TECHNICAL REPORT 3274
APRIL 2022

FY21 Annual Report on Pacific Missile Range Facility Marine Mammal Monitoring

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NIWC Pacific

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Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001

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NIWC Pacific
San Diego, CA 92152-5001

NIWC Pacific
San Diego, California 92152-5001

A. D. Gainer, CAPT, USN
Commanding Officer

W. R. Bonwit
Executive Director

ADMINISTRATIVE INFORMATION

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Released by
Mark Xitco, Division Head
Reconnaissance and Interdiction Division

Under authority of
Michael McMillan, Department Head
Intelligence, Surveillance, and
Reconnaissance Department

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EXECUTIVE SUMMARY

This report documents Naval Information Warfare Center (NIWC) Pacific marine mammal monitoring efforts in fiscal year (FY) 2021 for Commander, Pacific Fleet (COMPACFLT) at the Pacific Missile Range Facility (PMRF), Kaua‘i, Hawai‘i. The following list highlights tasks completed in FY21 in support of COMPACFLT monitoring goals:

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 3203.7 hours of new data collected from September 4, 2020 to August 26, 2021, although there was a gap in data collection between March and June of 2021 due to the failure of the legacy recorder. The new recorder was successfully installed in June 2021.
2. Abundance results for minke whales from September 4, 2020 to August 26, 2021 indicated that a maximum of ten minke whales were detected in a 10-minute snapshot period in January 2021; however, this number was inflated due to some duplicate tracks being generated, likely due to the presence of minke whales calling at the rapid call rate. This phenomenon was investigated in detail, with an examination of individual minke tracks between August 2012 and July 2017. Hidden Markov Models (HMMs) were applied to quantify the relationship between an individual animal’s call rate and the distance to the closest conspecific(s). It was discovered that the probability that the rapid call rate would occur increased as the distance to the nearest minke whale decreased.
3. Abundance results for humpback whales found a maximum of only one singing whale at any given 10-minute snapshot period from October 2020 through January 2021. In addition, HMMs and generalized estimating equations (GEEs) were also applied to three years of satellite-tag track data to investigate movement and dive behavior of humpback whales in Hawai‘i.
4. Abundance results for the low-frequency baleen whales (from C++ processing algorithms) found a maximum of three tracks that occurred in 10-minute snapshot periods in November and December 2020. No tracks were found in July and August of 2021, indicating no low-frequency baleen whales (namely Bryde’s whales, which are potentially present year-round) were present or vocalizing at that time. When looking at individual species results (from the Matlab Generalized Power Law [GPL] algorithm), there was a maximum of four fin whales in December 2020, a maximum of two Bryde’s whales in October 2020, and a maximum of one each of 40-kHz downsweep calls (likely fin/sei) in December 2020 and of unknown call types in November 2020. Blue whales were detected in December 2020 and January 2021, but were not tracked due to low localization accuracy.
5. Abundance results for odontocetes from September 4, 2020 to August 26, 2021 included Blainville’s, Cross Seamount (BWC), and Cuvier’s beaked whales, sperm whales, and killer whales. The number of Blainville’s beaked whale dives was corrected based on sample validation of five FY21 baseline recordings (91% true positive rate and 9% false positive rate); there was a maximum of 2.47 dives/hr in July 2021. The number of fully validated BWC and Cuvier’s beaked whale dives occurred far less frequently than Blainville’s beaked whale dives, resulting in a maximum of 0.23 dives/hr in December 2020 for BWC beaked whales and 0.23 dives/hr for Cuvier’s beaked whales in July 2021. Two groups of killer whales producing the high-frequency

modulated (HFM) call were detected in FY21, in December 2020 and July 2021. There was a maximum of one sperm whale track detected in two different 10-minute snapshot periods in December 2020; no other sperm whale tracks were detected in available FY21 data.

