets contained 199 validated true positive dives (28.4% true positive rate) and 502 validated false positive dives (71.6% false positive rate). Work on the CSM click classifier continues to improve performance to reduce misclassification of CSM clicks. The total number of manually validated CSM beaked whale dives that occurred during an hour of full bandwidth data collection (Figure 16) was typically one dive (light blue) with occasionally two dives (yellow) occurring. A maximum of three dives (dark red) were detected in one-hour bins in October and December 2019, and February and May 2020. The maximum number of dives reflects the number of dives that started in an hour bin.

The monthly number of manually validated dives per hour of recording effort ranged from zero dives/hour in September 2020 to 0.45 dives/hour in July 2020 (Table 4). Between September 2019 and September 2020 there was an overall rate of 0.11 dives/hour. The monthly number of dives normalized by recording effort is the sum of dives that occurred in a month, divided by the sum of hours of recording effort for that month. CSM dives occurred on the range in every month that had recording effort except for September 2020. Unlike Blainville’s and Cuvier’s beaked whales, there is a clear diel trend in the occurrence of CSM dives at night, with few instances of dives occurring shortly after sunrise.

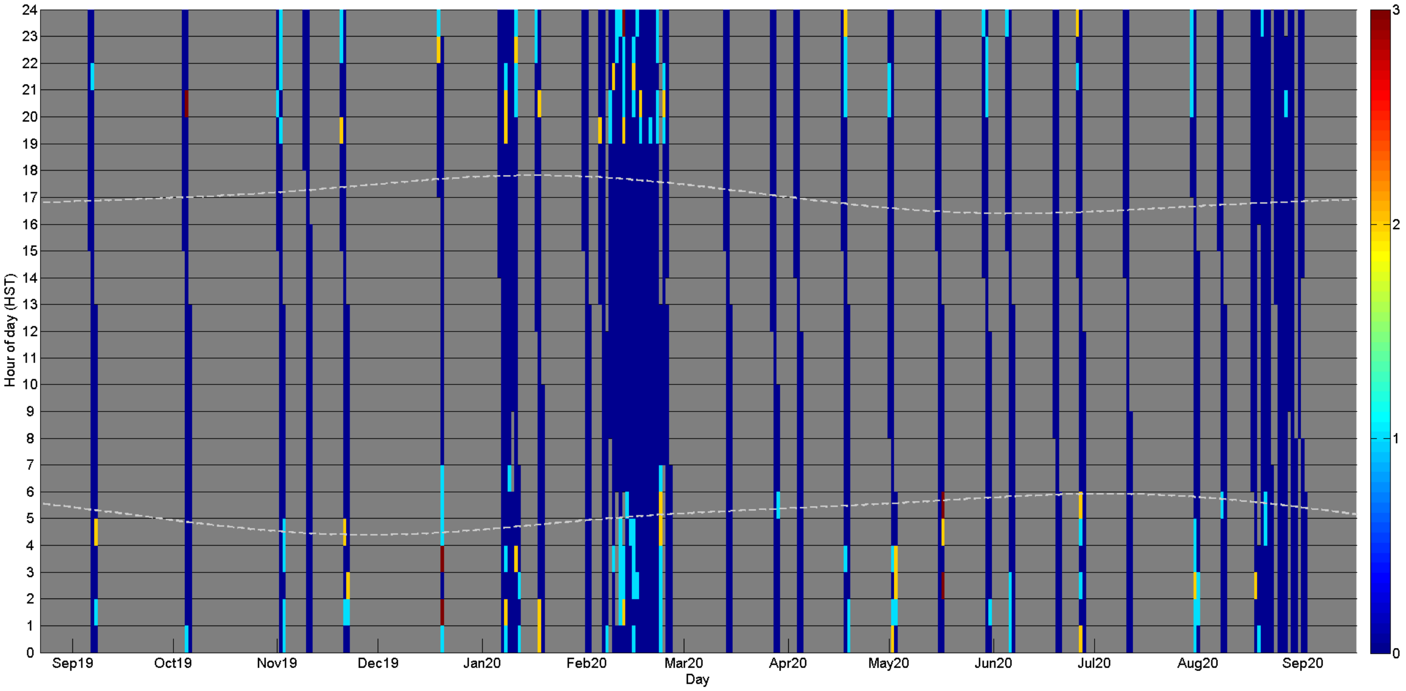

Figure 16: The total number of manually validated CSM beaked whale dives per hour from September 2019 to September 2020. Results are from full bandwidth data collections, including data collected during the February and August SCCs. The total number of dives in a one-hour bin ranged from one (light blue) to three (dark red). Gray areas indicate periods when full bandwidth data were not available. The gray dashed line indicates sunrise and sunset times.

Table 4: FY20 CSM beaked whale manually validated dive summary

Date	Sum of Dives	Hours of Effort	Dives/Hour
2019	**43**	**255.50**	**0.17**
Sep	7	45.33	0.15
Oct	4	45.33	0.09
Nov	19	136.00	0.14
Dec	13	28.83	0.45
2020	**156**	**1550.00**	**0.10**
Jan	27	177.33	0.15
Feb	61	490.33	0.12
Mar	2	90.67	0.02
Apr	8	90.67	0.09
May	25	136.00	0.18
Jun	13	136.00	0.10
Jul	10	62.17	0.16
Aug	10	333.50	0.03
Sep	0	33.33	0.00

4.2.7 Longman's Beaked Whales

Adjustments to the beaked whale classifier are currently in progress in order to isolate clicks attributed to Longman's beaked whales, which are known to occur in Hawaiian waters (Rankin et al. 2011). Clicks that match the published description of Longman's beaked whale frequency-modulated (FM) clicks (upsweep centered at about 25 kHz with an average inter-click interval of about 0.36) have previously been observed in PMRF data while assessing false positive and negative rates for the existing beaked whale classifier (Figure 17). The recording beginning on September 7, 2019 was found to contain all four beaked whale species of interest and is consequently the current focus of attempts to tune the beaked whale classifier to both identify the Longman's beaked whale FM click and improve the false negative rates of the Cuvier's and CSM beaked whale classifiers.

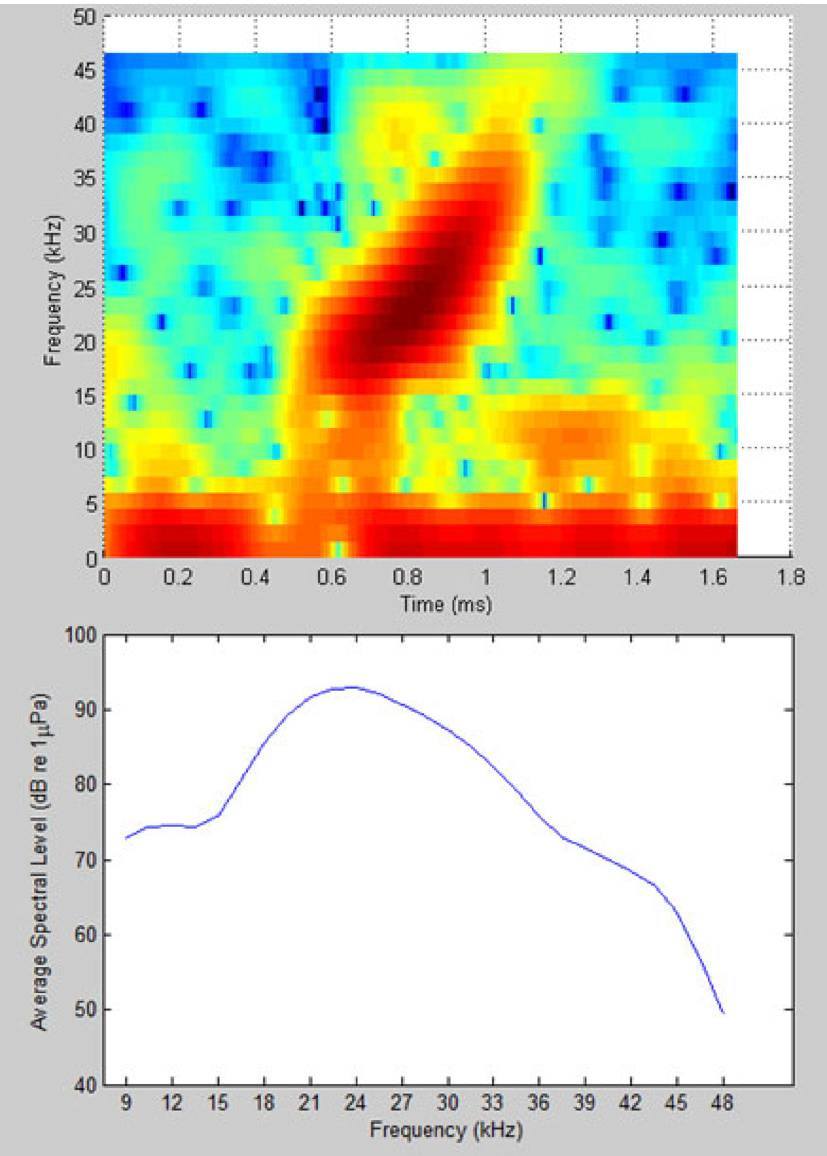

Figure 17: An example spectrogram (top) and spectrum (bottom) of a Longman's beaked whale click detected on September 7, 2019.

4.2.8 Killer Whales

All unclassified baseline full bandwidth data recorded between September 2019 and September 2020 were automatically processed for killer whale groups that produced the high-frequency modulated (HFM) call (aka HFM whistle), utilizing the same detection and grouping methods first described in Martin et al. (2018). Decimated data were not processed since they do not have sufficient bandwidth for the detectable portion of killer whale HFM calls (10-35 kHz), and classified full bandwidth data were not processed since the presence of anthropogenic sources results in a high false positive rate and the automatic results need to be fully manually investigated. In FY20, no killer whale HFM call groups were detected. This result is reasonable since Martin et al. (2019) documented a low-level of occurrence of HFM call groups between February 2002 and August 2018. In that report, data collection occurred in 155 months and HFM call groups were manually validated to occur in 22 months, with typically 1-2 groups detected in a month.

As observed in last year's report (Martin et al. 2020), almost all dives consisting of high-frequency modulated (HFM) whistles attributable to killer whales that were detected between August 21, 2018 and August 24, 2019 occurred during daylight hours. The single exception was a dive that occurred just before sunrise. This year, every manually validated killer whale dive consisting of HFM whistles since 2002 was examined for this apparent diurnal trend. Each dive start time was assigned to one of four illumination categories based on whether the sun was up or the moon was out and illuminated (Figure 18). Out of a total of 48 HFM dive detections, 77.1% began during daylight hours and the other 22.9% began when the moon was over three-quarters full, indicating a very strong trend that is not just diurnal, but potentially dependent on illumination. When every hour of effort is assigned to the same illumination categories, a chi-square test provides further evidence that these dives are not random with respect to illumination (X^2 (df = 3, N = 46) = 16.02, $p < 0.01$).