6. The statistical models developed by collaborators at the University of St. Andrews Centre for Research into Ecological and Environmental Modelling (CREEM) during the Office of Naval Research (ONR)-sponsored behavioral response evaluations (BREVE) project were finalized and given to NIWC Pacific to utilize on classified data for higher resolution analyses. HMMs were developed to examine movement behavior during the different phases of the Submarine Command Course (SCC) training events and found that minke whales engaged in the faster, more directed movement state in the During phase, but exhibited the slower, less directed state in all other phases. The minke whales also demonstrated a strong preference in the direction of their movement in the During phase, with animals north of the main area of training activity preferentially moving north, while animals west of the area of activity moved west and north (Durbach et al., 2021).
7. Disturbance analyses were conducted at PMRF for Blainville's, BWC, and Cuvier's beaked whales during the August 2021 SCC training event as well as during a unit level training (ULT) event that occurred prior to the SCC. All beaked whale dives per hour of effort during non-training phases (i.e. Pre-ULT, Post-ULT/Pre-SCC, Between, and Post-SCC phases), and during the training (ULT, which did include surface ship hull-mounted mid-frequency active sonar (MFAS), Phase A, which does not include surface ship hull-mounted MFAS, and Phase B, which does include surface ship hull-mounted MFAS) were investigated. As expected, all three species demonstrated reduced group vocal periods (GVPs) during the various training phases and a return to foraging behavior after the training.
8. An in-depth noise analysis was conducted on FY20 data to investigate whether the anthropause that has been detected in many other systems, both terrestrial and aquatic, during the coronavirus disease 2019 (COVID-19) pandemic also occurred at PMRF. This analysis looked at spectral densities across the full 96-kHz bandwidth as well as at five bands of interest to detect either a quieting in bands of anthropogenic noise or an increase in sound levels in bands of marine mammal activity. Although there were statistically significant differences across the year in all five bands, there was no clear trend related to the initial three-month period of COVID-19, and the results likely reflect natural variation in noise levels. These results could be compared to other years of data to see if similar trends are found.
9. A collaboration with Naval Undersea Warfare Center (NUWC) Newport led to the adaptation and application of the Navy Acoustic Range Whale Analysis (NARWHAL) detection, classification, localization, tracking and noise analysis algorithms on data from the Southern California Anti-Submarine Warfare Range (SOAR). Fin whale tracks from select datasets recorded by NUWC Newport between October 2012 and November 2019 were generated, while an ambient noise analysis and calibration effort was conducted on multiple datasets recorded at SOAR and PMRF by both NUWC Newport and NIWC Pacific.

ACRONYMS

ADC	Analog-to-Digital Converter
AIC	Akaike Information Criterion
ANOVA	Analysis of Variance
ARS	Area Restricted Search
ATO	Authority to Operate
BARSTUR	Barking Sands Tactical Underwater Range
BREVE	Behavioral Response Evaluations
BRS	Behavioral Response Study
BSURE	Barking Sands Underwater Range Expansion
BWC	Cross Seamount beaked whale signal
COMPACFLT	Commander, Pacific Fleet
COVID-19	Coronavirus Disease 2019
crawl	Continuous-time correlated random walk model R package *crawl* (Johnson and London, 2018)
CREEM	Centre for Research into Ecological and Environmental Modeling
CY	Calendar Year
DCL	Detection Classification Localization
DICASS	Directional Command-Activated Sonobuoy System
DIFAR	Directional Frequency Analysis and Recording
DLNR	Department of Land and Natural Resources
EBREVE	Environmentally-influenced Behavioral Response Evaluations
FFT	Fast Fourier transform
FY	Fiscal Year
GAM	Generalized Additive Model
GEE	Generalized Estimating Equation
GPL	Generalized Power Law
GVP	Group Vocal Period
HFM	High Frequency Modulated
HMM	Hidden Markov Model
ICI	Inter-Click Interval
INI	Inter-Note Interval
LFA	Low-Frequency Active
LIMPET	Low-Impact Minimally Percutaneous External electronics Tag
LOW SWARM	Low-frequency Sources with Whale Acoustic Reconnaissance for Mitigation
LMR	Living Marne Resources Program
LSQ	Least Squared Error
M3	Marine Mammal Monitoring Program at NOPF Dam Neck

M3R	Marine Mammal Monitoring on Navy Ranges
MFAS	Mid-Frequency Active Sonar
NaN	Not A Number
NARWHAL	Navy Acoustic Range Whale Analysis
NIWC Pacific	Naval Information Warfare Center Pacific
NMMF	National Marine Mammal Foundation
NOPF Dam Neck	Naval Ocean Processing Facility Dam Neck
NUWC Newport	Naval Undersea Warfare Center Newport
ONR	Office of Naval Research
PAM	Passive Acoustic Monitoring
PMRF	Pacific Missile Range Facility
SCC	Submarine Command Course
SEED	SMART Scholar Seed Grant
SMART	Science, Mathematics, and Research for Transformation
SOAR	Southern California Anti-Submarine Warfare Range
ULT	Unit Level Training
U.S.	United States
WARP	Whale Acoustic Reconnaissance Project

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1. INTRODUCTION

In fiscal year (FY) 2021 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), Kaua‘i, Hawai‘i to monitor vocalizing marine mammals both during baseline periods and during United States (U.S.) Navy training activities.

The FY21 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) Analyze background noise levels during 2020 at PMRF and in association with Naval Undersea Warfare Center (NUWC) Newport at the Southern California Anti-Submarine Warfare Range (SOAR);

4) Estimate sound levels to which marine mammals are exposed during U.S. Navy training with hull-mounted mid-frequency active sonar (MFAS), as well as other sources of noise (e.g. torpedoes, surface ships), and investigate behavioral responses;

5) Install the updated acoustic recording system at PMRF in June 2021;

6) Assess the acoustic cue rates of baleen whales at PMRF;

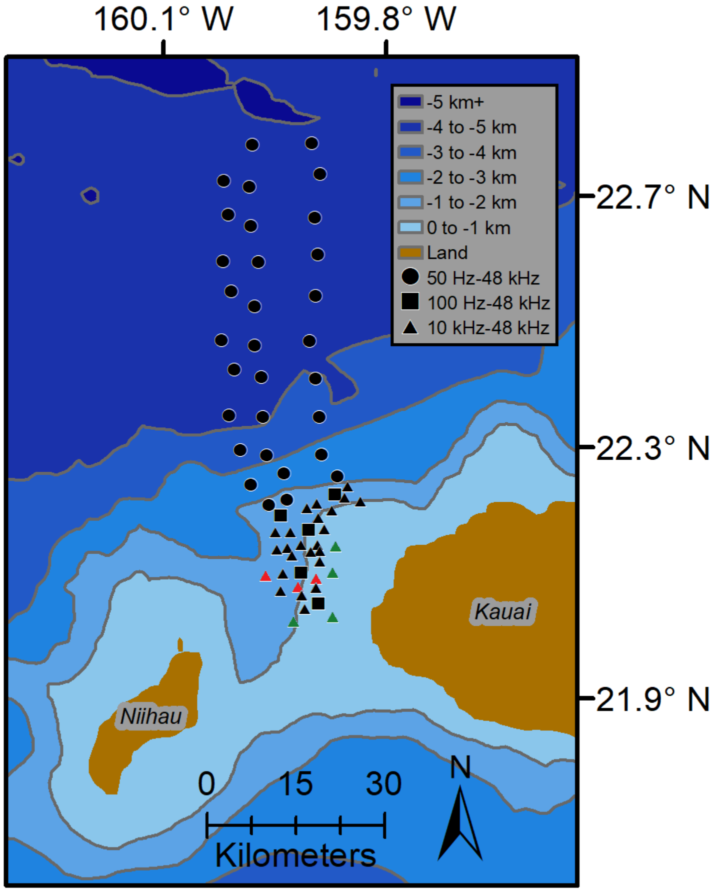
7) Collaborate with researchers conducting other monitoring efforts (e.g. MFAS exposure and response by tagged animals), including other U.S. Navy laboratories, academic institutions, and research organizations, to fill data gaps and provide a more complete monitoring data product.

This report also highlights specific analyses that were conducted in FY21 in pursuit of the above goals, including fin whale swim kinematics in relation to environmental variables and song patterns, humpback whale movement and dive behavior, long-term occurrence patterns of the Cross Seamount beaked whale signal (BWC), minke whale cue rates and calling behavior, an analysis of ambient noise data at PMRF in 2020, and a comparison of ambient noise analyses at both PMRF and SOAR conducted by NIWC Pacific and NUWC Newport, as well as a comparison of NIWC Pacific and NUWC Newport low-frequency baleen whale detections at SOAR.

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. Standard 45-hour full bandwidth (96 kHz) recordings and longer decimated recordings at the reduced sample rate of 6 kHz were conducted from September of 2020 through January of 2021 at least twice per month. A few longer decimated recordings from late June through August 2020, which were unavailable for last year's report, are also included this FY.



- Symbols indicate the approximate location of the 62 hydrophones recorded through January 2021 and their frequency response range. Starting in summer 2021, recording of the three red hydrophones ended and recording the four green hydrophones began, for a total of 63 hydrophones currently recorded.

Figure 1. Hydrophone array configuration at PMRF's instrumented range.

Until February 2021, the set of 62 hydrophones was comprised of 36 wide-band and 26 high-pass hydrophones. At the beginning of February 2021, the motherboard of the NIWC Pacific legacy recorder failed after a power outage and was no longer operational. Recordings were made before, during, and after the February SCC using the M3R packet recorder with permission of NUWC Newport. Unfortunately, unbeknownst to either organization, one of three data acquisition cards associated with the M3R recorder had failed and only 46 hydrophones were recorded during this time, the identities of which were impossible to determine. These issues (see Section 3.1 for more details) led to that data being stored but not analyzed for this report.