Not much is known about the behavior of killer whales in Hawaiian waters or the function of HFM whistles. Some have proposed that the whistles may be used for long-range echolocation – either for foraging or for navigation – or for communication in situations where the animals wish to avoid detection by prey or competitors (Simonis et al. 2012, Samarra et al. 2010). These results indicate that their purpose may have something do with visibility. For example, perhaps they are following prey associated with diel vertical migration and when that layer is at depth during the day or in bright moonlight, the predators must resort to echolocation or vocal communication. Alternatively, perhaps the animals are engaged in activities in darkness that require complete silence (such as prey pursuit), and the increased vocal activity in brighter conditions indicates a relaxing of those conditions. More information about killer whale behavior in the area, via visual surveys or passive acoustic detection of other, better known killer whale vocalizations (e.g. clicks, lower-frequency whistles, pulsed calls) may help inform the purpose of these calls and inform investigations in how other species in the area – including other cetaceans – may respond to killer whale presence.

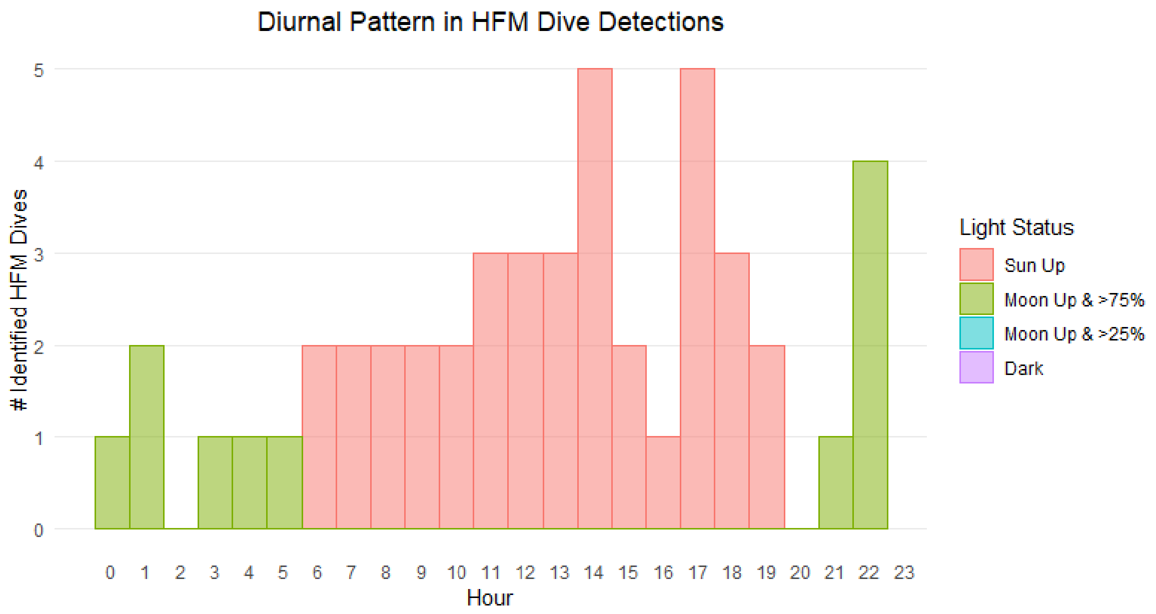

Figure 18: Hourly distribution of 48 killer whale dives consisting of HFM whistle detections. Colors correspond to different illumination categories: "Sun Up" (after sunrise and before sunset), "Moon Up & >75%" (the sun is down, but the moon is up and over 75% illuminated), "Moon Up & >25%" (the sun is down, but the moon is up and between 25% and 75% illuminated), and "Dark" (the sun is down and the moon is less than 25% illuminated).

4.2.9 Sperm Whales

Advances to the sperm whale detection and localization algorithms and the tracking process were previously described in Martin et al. (2019) and Martin et al. (2020). These improved processes were applied to all available data available at the time (February 2002 to August 2019; Martin et al. 2020). The same processes were applied to FY20 recordings and the maximum number of automatically-tracked sperm whales in snapshots for 10-minute periods for each hour of the day are presented in Figure 19. These results utilized the smaller study area focused on the hydrophone array and includes all full bandwidth data except for data recorded during the February and August SCCs, since the version of the NARWHAL algorithms with updates for the sperm whale detector has not yet been validated to assess potential false positives in those data. The maximum number of sperm whale tracks detected in a one-hour bin ranged from one (blue) to four (dark red) (Figure 19). Due to the calling characteristics of sperm whales, discriminating individuals can be challenging under certain conditions. When whales are solitary, widely spaced, or slow clicking, there is higher confidence that a track equates to an individual whale. However, sperm whales can form close foraging groups, during which click rates increase and localizations from multiple individuals can result in tracks being combined and split which can underestimate and overestimate the number of individuals.

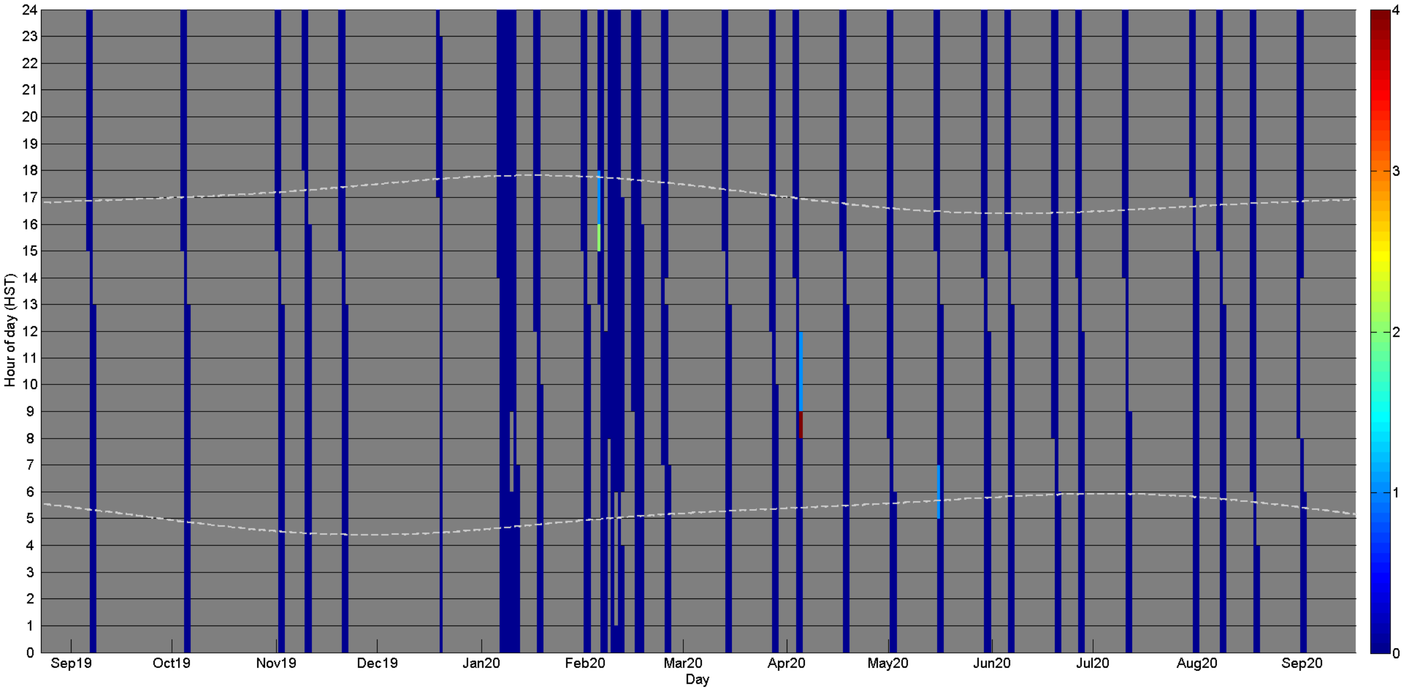

Figure 19: The maximum number of sperm whales detected in a 10-minute snapshot period for each hour of the day from September 2019 to September 2020 ranged from one (light blue) to four (dark red). Dark blue regions indicate periods of effort when acoustic recordings were collected and 0 whale tracks were present. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

4.3 DISTURBANCE ANALYSIS

4.3.1 Disturbance Analysis Improvements

The methods for estimating RLs on whales exposed to MFAS during U.S. Navy training at PMRF were improved in FY20 in multiple ways, including fitting a continuous-time correlated random walk model to the tag positions using the R package *crawl* (Johnson and London, 2018) to generate Correlated Random Walk (CRW) tracks, and by using the associated location error and measured and modeled whale depths to represent the RLs as 3D sound fields. The collaborative analysis (see Section 5) with Cascadia Research Collective and Southall Environmental Associates Inc. is a re-examination of several years of satellite-tagged whale data using these advanced methods and the full analysis and results are provided in a separate report (Henderson et al. 2021). The existing PAM disturbance analysis methods were modified to utilize the CRW tracks with satellite-tagged whale positions interpolated to every 5 minutes and to estimate all exposures from all surface ship MFAS sources. The satellite-tagged whales' CRW tracks can either be represented by a single track with standard errors in x and y (similar to current PAM derived tracks of baleen and sperm whales), or via some number of imputed tracks. Schick et al. (2019) used 100 imputed tracks for their analysis of satellite tagged pilot whales, and so we also utilized 100 imputed tracks for our analysis for comparison. The satellite tag data often included dive sensor data which provides auxiliary information to refine the whale's 3D location by reducing the potential depth regime in which the whale was located, thus refining the estimated RLs. This approach represents a major improvement to the methods previously applied to satellite tagged whales (Baird et al. 2017, Baird et al. 2019) which had evolved over time and utilized small sample sizes of 2D estimated RL exposures on each tagged whale, and included one estimate near the surface and one at a typical species' dive depth.

4.3.2 FY20 Disturbance Analysis

Standard disturbance analysis processes utilized in past reports (e.g. Martin et al. 2018) were performed for minke whales and Blainville's beaked whales for FY20, since these were the only PAM animal tracks or dives that overlapped with ship presence and sonar transmissions during the February and August 2020 SCCs. Minke whale tracks were analyzed relative to all concurrent ship positions and all MFAS transmissions in 5-minute bins, with an additional buffer of two 5-minute bins added before and after a track to capture any adjacent exposures that would otherwise not be accounted for. The number of beaked whale dives per hour were examined by comparing dives per hour during non-training phases in February and August to dives per hour during the SCC training events. Due to security limitations, ship-whale geometries were generalized in 45° sectors and the number of ships participating in an event was generalized as one or more.