Due to coronavirus disease 2019 (COVID-19) pandemic related travel restrictions, WARP team members were not able to travel to PMRF to troubleshoot the legacy recorder and install the new updated recorder until June 2021. Therefore, no data were recorded from March through June of 2021. However, the new recorder was successfully installed at the end of June (details in Section 3.1). Data collection on the new recorder began in July 2021. Due to the specifications of the new system, an additional channel was available and was assigned to record a high-pass hydrophone, bringing the total number of hydrophones recorded to 63. In addition, three high-pass hydrophones that were previously recorded up to January 2021 had failed and those channels were reassigned to record three other high-pass hydrophones. Several recordings were made from July through September of 2021. The new recorder appears to be working well, and one of its improvements is that larger hard drives can be utilized to record longer datasets; therefore, recordings can be made continuously over multiple days, vastly improving the continuity of future data.

2.2 NAVY ACOUSTIC RANGE WHALE ANALYSIS (NARWHAL) ALGORITHM SUITE

2.2.1 Automated Detection, Classification, and Localization Algorithms

A suite of several algorithms is utilized to process recorded data for marine mammal vocalizations and have been previously detailed (Helble et al. 2012, Helble et al. 2015, Helble et al. 2016, Helble et al., 2020, Henderson et al. 2016, Henderson et al. 2018, Manzano-Roth et al. 2016, Martin et al. 2015). One custom C++ algorithm automatically detects and classifies two types of baleen whale vocalizations (minke whale boing calls and low-frequency calls that could be attributable to Bryde's, sei, fin, or blue whales), five odontocete vocalizations (Blainville's, BWC, and Cuvier's beaked whale clicks, sperm whale clicks, and killer whale high-frequency modulated (HFM) whistles), and MFAS transmissions. Another C++ algorithm localizes detected baleen whale calls, sperm whale clicks, and MFAS transmissions. A separate Matlab Generalized Power Law (GPL) algorithm detects and localizes humpback whale song, certain types of blue whale calls, and low-frequency calls. GPL then further attempts to classify these localizations as fin whale song, Bryde's whale calls, 40-Hz downsweeps (attributable to fin and/or sei whales), or other calls attributable to one or more of these baleen species. Finally, an analyst manually validates the blue whale detections, low-frequency classifications, and beaked and killer whale classifications.

Beaked whale clicks and killer whale HFM whistles are not able to be localized at PMRF due to a combination of the directionality and frequency of the calls and the distance between hydrophones, but another algorithm (in Matlab) is used to group those vocalizations that occur on neighboring hydrophones within a certain timeframe. Beaked whales emit echolocation clicks at depth while they are diving in close association with other conspecifics, therefore groups of their clicks are referred to as group vocal periods (GVPs), which are used here to quantify abundance. All BWC and Cuvier's beaked whale GVPs, and a subset of Blainville's beaked whale GVPs are validated using the raw acoustic data. Killer whale HFM whistles are less well understood, so those associations are simply referred to as groups. Due to the rarity of HFM whistles at PMRF, all groups are validated using the raw acoustic data.

After localization, an automated localization association tracker (LAT) algorithm in Matlab (described in Klay et al. 2015) uses spatial and temporal parameters based on general calling rate expectations for different species to connect localizations into tracks. Systematic snapshots of existing tracks every 10-minutes enables a census-type abundance estimate for calling whales that are able to be localized and tracked. For individual whale track results presented in Section 3.2, a smaller study area of ~1,200 km^2 (22.8° to 22.275° N-S and -159.85° to -160.05° E-W) that encompasses the hydrophone array, was utilized for tracking. Low-frequency baleen whale tracks in Section 3.2.3 that were processed with the Matlab GPL algorithm and classified as fin whale song, Bryde's whale calls, 40-Hz downsweeps (attributable to fin and/or sei whales), or other calls attributable to one or more of these baleen species, 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. Although the Matlab GPL-processed low-frequency baleen whale tracks in Section 3.2.3 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.

Relative abundance estimates based on these track snapshots or using the group dive metric described for beaked whales and killer whales are constrained by the number of animals vocalizing, which can depend on life stage, sex, and behavioral state. Cue rates and intraspecies proximity (relative to localization precision) also play a role. These metrics therefore correspond to a minimum density of animals in the study area. As with any PAM analysis, population abundance estimates require additional baseline population information, including the ratio of calling animals to all animals. For odontocetes that cannot be localized but emit vocalizations based on foraging (such as echolocation in beaked whales), group dives could be conceivably converted to a minimum density estimate if the average group size were known and relatively stable.

2.2.2 Improvements to processing algorithms

In FY21, two different code baselines (baseline 4 and the newer baseline 5) for the custom C++ algorithms have been used to classify, localize, and track marine mammal vocalizations. This is due to capabilities that have been developed in baseline 5 and tested on individual species (e.g. detecting and classifying killer whale HFM whistles, improvements to sperm whale localization and tracking, and the ongoing improvement and addition of different beaked whale species), but have not yet been exhaustively tested on other species to ensure that they are at worst unaffected by the algorithm changes. Efforts to thoroughly document and archive these changes and quantify their impact on all species at every processing stage (detection, classification, localization or grouping, and tracking) were initiated this FY. WARP will continue to characterize the performance between baseline 4 and 5 to understand how changes to the C++ algorithms affect results, and these findings will be used to guide a full transition to baseline 5.

2.2.2.1 Adaptation of Tracking Code to SOAR

NUWC Newport shared archived raw packet-formatted data as part of a collaboration to test existing NARWHAL algorithms for detecting and localizing marine mammals and measuring ambient noise at SOAR (see Introduction and Section 2.2.2). Getting the data in a format compatible with NARWHAL and properly time-aligned to prevent localization errors was a significant effort due to a variety of factors, including fundamental differences in how the data is laid down (packet vs. multiplexed), time-synchronized, and organized, changes in some data aspects over the years (e.g. changes to the A/D boards), and because of unanticipated data quality issues (packet errors, hydrophone outages). Of the 47 recording periods of various lengths and qualities shared, WARP selected 15 datasets with the longest durations for analysis. WARP also included three of our own recorded SOAR datasets in order to ground-truth results to previously generated fin whale tracks. The dates, times, durations, and preliminary maximum number of fin whale tracks in a 10-min snapshot (the same metric used for baleen whales at PMRF, described in Section 2.2.1) for the selected recordings can be found in Table 10. It should be noted that the tracks/snapshot metric and underlying calculations have not been tuned, or optimized, for fin whales at SOAR. Therefore, results are considered preliminary and require additional verification efforts.

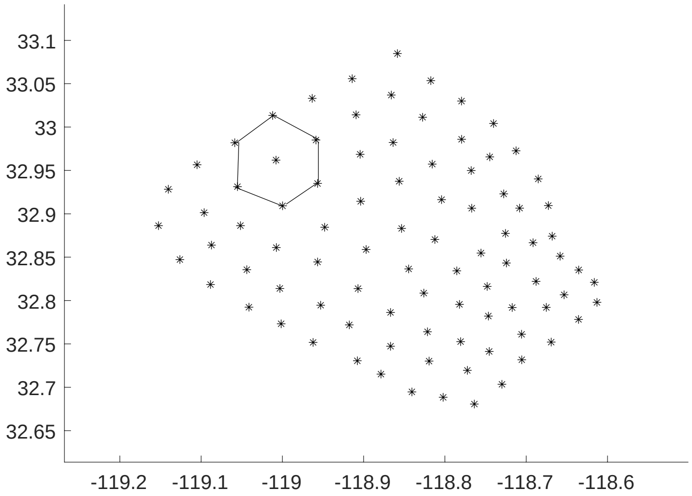


Figure 2. Approximate hydrophone locations at SOAR with example hexagon array illustrating the center hydrophone and support hydrophones used for localization within that region.

In order to track baleen whales at SOAR, parts of the NARWHAL algorithm suite were adapted for use at this range, which records a different raw data format and consists of a different number and arrangement of hydrophones (89 hydrophones placed in a hexagonal pattern spaced about 3 km apart; see Figure 2). Since fin whales are known to transit SOAR (Scales et al. 2017) the Matlab GPL algorithm that is specifically designed to detect and classify fin whale song was modified for this investigative effort, including determining and explicitly defining the subsets of hydrophones to be used by the algorithm as arrays for localization. The hydrophone configuration at SOAR naturally lends itself to an array design containing a center hydrophone surrounded by six supporting hydrophones. A total of 26 center hydrophones were used for localization to cover the area shown in Figure 2, with some arrays containing fewer than six supporting hydrophones (particularly along the range edges). Due to the number of hydrophones and arrays, the computational processing time for the Matlab GPL algorithm is longer than for PMRF, but the detection and localization process can still execute faster-than-real-time using the WARP computing resources. WARP also adjusted the ambient noise analysis algorithm for application at SOAR (see Section 2.2.4). Fifteen different datasets between October 2012 and November 2019 averaging 31.8 hours each, plus three datasets from December 2015 for ground-truthing, were processed with the adapted algorithms, with the results summarized in Section 3.5.