4.3.2.1 Minke Whales

During the February 2020 SCC, three minke whale tracks overlapped with ship presence and sonar transmissions. Examining these tracks individually and in chronological order, first, track 1 is depicted in blue in Figure 20. This track started on February 20th at 17:49 GMT and 22.75° latitude and -159.85° longitude and traveled northwest. Track 1 ended at 20:05 GMT and 22.80° longitude and -159.9° longitude, and completely overlapped with ship presence but was not exposed to any MFAS transmissions. This track's time history relative to the closest ship(s) is in the top panel of Figure 21 and shows ship(s) approaching this whale from 40.1 km to a closest point of approach of 11.9 km on February 20th between 18:49 and 18:54 GMT. At the closest point of approach, the animal was off the starboard beam sector of the closest ship (angle off bow: 45° to 135°) and was accompanied by a 17 min gap in the whale's call interval. The closest ship(s) then opened in range for the remainder of the whale's track with the whale resuming normal call intervals. This close approach may have elicited a behavioral response, with the animal briefly changing its call rate by skipping 2 calls.

Second, track 2 is depicted in orange in Figure 20 and started on February 21st at 18:20 GMT and 22.57° latitude and -159.87° longitude, and ended at 20:19 GMT and 22.6° latitude and -160.04° longitude. This is the only minke whale track during the February 2020 SCC that was exposed to MFAS transmissions. Although calls from track 2 did not directly overlap with sonar, the disturbance analysis process captures any overlap with MFAS transmissions 10 minutes before the start, and after the end of a track. In this case, the last MFAS transmission occurred on February 21st at 18:10 GMT, and only the first bin from track 2 was analyzed for RL estimation. This track's time history relative to the closest ship is in the middle panel of Figure 21 and shows a closest point of approach to a ship transmitting MFAS for the first bin only of 22.6 km with the whale in the port beam sector of the ship (angle off bow: -45° to -135°). The cumulative sound exposure level (cSEL) for the first bin, and therefore the entire animal track, was 157 dB cSEL re: 1µPa^{2}s. For the remainder of this track there were no MFAS transmissions but ships were present. While the animal continued to travel north, the distance to another ship had a closest point of approach of 8.1 km on February 21st between 18:50 and 18:55 GMT, with the animal in the port beam sector. After this encounter the whale's heading changed from north to northwest for the next two localizations, then changed to west. For the remainder of the track the whale exhibited an increase in speed and had a directed heading while it traveled across the study area. This was likely a behavioral response to a close approach to a ship not transmitting MFAS.

Lastly, track 3 is depicted in red in Figure 20 and started on February 22nd at 00:11 (GMT) at 22.38° latitude and -160.04° longitude, and ended at 03:45 (GMT) at 22.43° latitude and -159.86° longitude. The closest point of approach to a ship not transmitting sonar was 896 m and occurred on February 22nd between 03:06 to 03:11 (GMT), and is shown in the bottom panel of Figure 21. This is the closest distance between a ship and animal that we have ever reported for PMRF (although Martin et al. 2019 reported a minimum distance of 1 km between a ship not transmitting sonar and a minke whale). Despite this very close encounter, track 3 did not exhibit any apparent change in heading or a large deviation from the nominal call rate for the duration of the track. In comparison, tracks 1 and 2 may have elicited behavioral responses to approaches at 11.9 km and 8.1 km respectively. This further demonstrates that the trigger for a behavioral response can vary between individuals of the same species.

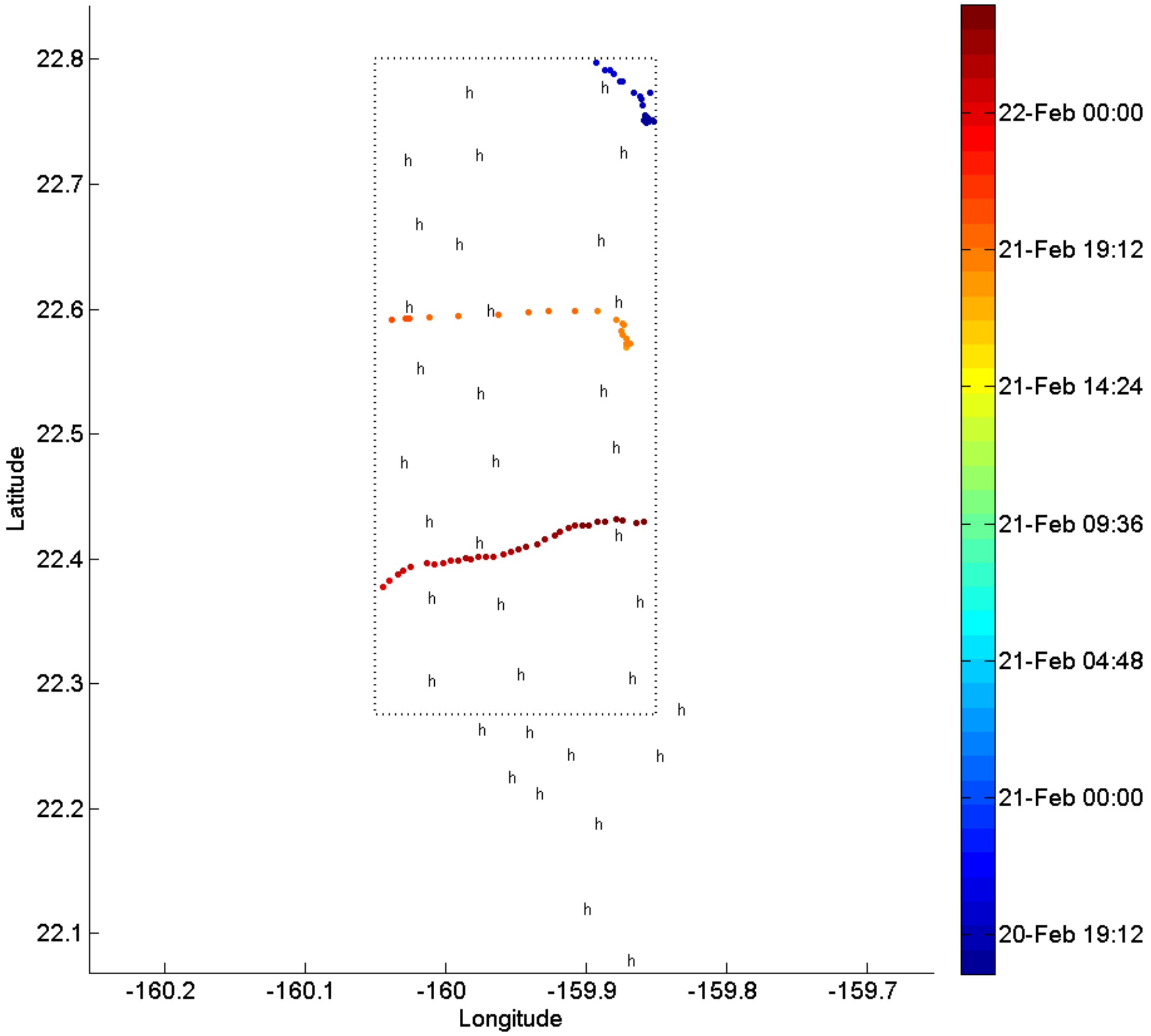

Figure 20: All three minke whale tracks that overlapped with ship presence and MFAS transmissions during the February 2020 SCC. Tracked call localizations are colored by time - track 1 (blue), track 2 (orange), and track 3 (red). The dashed box outlines the smaller study area extent for tracking animals. Approximate hydrophone locations are indicated with "h" symbols.

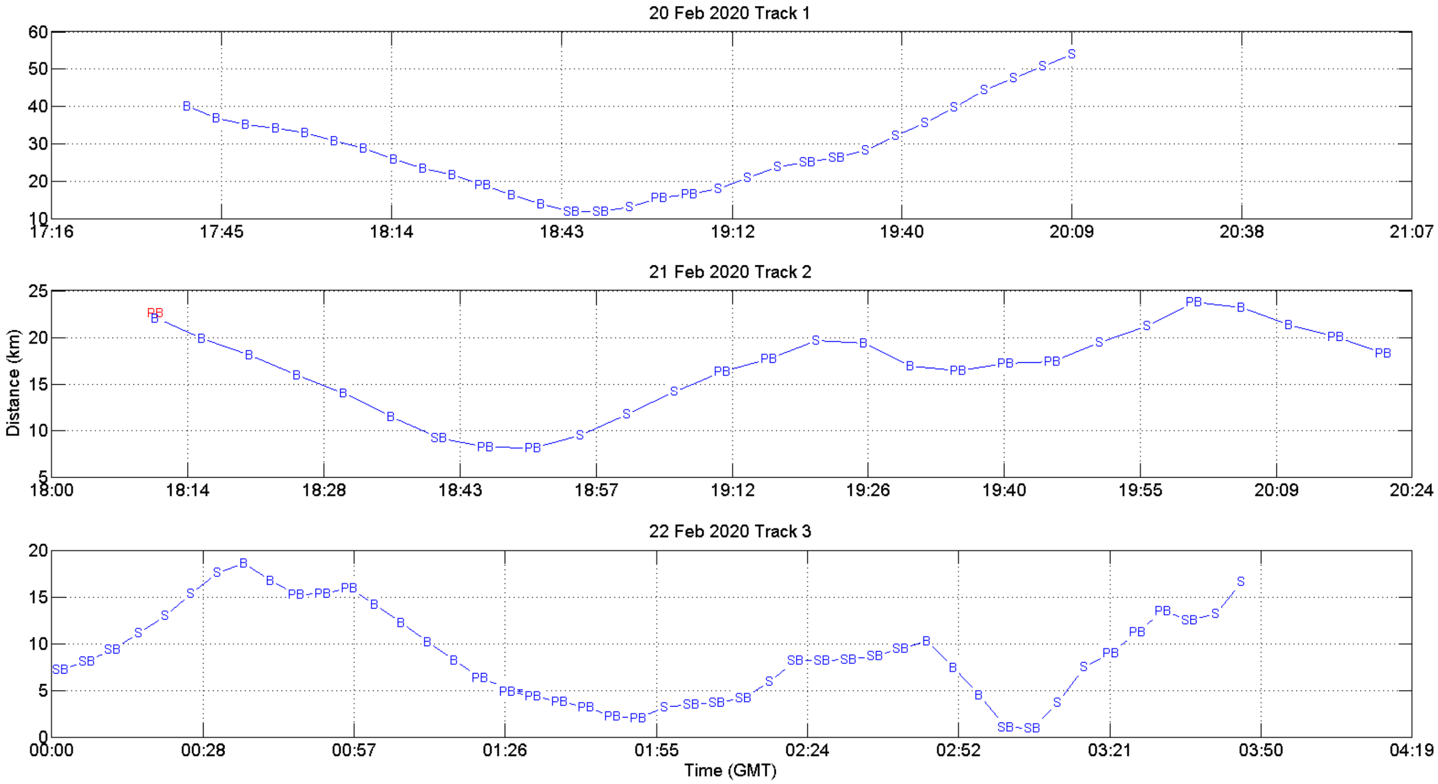

Figure 21: Distance to the closest ship (blue) and closest ship transmitting MFAS (red) in 5-minute bins for all three minke whale tracks that overlapped with ship presence and MFAS transmissions during the February 2020 SCC. Markers indicate distance and the animal’s location relative to the closest ship’s heading (B=bow [-45° to 45°], S=stern [-135° to 135°], SB=starboard beam [45° to 135°], PB=port beam [-45° to -135°]).