2.2.3 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 proximity of ships (even when not transmitting MFAS), thereby conducting an opportunistic, passive acoustic behavioral response study (BRS). When overlap occurs with whale tracks, 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 SCCs as determined by PAM analysis of MFAS localizations), propagation modeling is conducted to calculate sound levels that an animal may have received from multiple ships over the duration it was acoustically active.

In FY22, the NIWC Pacific WARP Laboratory will begin to extend the disturbance analysis processing to include exposures from helicopter dipping sonar (e.g. AN/AQS-22 and AN/AQS-13) and sonobuoys (e.g. Directional Command-Activated Sonobuoy System [DICASS] and Directional Frequency Analysis and Recording [DIFAR]). Some transmissions from helicopter dipping sonar and sonobuoys that occur during the SCC are already detected, classified, and localized by the custom C++ algorithms in the NARWHAL suite. In addition, the time and location of when these sources are deployed are logged in PMRF range products (i.e. Tsunami) that we currently receive. With the addition of the sonar detector developed in a concurrent Living Marine Resources Program (LMR) project (see Section 4.4), these additional MFAS sources should be detected, along with additional sources (e.g. torpedoes) that are not currently detected by the NARWHAL detectors.

The Office of Naval Research (ONR) project Behavioral Response Evaluations (BREVE) employing robust baselines and actual Navy training was officially completed in FY21. The majority of work was completed early in FY21 followed by publication of recent results (Durbach et al. 2021). The code for the Hidden Markov Modeling (HMM) statistical methods utilized in the BREVE effort are now being evaluated at NIWC Pacific. Transitioning of the BREVE code to COMPACFLT applications is underway with investigations of local vs. global minima via use of alternative initial parameter selections as determined by the log likelihood values for the current dataset. Additional transition efforts include utilizing full resolution ship heading information in a classified venue, rather than binning in five-minute intervals as was done in BREVE. Since actual distances from MFAS ships to whales were provided in the unclassified data analyzed by Durbach et al. (2021), only cardinal directions for ship headings in 90° quadrants were utilized due to security limitations. The full resolution ship information may result in the Akaike information criterion (AIC)-selected model including some effects due to estimated received levels or distances to ships, which were not included in the AIC-selected model in BREVE. Additionally, the use of a third HMM state is under consideration to represent whale repulsion from MFAS ships (similar to effort reported by Mul et al. [2020] which utilized a third HMM state to represent killer whale attraction to fisheries).

2.2.4 Noise Analyses

Noise analyses conducted at PMRF characterize noise in 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 by Martin et al. (2021), 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 ambient noise.

In FY21, a statistical analysis was conducted on several frequency bands to compare ambient noise levels through 2020 to determine if the COVID-19 related “anthropause” could be detected at PMRF, either as a reduction in levels in bands associated with anthropogenic sound or as an increase in levels associated with biological activity. These results are summarized in Section 3.4.1.

In addition, a collaboration was undertaken between WARP and NUWC Newport to quantify ambient noise levels across recorders and to develop and validate a method to estimate ambient noise using the archived data products recorded almost continuously by NUWC Newport (Section 3.4.2). NUWC Newport’s M3R system is installed at all the Navy instrumented ranges. While this system can record raw data on the packet recorder, the primary data streams are the archived detection reports and binary spectrograms, which are recorded almost continuously. At PMRF, NIWC Pacific has a separate system that only records raw data periodically, but has been calibrated with a transfer function, allowing us to measure received levels of signals of interest as well as ambient noise levels. In order to cross-calibrate these two systems, and to allow NUWC Newport to estimate ambient noise levels using their archived data products, NIWC Pacific and NUWC Newport conducted an ambient noise level comparison at both PMRF and SOAR, estimating offset values between the two systems and between the packet recorder and a “sprinkle analysis” of their archived data.

This was done by calculating the same metric of noise, the spectral density (in dB re 1 V/Hz), from data recorded during the same time period on the NIWC Pacific legacy recorder and the NUWC M3R packet recorder and then estimating the offset between the two values. A “sprinkle analysis” was then conducted on the archived data products from the same time period. The “sprinkle” refers to the automatic detection reports of the system being triggered by noise occurring over a preset noise variable threshold for each time-frequency bin (Morrissey 2021). By aggregating these detection reports over time, a statistically significant number of samples can be collected for each bin, which can then be averaged to obtain an estimate of the ambient noise level. For more details on this analysis, refer to Morrissey (2021).