4.3.2.2 Blainville’s Beaked Whales

The number of Blainville’s beaked whale dives per hour of effort during non-training phases (i.e. Before, Between, and After phases), and during the SCC training event (i.e. Phase A [does not include hull mounted surface ship MFAS] and Phase B [includes surface ship hull mounted sonar]) are shown for February 2020 (Figure 22) and August 2020 (Figure 23). These results are a subset of the data included in Section 4.2.4 and therefore the number of dives per hour has also been adjusted based on the true positive (96%) and false positive (4%) rates from subset validation of Blainville’s beaked whale auto grouped dives from four random baseline recordings. As with the results in Section 4.2.4, this adjustment also results in a fractional number of dives seen in Table 5. As a note, none of the Blainville’s beaked whale dives from classified full bandwidth data collected during the February and August 2020 SCCs were validated, and it is possible that the true positive and false positive rates during the SCC training events are different than the baseline rates due to the presence of anthropogenic sound sources. Therefore, the results in Table 5, Figure 22, and Figure 23 may be biased particularly in Phase A, Phase B, and the Between phases of the training event. The potential also exists for the results in the Before and After phases, particularly periods of time around the start and end of the training event, to be biased as well since platforms and sources are still in the vicinity of the range.

Table 5 shows the start of the first recording and the end of the last recording for each phase to help identify the different phases in Figure 22 and Figure 23. It is important to note that when a phase end time and the next phase start time have the same time (e.g. February 2020 Before and Phase A in Table 5) that recordings stopped and started in the same hour and were usually minutes apart. Based on the February 2020 dives per hour metric in Table 5, an apparent reduction in dives per hour occurred from the Before phase (1.98 dives/hour) to Phase A of the SCC training event (0.24 dives/hour). This pattern was also observed in Henderson et al. (2019) and Martin et al. (2020), which examined dive rates across phases for 16 SCCs. In the Between phase the number of dives per hour increased to 1.05, then decreased again in Phase B of the SCC training event to 0.76 dives/hour. In the After phase, dives per hour increased to 2.30, which was higher than the dives per hour in the Before phase. It is interesting to note that the dives per hour in Phase A of the February 2020 SCC is lower than the dives per hour in Phase B. This is just the result for a single SCC and the long-term trend for Blainville's beaked whale dives for 16 SCCs from 2011-2018 was that dives per half hour start decreasing during Phase A and then decrease further during Phase B, for an overall lowest dive rate during Phase B. A lower dive rate in Phase A than in Phase B may be environmentally driven. Personnel from the NIWC WARP Laboratory were at PMRF during the February 2020 SCC and noted that the weather was stormy, and on February 14th during Phase A the Beaufort sea state was 4 to 5. Minke and humpback whales were documented to cease calling during a storm in January 2017 (Martin et al. 2019), and further investigation is warranted to determine if Blainville's beaked whales reduced diving during a storm in February 2020 that coincided with the SCC. Results for August 2020 had a reduction in dives per hour from the Before phase (1.41 dives/hour) to Phase A (0.90 dives/hour). The dives per hour slightly increased in the Between phase (0.93 dives/hour) followed by a decrease in Phase B (0.64). In the After phase, dives per hour increased to 1.45 dives/hour, which was slightly higher than the Before phase. The August 2020 results follow the long-term trend from Martin et al. (2020) in which dives per hour were lower in Phase B (0.64 dives/hour) compared to Phase A (0.90 dives/hour).

Table 5: Statistics for Blainville's beaked whale dives per hour baseline and exposure conditions in February and August 2020.

Start Hour (GMT)	End Hour (GMT)	Phase	Hours	Dives	Dives/Hour
01 Feb 0100	13 Feb 0200	Before	186.33	368.12	1.98
13 Feb 0200	15 Feb 1800	Phase A	64.17	15.61	0.24
15 Feb 1900	19 Feb 0100	Between	77.83	81.70	1.05
19 Feb 0100	23 Feb 2200	Phase B	116.83	89.05	0.76
24 Feb 1700	26 Feb 1600	After	45.17	103.73	2.30
01 Aug 0000	19 Aug 1300	Before	135.83	190.94	1.41
20 Aug 0200	22 Aug 0900	Phase A	55.00	49.57	0.90
22 Aug 0900	25 Aug 0500	Between	36.67	33.97	0.93
25 Aug 0500	30 Aug 1700	Phase B	121.00	78.03	0.64
31 Aug 1800	02 Sep 1500	After	38.67	56.00	1.45

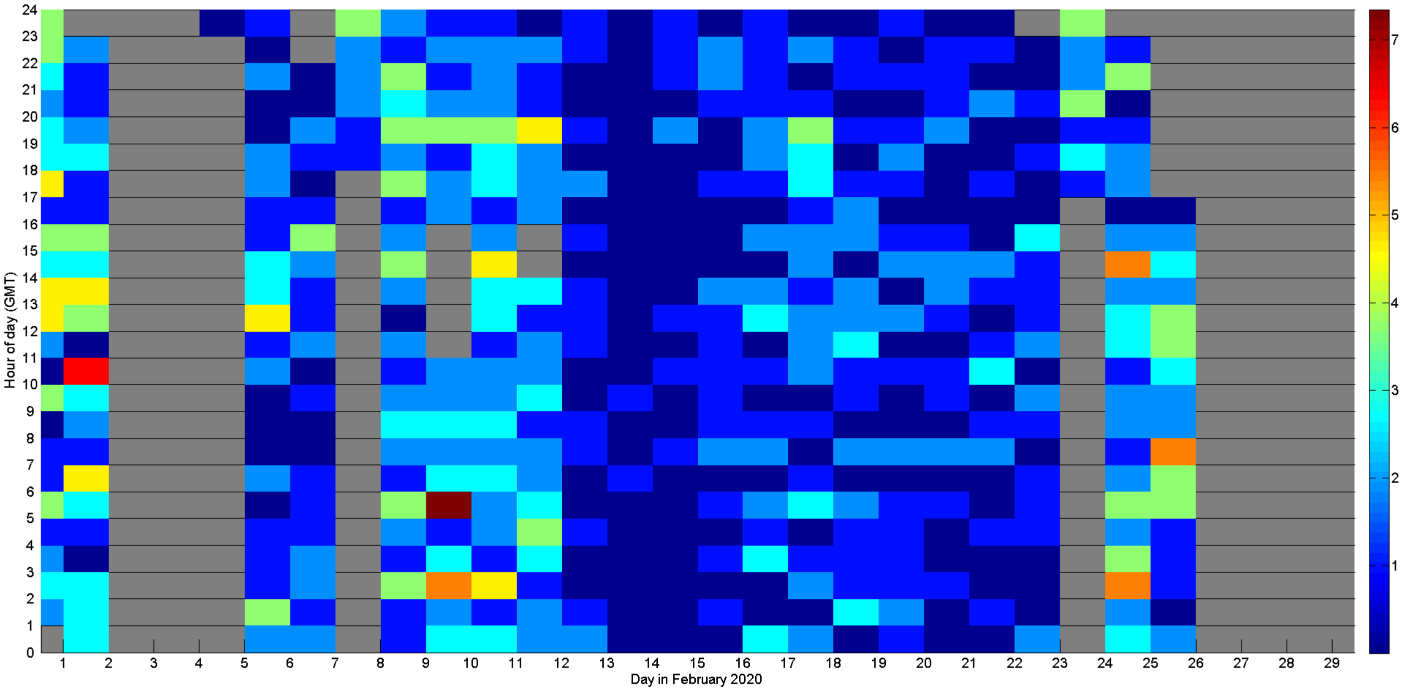

Figure 22: Blainville's beaked whale dives per hour corrected by the subset validated true positive rate of 96% and false positive rate of 4%. There was a maximum of 7.34 dives/hour (dark red) and a minimum of 0.92 dives/hour (blue). Results are shown for all February recordings during non-training phases and during the SCC training event. Note that time on the y-axis is referenced to GMT. Gray areas indicate periods when full bandwidth data were not available.

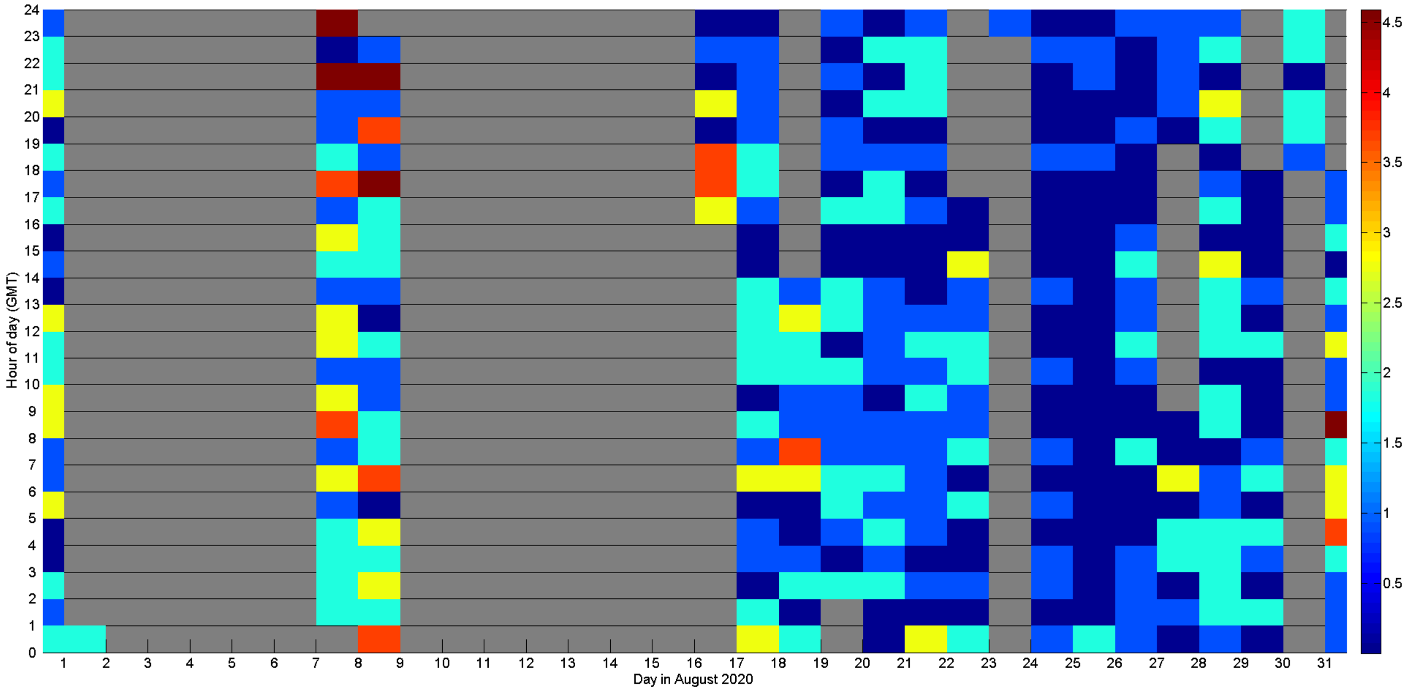

Figure 23: Blainville's beaked whale dives per hour corrected by the subset validated true positive rate of 96% and false positive rate of 4%. There was a maximum of 4.59 dives/hour (dark red) and a minimum of 0.92 dives/hour (medium blue). Results are shown for all August recordings during non-training phases and during the SCC training event. Note that time on the y-axis is referenced to GMT. Gray areas indicate periods when full bandwidth data were not available.

4.4 NOISE ANALYSIS

4.4.1 Humpback Whale Lombard Effect

Ambient noise analysis results are useful for assessing the impact of changing ocean noise conditions on marine mammals on the range, and as such we highlight how these measurements were used in FY20 to quantify the Lombard effect in both minke and humpback whales. Helble et al. (2020a) investigated the Lombard effect in minke whales, and the methods and results were summarized and included in the FY19 report (Martin et al. 2020). Follow-on work in FY20 by Guazzo et al. (2020) utilized similar methods in Helble et al. (2020a) to investigate the Lombard effect in humpback whales.

Many animals increase the intensity of their vocalizations in increased background noise. This response is known as the Lombard effect. While some previous studies about cetaceans report a 1 dB increase in the source level (SL) for every dB increase in the background noise level (NL) (e.g., Dunlop 2016, Dunlop et al. 2014, Fournet et al. 2018), more recent data have not supported this compensation ability. The purpose of the studies on minke whales and humpback whales were to test for a relationship between the SLs of their vocalizations and the corresponding background NLs. The findings in these studies also have important implications for acoustic animal density studies, which may use SL to estimate probability of detection.

Humpback whale song units were studied in a similar way to the minke whale boings in Helble et al. (2020a). Opportunistic recordings during 2012–2017 were used to detect and track 524 humpback whale encounters comprised of 83,974 song units on the PMRF hydrophones. Received levels were added to their estimated transmission losses to calculate SLs, and both SLs and NLs were measured over 150–1000 Hz. Humpback whale song units had a median SL of 173 dB re 1 µPa at 1 m, and SLs increased by 0.53 dB/1 dB increase in background NLs (Figure 24). These changes occurred in real time on hourly and daily time scales. Increases in ambient noise could reduce male humpback whale communication space in the important breeding area off Hawaii. The Lombard response for humpback whales was stronger than that observed for minke whales in the same study area, which may be because of the larger size of humpback whales and/or the diversity of unit types that they produce. However, this SL increase for song units of 0.53 dB/ 1 dB increase in NL is substantially lower than the 0.8–1.5 dB/1 dB increase reported in previous publications for social calls (Dunlop 2016, Dunlop et al. 2014, Fournet et al. 2018). The maximum intensity of vocalizations produced by an animal is likely limited by physiology, and since social calls are less intense than song units, perhaps the whales have a greater dynamic range to increase their social call SLs than to increase their song unit SLs. Since these vocalization changes may be dependent on location or behavioral state, more work is needed at other locations and with other species (Guazzo et al. 2020).

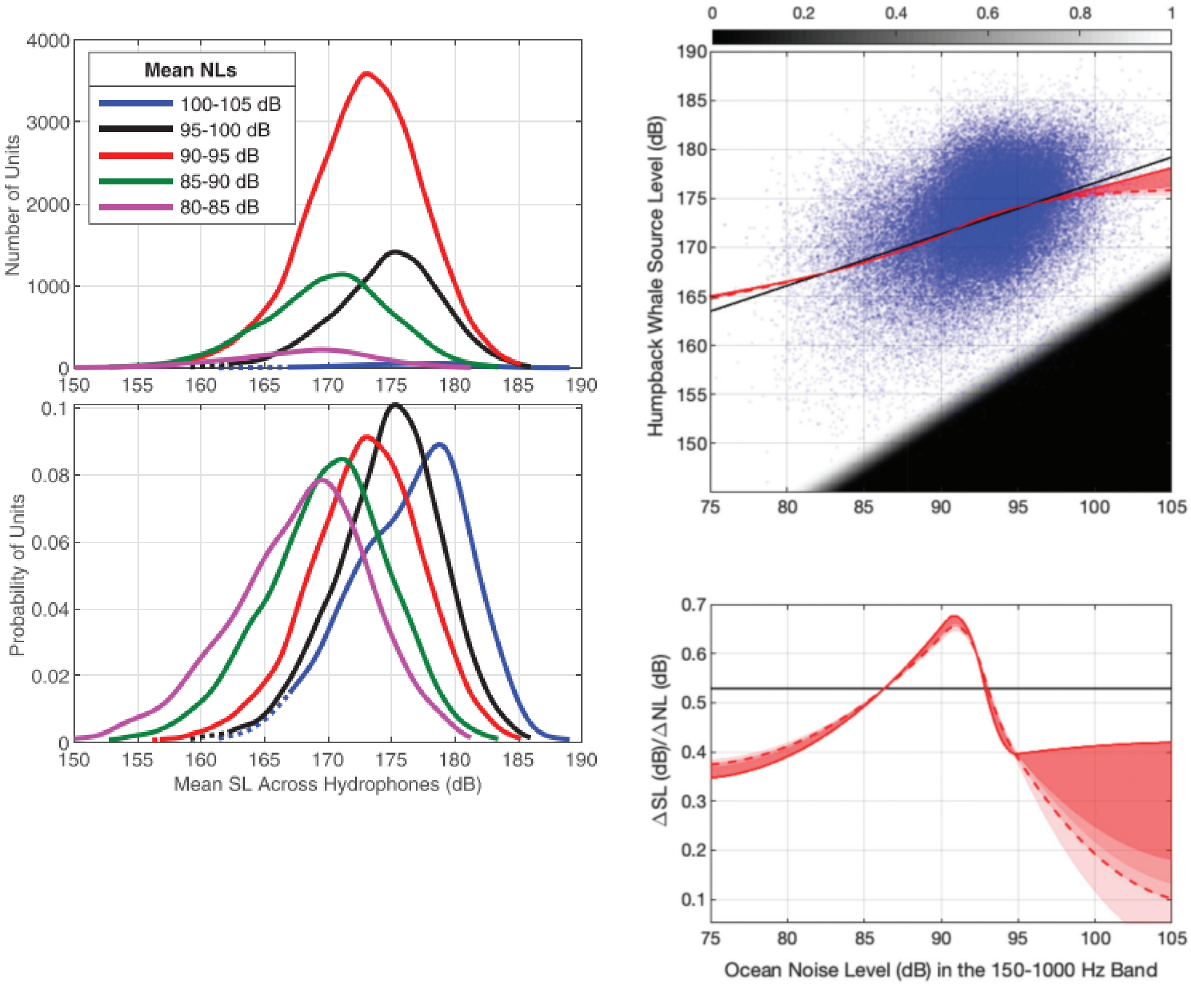

Figure 24. Overlapping fitted histograms of estimated humpback whale song unit SLs for given NL bands restricted to a horizontal distance between 2 and 10 km from the center hydrophone (left). The scatter plot (upper right) shows all of the SLs of humpback whale song units and their corresponding NLs. The grayscale region indicates the probability of localization averaged over all subarrays. The black line shows the linear fit to the data and the red line shows the generalized additive model fits with a range of decay constants to model the distribution of calls that may have been masked. The slopes of these fits are displayed in the lower right plot. All NL values are in units of dB re 1 µPa and SL values are in units of dB re 1 µPa at 1 m. (Figures 7 and 8 from Guazzo et al. 2020)

4.4.2 Minke Whale Detection Band Integrated Power Spectral Density Levels

An investigation of the integrated power spectral density levels over the minke whale boing detection band (1320 Hz to 1440 Hz) was conducted for multiple weeks of data during the baleen whale season, and included three SCC training events conducted in February 2014, 2015, and 2017. This is the first time we are reporting details for NLs during SCC training events. Each SCC training event consists of multiple days of training termed Phase A and Phase B (the only period with surface ship MFAS activities) as described in Section 4.3.2.2. A single hydrophone located near the geometric center of the BSURE hydrophone array at a depth of approximately 4,400 m (hydrophone K-5) was utilized in this analysis.

Power spectral density (PSD) levels were estimated for all available recorded data from February 2014; January, February, and March 2015; and January, February, and March (which crossed over to early April) 2017. This analysis utilized decimated data collected at the 6 kHz sample rate, and full bandwidth data collected at the 96 kHz sample rate that were downsampled to 6 kHz *ex-situ*. While noise levels in the minke whale boing detection band have been presented before (e.g. Martin et al. 2019), those levels were averages over longer periods of time (years vice days), and used a slightly different band of 1350 to 1450 Hz, while a band of 1320 to 1440 Hz is used in the current analysis since it is the same band used by the C++ detection and localization algorithm described in Section 3.1. Here the 10th, 50th, and 90th percentiles of the PSD in the minke whale detection band were calculated for each minute, and were based upon one second PSD levels integrated over the minke whale detection band. Presenting the three different percentiles allows one to obtain insight into how variable the various sounds in a species' detection band behave, with typical separations on the order of a few dB when little acoustic activity is present, and growing to over 25 dB when loud sounds are present. The 90th percentile data are dominated by a variety of sources with energy in this band, including sperm whale clicks, nearby calling whales, and anthropogenic sounds such as MFAS transmissions. These data help inform where more detailed analysis of the full bandwidth data is warranted to better understand the sources of sounds.