The outputs from the sprinkle analysis were in V_{rms}^2 and were converted to spectral densities using:

Equation 1: $X \text{ dB re } 1 \text{ V/Hz} = 20 \log10 ((V_{rms}^2)/46.875)$

Note that the units are in dB re 1 V/Hz because the system transfer function has not yet been applied to convert to dB re 1 $\mu Pa^2/Hz$. In addition, Equation 1 was empirically derived in order to align the curves, and does not reflect the absolute value of the outputs. The number of frequency bins in each data structure also differed, so the sprinkle analysis output had to be interpolated to normalize the data to a 1 Hz bandwidth. The resulting values for the M3R packet recorder were subtracted from the NIWC Pacific recorder results across the full bandwidth of each phone, and the sprinkle results were subtracted from the packet recorder results. These were then averaged for each phone over the four-hour periods and then for all wide-band and high-pass hydrophones to get a single offset value.

A similar analysis was conducted using SOAR data (DiMarzio et al. 2022), although an offset value could only be calculated between M3R packet data (using the NARWHAL algorithms) and archived detection reports. The same conversion factor (Equation 1) was used on the sprinkle analysis data to convert the values from V_{rms}^2 to dB re 1 V/Hz. However, rather than interpolating the number of frequency bins, the NIWC frequency bin vector was simply multiplied by 5.86 to reach the same number of frequency bins in order to correct from a 5.86 Hz bandwidth to a 1 Hz bandwidth.

3. RESULTS AND DISCUSSION

3.1 PMRF RANGE DATA COLLECTION RESULTS

The FY21 data processed for this report spanned September 4, 2020 to August 26, 2021. The previous annual report (Martin et al. 2021) included data recorded between September 7, 2019 and September 2, 2020. However, in FY21, four previously unreported decimated recordings from June and August 2020 were also processed, and results are discussed in Section 3.2. The hours of decimated and full bandwidth data recorded on the NIWC Pacific legacy recorder (June 2020 to January 2021), and full bandwidth data collected on the new NIWC Pacific recorder (July and August 2021) are provided in Table 1. With the hours of unreported decimated data added from the FY20 dataset, there was a 2.5% increase in hours of decimated data in the FY21 dataset compared to FY20. However, there was a 33% decrease in hours of full bandwidth data collected due to the failure of the NIWC Pacific legacy recorder as previously discussed in Section 2.1. It is important to note that most of the FY21 full bandwidth recordings were collected in July and August of 2021 on the new NIWC Pacific recorder, which highlights the enhanced capability to collect longer periods of continuous full bandwidth data.

Table 1. Total hours of recording effort for full bandwidth and decimated data collections for previously unreported FY20 data (June and August 2020) and FY21 data (September 2020 to August 2021).

Data type (recorder)	Hydrophones	Hours
96 kHz full bandwidth (NIWC Pacific legacy recorder)	62	362.7
6 kHz decimated bandwidth (NIWC Pacific legacy recorder)	36	1419.8
6 kHz decimated bandwidth unreported from FY20 dataset (NIWC Pacific legacy recorder)	36	304.0
96 kHz full bandwidth (New NIWC Pacific recorder)	63	1117.2

3.1.1 Recorder Installation at PMRF

Due to the age of the NIWC Pacific legacy recorder that has been operational at PMRF since 2002, the WARP Laboratory spent several years assisting NUWC Newport with improvements to their M3R packet recorder program in anticipation of migrating data collection to the M3R packet recorder. However, ultimately it was determined that there were issues in the M3R analog-to-digital converter (ADC) boards that could not be overcome without replacing the boards. In order to maintain technical and operational oversight of the recording system and ensure continued recording of raw acoustic data, the WARP Laboratory purchased new ADC boards and built a new, separate stand-alone recorder that was authority-to-operate (ATO) compliant. This new system could be deployed in the M3R rack to reduce the physical space it occupied at PMRF and still be very simple to operate.

A General Standards sigma-delta ADC board with a ±1 V input range was selected for the new system as it can handle up to 64 input channels per board (the previous system utilized two separate time synchronized 32-channel ADC boards). This added an additional channel for recording as only one time-synchronized IRIG-B signal input was necessary for the single board. CAT7 cables with four twisted wire pairs per cable were also utilized; this allowed four channels to be wired per cable, thereby reducing the number of cables run under the floor.