A sample of results for the three PSD percentiles in the minke whale detection band are shown for January 11-27, 2017 (Figure 25) with the 90th percentile level shown in red, 50th percentile level in blue, and the 10th percentile level in green. Average noise levels during this data collection have previously been described (Martin et.al. 2019 and Martin et.al. 2020) in relationship to a storm on January 21-22, 2017 which impacted the minke whale boing calling behavior for over 2 days. The 10th percentile levels in the minke whale detection band in Figure 25 exceed 80 dB continuously over the timeframe of the storm which supports the previous analysis and is important given it is a natural event which disrupts minke whale boing calling behavior, similar to anthropogenic noises such as MFAS.

Importantly a daily cyclic pattern is also evident in Figure 25 with the 10th percentile data peaking over 80 dB around 06:00 GMT daily (20:00 HST which is about 2 hours after sunset) for short periods of time (approximately 30 minutes). A review of raw data during some of these peaks revealed broadband energy between 1400 and 1800 Hz that increased by 12 dB to 17 dB over the half hour period of the peaks. Figure 26 provides a one-minute spectrogram of the data on January 16, 2017 from 06:14 to 06:15 GMT (near its peak levels in Figure 25). The band of energy centered at approximately 1600 Hz is obvious in Figure 26, as are sounds from other marine mammals (a minke whale boing call, humpback whale song units and fin whale 20 Hz calls). The minke whale boing call seen between the time axis 29:20 and 29:25 is on the edge of this broadband noise band, which reduces the signal to noise ratio which in turn affects detection, classification, and localization of distant calls. The boing calls in Figure 26 have a signal to noise ratio of 23 dB on the edge of the noise band, which is reduced by approximately 7 dB compared to calls a half hour earlier, before the 1600 Hz noise band appeared.

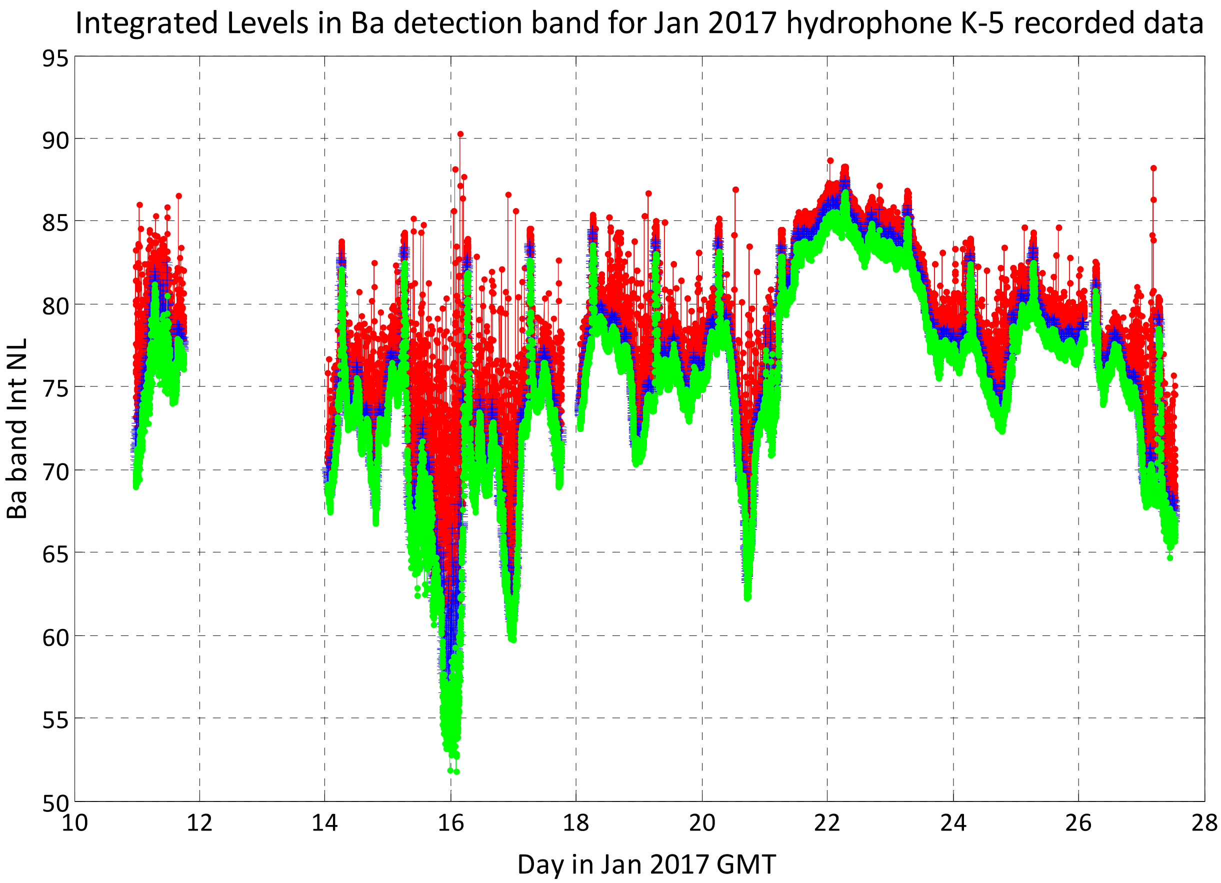

Figure 25: Minke whale boing detection band (1320 Hz to 1440 Hz) integrated spectral levels 90th (red), 50th (blue), and 10th (green) percentiles for hydrophone K-5 from January 11-27, 2017. Note the short-term peaks in noise in the 90th percentile data that are similar to the sustained noise levels during the storm on January 22 to 23, as well as the daily peaks in all levels at approximately 6:00 GMT.

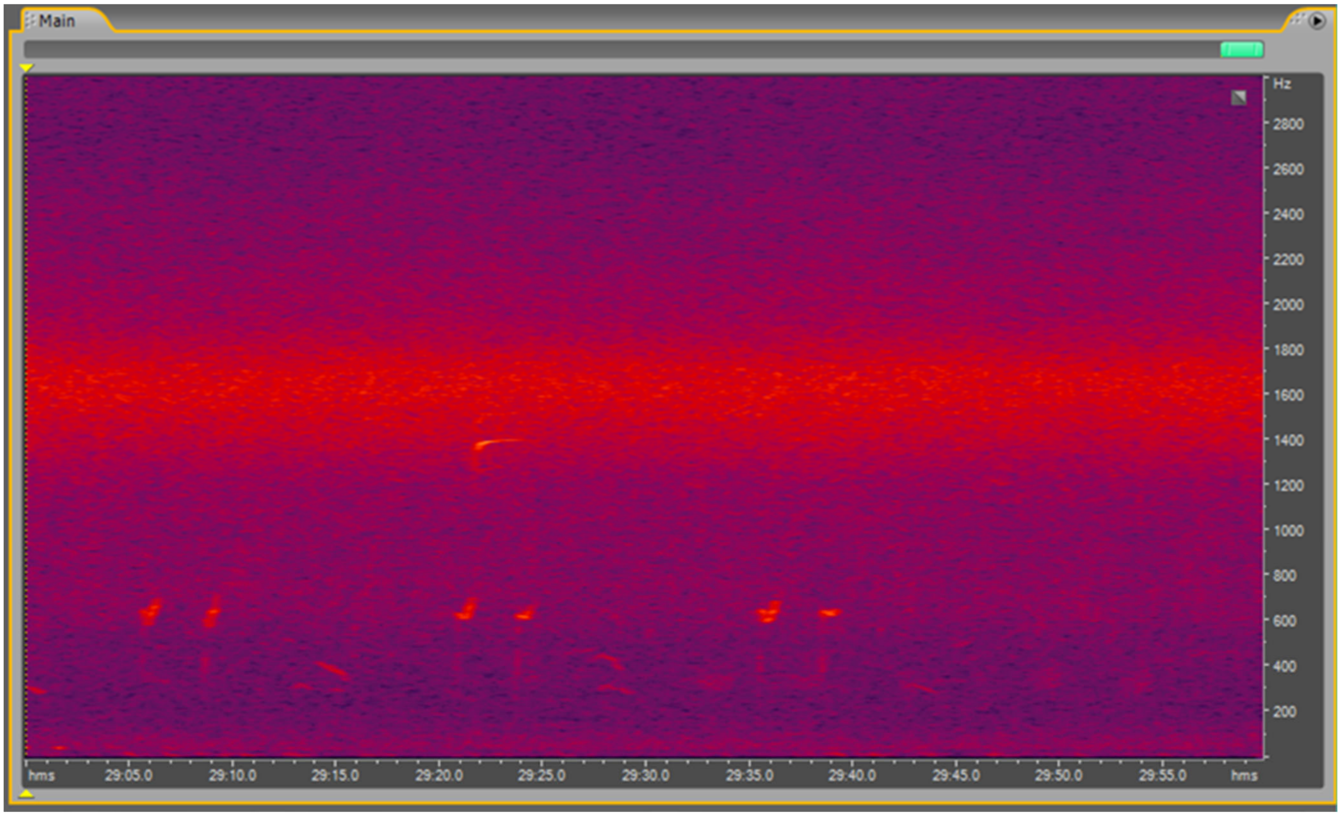

Figure 26: A spectrogram from 06:14 to 06:15 GMT on January 16, 2017 hydrophone K-5. The band of energy around 1400 to 1800 Hz is approximately 15 dB higher than 29 minutes earlier. The minke whale boing call present around 29:23 s at 1397 Hz is on the edge of this noise band, reducing its signal to noise ratio by 7 dB. Humpback whale song units are present between 200 Hz and 800 Hz.

The sources of these daily relatively short duration broadband levels between 1400 Hz and 1800 Hz are unknown. One hypothesis is the sounds are related to the diel vertical migration after sunset of micronekton/nekton species and mesopelagic fish that could be producing sounds as they rise from the depths, or the energy in the band could be related to predators of micronekton/nekton. The freshwater croaking gourami fish (*Trichopsis vittata*) has been documented to produce a 'stringed' type sound, generated by vibrations in the tendons of the pectoral fins during movement that, for adults, peaks around this same band (Wysocki and Ladich 2001). It is therefore not unreasonable that some species of the vertical migration in Hawaii occurring around sunset could be producing sounds responsible for this increased band of energy.

Figure 27 illustrates the minke whale detection band integrated PSD levels for February 2017, which includes for the first time periods of U.S. Navy SCC training activities, indicated in 10th percentile data (cyan) vice the 10th percentile data (green) for periods without U.S. Navy SCC training activity. An important takeaway from the data presented in Figure 27 is that the SCC Phase B PSD levels (February 15-18) are elevated, with short term peaks over 90 dB that correspond to periods with MFAS activity, These noise peaks could mask whale calls if the call arrives at the hydrophone simultaneously with the MFAS transmissions. While this elevated noise level could result in missing some calls in a minke whale's track, it is not expected to result in missing tracks. Figure 27 also indicates that the SCC Phase A levels (February 9-11) are similar to baseline periods, which should not significantly impact minke whale boing call PAM processing. A third takeaway is that the 90th percentile levels that exceed 100 dB on February 7, 2017 from 02:30 to 12:00 GMT are attributed to tracked humpback whale song units. The whale's closest point of approach (13 km) to hydrophone K-5 corresponds to the peak level at 06:25 on February 7, 2017 and the duration of the high peak levels also corresponds to the humpback whale's track duration.

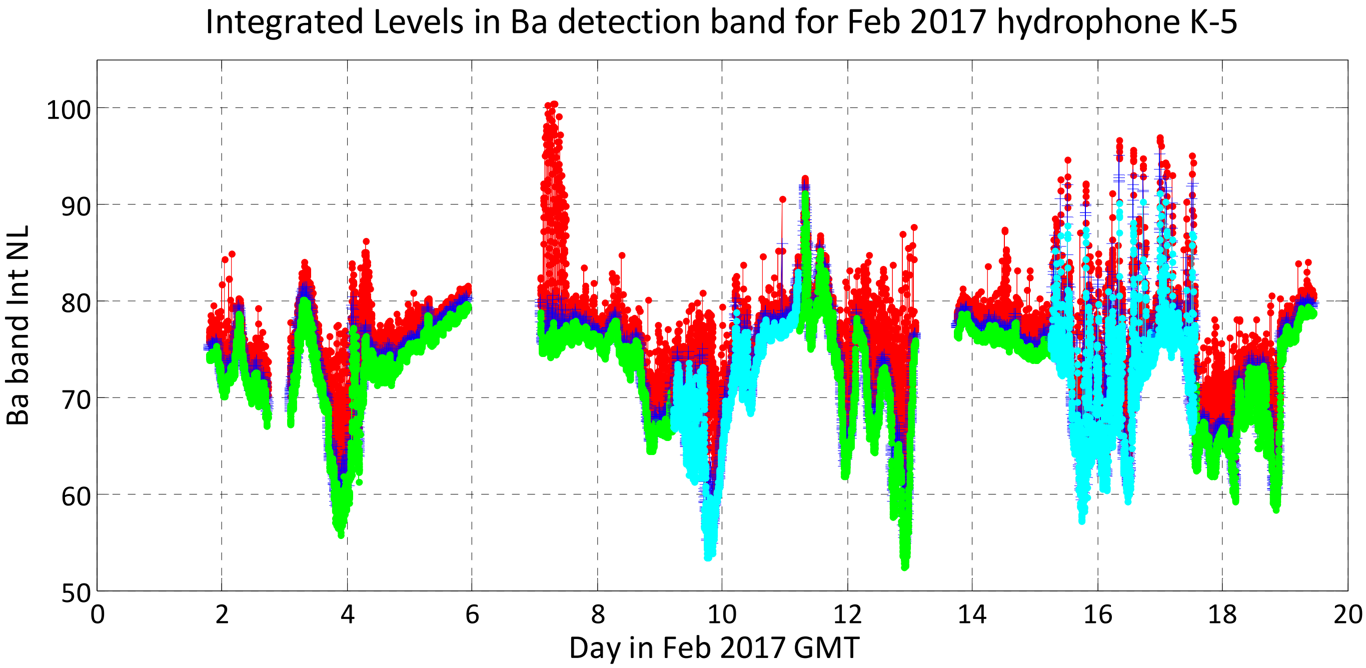

Figure 27: February 2017 integrated spectral levels over the minke whale boing detection band for available recorded data. Depicted are the 90th percentile (red), 50th percentile (blue), and 10th percentile (cyan during periods of U.S. Navy training on February 9-11 and 15-17, and green for periods not during U.S. Navy training). The three percentiles are calculated using 1 second of data every minute of the day.

5. Concurrent and Related Efforts

- The Office of Naval Research (ONR) effort titled Behavioral Response Evaluation (BREVE) began in Aug 2016 and is focused on investigating behavioral responses of baleen whales at PMRF to MFAS transmissions utilizing PAM whale localizations and tracks coupled with ship movement information from PMRF. The effort has performed spatial analysis to document minke whale calling behavior and spatial redistributions at PMRF in a before, during and after paradigm to MFAS activities (Harris et al. 2019). The effort has also shown that minke whales increase speed and their movements become more directed during periods of MFAS activities (Harris et al. 2018). The latest efforts reinforce that more directed movement and higher speeds are strong indicators of a response to MFAS ship activities for minke whales (Durbach et al. 2021).

- The ONR effort titled Environmentally-influenced Behavioral Response Evaluations (E-BREVE) is an extension of BREVE and is focused on understanding the impact of environmental changes on baleen whale behavior at PMRF. We are using some of the tools developed for BREVE to do this analysis. For example, in one task we are analyzing the swimming behavior of singing fin whales and using Hidden Markov Models to assess how different variables are related to their behavioral state (fast and directed vs. slow and turning), as was described by Durbach et al. (2021). We have tested wind speed and wave height as variables in these models, but so far, time of day and calling rate seem to be most related to behavioral state. Environmental data were downloaded from the National Oceanic and Atmospheric Administration’s (NOAA’s) Environmental Research Division Data Access Program (ERDAP) server via Tethys (Roche et al. 2013) for all periods of acoustic recording effort from 2011 through 2017. Environmental data included sunrise and sunset times, phases of lunar illumination, chlorophyll A levels, front locations, water temperature, salinity, current direction and strength (the latter three at the surface, 30 m depth, 120 m depth, and 800 m depth), and wind direction and velocity. Other modeled variables included the year and season, and Pacific Decadal Oscillation and El Niño Southern Oscillation anomaly values. These were averaged over each day of effort, and then generalized additive models were developed for humpback, minke, and fin whales with track occurrence as the predictor variable in each species’ model. The results of these models indicated different suites of environmental parameters were associated with the presence of each species, and could potentially be used to predict future occurrence patterns in Hawaii. The localization data for each of these three species will also be uploaded into Tethys and will be made available for other Tethys users.

- The LMR effort entitled “Standardizing Methods and Nomenclature for Automated Detection of Navy Sonar” began in 2019 and will conclude in 2022. This project is focused on assessing a few existing sonar detectors that were developed by various non-Navy organizations and scoring their detection results on several datasets of sonar data recorded on different instruments in a variety of depths and environments. Once these assessments are completed, the strengths of each detector can be summarized and used to develop a more standardized sonar detector that can be applied globally in various environments and on a range of sonar sources. This will allow the greater bioacoustics community that analyzes the presence and impact of sonar on marine mammals to present more comparable results, which will be more informative to Navy decision makers than the current wide-ranging results. In addition, non-classified nomenclature will be developed and shared that describes various sonar signals in a standardized format so that these improved results can also be discussed using the same vocabulary. Deliverables include both the detector itself as well as peer-reviewed publications and conference presentations describing the detector, the evaluation and scoring process and results, and the finalized sonar nomenclature.

- Satellite tag data obtained by the Cascadia Research Collective off Kauai (on or near the PMRF range) from short-finned pilot whales, rough-toothed dolphins, and bottlenose dolphins from 2011 through 2020 is being reanalyzed using improved methodologies to estimate RLs of sonar throughout each exposure period in three dimensions. Previous methods have only estimated RLs at coarse depth estimates and only at the time of each Argos tag location update, which are often separated by several hours. This coarse analysis precluded very accurate assessments of RL and potential behavioral responses. The ongoing analysis with a finer spatial and depth resolution, using error ellipses around each interpolated location, allows us to statistically estimate RLs accounting for measurement errors of each location. This provides a more accurate representation of the levels the animals were likely receiving throughout each exposure period. A summary report is planned at the end of CY20, and a follow-on peer review publication is also planned for the spring of CY21.

6. FY20 Publications

Guazzo, R. A., Helble, T. A., Alongi, G. C., Durbach, I. N., Martin, C. R., Martin, S. W., and Henderson, E. E. (2020). The Lombard effect in singing humpback whales: Source levels increase as ambient ocean noise levels increase. The Journal of the Acoustical Society of America 148(2): 542-555.

Harris, C.M., Martin, S.W., Martin, C.R., Helble, T.A., Henderson, E.E., Paxton, C.G.M., and Thomas, L. (2019). Changes in the spatial distribution of acoustically-derived minke whale (Balaenoptera acutorostrata) tracks in response to navy training. Aquatic Mammals, 45(6), 661-674.

Helble, T. A., Guazzo, R. A., Alongi, G. C., Martin, C. R., Martin, S. W., & Henderson, E. E. (2020b). Fin Whale Song Patterns Shift Over Time in the Central North Pacific. Frontiers in Marine Science, 7, 907.

Helble, T. A., Guazzo, R. A., Martin, C. R., Durbach, I. N., Alongi, G. C., Martin, S. W., Boyle, J. K., and Henderson, E. E. (2020a). Lombard effect: Minke whale boing call source levels vary with natural variations in ocean noise. The Journal of the Acoustical Society of America 147(2): 698-712.

7. FY20 Presentations

Alongi, G. C., Martin, S.W., Matsuyama, B.M., Martin, C.R., Manzano-Roth, R.A., and Henderson, E.E. (2019). Improvements in detection, localization, and tracking of sperm whales (Physeter macrocephalus) in Kauai. 178th Meeting of the Acoustical Society of America. 2-6 December 2019, San Diego, CA.

Guazzo, R. A., Helble, T. A., Martin, C. R., Durbach, I. N., Alongi, G. C., Martin, S. W., and Henderson, E. E. (2020). Humpback and Minke Whales Increase the Intensity of Their Calls in Increased Background Noise from Natural Sources. Ocean Sciences Meeting 2020.

Manzano-Roth, R.A., Henderson, E.E., Alongi, G.C., Martin, S.W., and Matsuyama, B.M. (2019). Long-term foraging dive characteristics of Cross Seamount beaked whales at the Pacific Missile Range Facility. 178th Meeting of the Acoustical Society of America. 2-6 December 2019, San Diego, CA.

Martin, C. R., Martin, S.W., Henderson, E.E., Helble, T.A., Alongi, G.C., and Matsuyama, B.M. (2019). Characterization of a bimodal call rate from tracked minke whales. 178th Meeting of the Acoustical Society of America. 2-6 December 2019, San Diego, CA.

REFERENCES

Alongi, G.C., Martin, S.W., Matsuyama, B.M., Martin, C.R., Manzano-Roth, R.A., and Henderson, E.E. (2019). Improvements in detection, localization, and tracking of sperm whales (Physeter macrocephalus) in Kauai. The Journal of the Acoustical Society of America, 146(4), p.2885.

Baird, R.W., S.W. Martin, R. Manzano-Roth, D.L. Webster, and B.L. Southall. (2017). Assessing exposure and response of three species of odontocetes to mid-frequency active sonar during submarine commanders courses at the Pacific Missile Range Facility: August 2013 through February 2015. Prepared for U.S. Pacific Fleet, submitted to NAVFAC PAC by HDR Environmental, Operations and Construction, Inc., Honolulu, Hawai‘i.

Baird, R.W., E.E. Henderson, S.W. Martin, and B.L. Southall. (2019). Assessing odontocete exposure and response to mid-frequency active sonar during Submarine Command Courses at the Pacific Missile Range Facility: 2016-2018. Prepared for Commander, Pacific Fleet, under Contract No. N62470-15-D-8006 Task Order KB16 issued to HDR, Inc., Honolulu, HI.

Dunlop, R. A., Cato, D.H., and Noad, M.J. (2014). Evidence of a Lombard response in migrating humpback whales (Megaptera novaeangliae). J. Acoust. Soc. Am. 136(1), 430–437.

Dunlop, R. A. (2016). Changes in vocal parameters with social context in humpback whales: Considering the effect of bystanders. Behav. Ecol. Sociobiol. 70(6), 857–870.

Durbach, I.N., Harris, C.M., Martin, C.R., Helble, T.A., Henderson, E.E., Ierley, G.R., Thomas, L., and Martin, S.W. (2021). Changes in the Movement and Calling Behaviour of Minke Whales (Balaenoptera acutorostrata) in Response to Navy Training. Frontiers in Marine Science, 8, 880.

Fournet, M. E. H., Matthews, L.P., Gabriele, C.M., Mellinger, D.K., and Klinck, H. (2018). Source levels of foraging humpback whale calls. J. Acoust. Soc. Am. 143(2), EL105–EL111.

Guazzo, R. A., Helble, T. A., Alongi, G. C., Durbach, I. N., Martin, C. R., Martin, S. W., and Henderson, E. E. (2020). The Lombard effect in singing humpback whales: Source levels increase as ambient ocean noise levels increase. The Journal of the Acoustical Society of America 148(2): 542-555.

Harris, C.M., Martin, S. W., Martin, C. R., Helble, T. A., Henderson, E. E., Paxton, C., and Thomas, L. (2018). Quantifying behavioural responses of minke whales to sonar activity during

Navy training exercises. 6th International Meeting on the Effects of Sound in the Ocean on Marine Mammals. 9-14 September 2018, The Hague, Netherlands.

Harris, C.M., Martin, S.W., Martin, C.R., Helble, T.A., Henderson, E.E., Paxton, C.G.M., and Thomas, L. (2019). Changes in the Spatial Distribution of Acoustically Derived Minke Whale (Balaenoptera acutorostrata) Tracks in Response to Navy Training. Aquatic Mammals, 45(6), p.661-674

Helble, T. A., Ierley, G.R., D'Spain, G.L., Roch, M.A., and Hildebrand, J.A. (2012). A generalized power-law detection algorithm for humpback whale vocalizations. J. Acoust. Soc. Am. 131(4), 2682-2699.

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

Helble, T. A., Martin, S.W., Ierley, G.R., and Henderson, E.E. (2016). Swim track kinematics and calling behavior attributed to Bryde's whales on the Navy's Pacific Missile Range Facility. J. Acoust. Soc. Am. 140(6), 4170-4177.

Helble, T.A., Guazzo, R.A., Martin, C.R., Durbach, I.N., Alongi, G.C., Martin, S.W., Boyle, J.K., and Henderson, E.E. (2020a). Lombard effect: minke whale boing call source levels vary with natural variations in ocean noise. Journal of the Acoustical Society of America 147(2), 698-712.

Helble, T. A., Guazzo, R. A., Alongi, G. C., Martin, C. R., Martin, S. W., and Henderson, E. E. (2020b). Fin Whale Song Patterns Shift Over Time in the Central North Pacific. Frontiers in Marine Science, 7, 907.

Henderson, E.E., Martin, S.W., Manzano-Roth, R.A., and Matsuyama, B.M. (2016). Occurrence and habitat use of foraging Blainville's beaked whales (Mesoplodon densirostris) on a U.S. Navy range in Hawaii. Aquatic Mammals 42(4), 549-562.

Henderson, E.E., Helble, T.A., Ierley, G.R., and Martin, S.W. (2018). Identifying behavioral states and habitat use of acoustically tracked humpback whales in Hawaii. Mar. Mamm. Sci. 34(1).

Henderson, E.E., Aschettino, J., Deakos, M., Alongi, G.C., and Leota, T. (2019). Blainville's beaked whales reduced foraging dives prior to the onset of hull-mounted MFAS sonar during Navy training events. 5th International Conference on Effects of Aquatic Noise on Marine Life, Den Haag, 7-12 July 2019.

Henderson, E.E., Martin, C.R., Baird, R.W., Kratofil, M.A., Martin, S.W., Southall, B.L. (2021). FY20 Summary Report on the Received Level Analysis of Satellite Tagged Odontocetes at the Pacific Missile Range Facility. Naval Information Warfare Center Pacific.

Johnson, D. S., and London, J. M. (2018). crawl: an R package for fitting continuous-time correlated random walk models to animal movement data. Zenodo.

Manzano-Roth, R., Henderson, E.E., Martin, S.W., Martin, C.R., and Matsuyama, B.M. (2016). Impacts of US Navy training events on Blainville's beaked whale (Mesoplodon densirostris) foraging dives in Hawaiian waters. Aquatic Mammals, 42(4), p.507.

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

Martin, C.R., Martin, S.W., Henderson, E.E., Helble, T.A., Manzano-Roth, R.A., and Matsuyama, B.M. (2016). SSC Pacific FY15 annual report on PMRF Marine Mammal Monitoring. Last accessed 17 Dec 2020. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/1223/

Martin, C.R., Martin, S.W., Henderson, E.E., Helble, T.A., Manzano-Roth, R.A., and Matsuyama, B.M. (2017). SSC Pacific FY16 annual report on PMRF Marine Mammal Monitoring. Last accessed 17 Dec 2020. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/1615/

Martin, C.R., Martin, S.W., Henderson, E.E., Helble, T.A., Manzano-Roth, R.A., Matsuyama, B.M., and Alongi, G.C. (2018). SSC Pacific FY17 annual report on PMRF Marine Mammal Monitoring. Last accessed 17 Dec 2020. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/1909/

Martin, C.R., Martin, S.W., Henderson, E.E., Helble, T.A., Manzano-Roth, R.A., Matsuyama, B.M., and Alongi, G.C. (2019). FY18 annual report on Pacific Missile Range Facility Marine Mammal Monitoring. Last accessed 17 Dec 2020. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/2024/

Martin, C.R., Henderson, E.E., Martin, S.W., Helble, T.A., Manzano-Roth, R.A., Matsuyama, B.M., Alongi, G.C., and Guazzo, R.A. (2020). FY19 annual report on Pacific Missile Range Facility Marine Mammal Monitoring. Last accessed 17 Dec 2020. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/2208/

Martin, S.W. and Matsuyama, B.M. (2014). Suspected Bryde's whales acoustically detected, localized and tracked using recorded data from the Pacific Missile Range Facility, Hawaii. Last accessed 17 Dec 2020. https://www.navymarinespeciesmonitoring.us/index.php/download_file/view/930/.

Rankin, S., Baumann-Pickering, S., Yack, T., and Barlow, J. (2011). Description of sounds recorded from Longman’s beaked whale, Indopacetus pacificus. The Journal of the Acoustical Society of America, 130(5), EL339-EL344.

Rankin, S. and Barlow, J. (2007). Vocalizations of the sei whale Balaenoptera borealis off the Hawaiian Islands. Bioacoustics 16.2, 137-145.

Roch, M.A., Baumann-Pickering, S., Batchelor, H., Hwang, D., Širović, A., Hildebrand, J.A., Berchok, C.L., Cholewiak, D., Munger, L.M., Oleson, E.M., and Van Parijs, S. (2013). Tethys: A workbench and database for passive acoustic metadata. In 2013 OCEANS-San Diego (pp. 1-5). IEEE.

Samarra, F. I., Deecke, V.B., Vinding, K., Rasmussen, M.H., Swift, R.J., and Miller, P.J.O. (2010). Killer whales (Orcinus orca) produce ultrasonic whistles. The Journal of the Acoustical Society of America, 128(5), EL205-EL210.

Schick, R.S., Bowers, M., DeRuiter, S., Friedlaender, A., Joseph, J., Margolina, T., Nowacek, D.P., and Southall, B.L. (2019). Accounting for uncertainty when modeling received levels for tagged cetaceans exposed to sonar. Aquatic Mammals, 45(6), 675-690.

Simonis, A. E., Baumann-Pickering, S., Oleson, E., Melcón, M. L., Gassmann, M., Wiggins, S. M., and Hildebrand, J. A. (2012). High-frequency modulated signals of killer whales (Orcinus orca) in the North Pacific. The Journal of the Acoustical Society of America, 131(4), EL295-EL301.

Stafford, K.M., Nieukirk, S.L., Fox, C.G. (2001). Geographic and seasonal variation of blue whale calls in the North Pacific. J. Cetacean Res. Manage., 3(1), 65-76.

Weirathmueller,M. J., Stafford, K.M.,Wilcock,W. S.D., Hilmo, R. S.,Dziak, R. P., and Tréhu, A.M. (2017). Spatial and temporal trends in fin whale vocalizations recorded in the NE Pacific Ocean between 2003-2013. PLoS ONE 12:e0186127. doi: 10.1371/journal.pone.0186127

Wysochi, L.E. and Ladich, F. (2001). The ontogenetic development of auditory sensitivity, vocalization and acoustic communication in the labyrinth fish Trichopsis vittata. J. Comp. Physiol. A. 187:177-187.

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