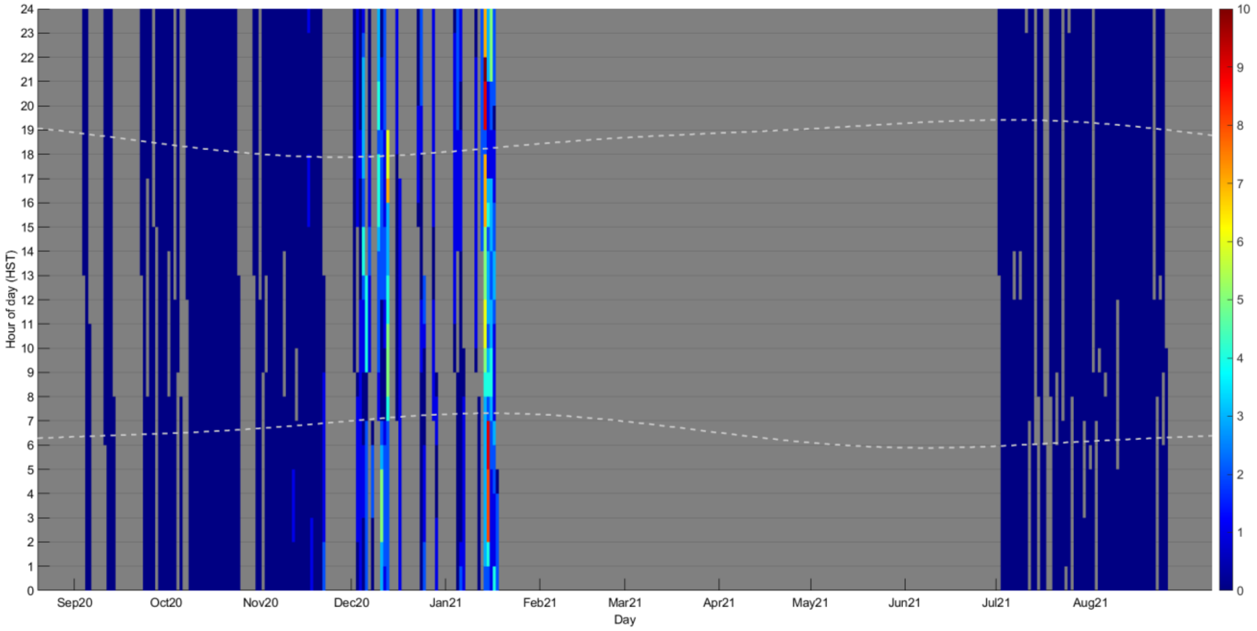
The new system was successfully installed at the end of June, and multiple recordings were made in July and August before, during, and after the SCC. Larger hard drives can be used on the new system, allowing full bandwidth data to be recorded continuously for several days, and so no decimated data are currently being recorded. This improves the continuity of the full bandwidth data, and reduces the effort for the PMRF range staff that make the recordings. A few recordings on the new system have exhibited some (recoverable) errors which were investigated. The problem appeared to be related to timing sequences for powering on, getting the operating system fully up, and required delays after configuring the ADC board before beginning data collections. This issue has been fixed in the WARP Laboratory and the system at PMRF will be updated prior to the next SCC.

3.2 ABUNDANCE AND DISTRIBUTION

3.2.1 Minke Whales

3.2.1.1 Snapshot Tracks Sep 2020 to Aug 2021

The maximum number of automatically-tracked, individual calling minke whales in a 10-minute snapshot period for each hour of the day from recordings made between September 2020 and August 2021 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 collected in August 2021. Minke whale seasonal presence started in November 2020 with hourly maximums of one to two individual whales detected in a one-hour bin. Seasonal presence typically occurs from fall to spring; unfortunately, due to data recording issues described in Section 2.1, the minke whale seasonal presence was not captured over the entire time they would have been present. There was a maximum of ten minke whales detected in a one-hour bin in January 2021. However, upon further inspection that estimate was artificially inflated due to duplicate tracks being generated. This is a known limitation of the tracking algorithm, specifically for minke whales. This typically occurs when the call density increases due to the presence of multiple calling whales or whales calling at the rapid call rate, and spurious or duplicate tracks are generated for multiple reasons (e.g. indirect path localizations, too narrow of a frequency threshold applied for minke whale boing call detections). We currently have tools to systematically investigate and correct for duplicate or spurious tracks. However, this is a time intensive process and a subject for additional future work (e.g. tuning tracking parameters, adding logic to the tracking algorithm to investigate tracks that are in close proximity to each other, and checking for indirect path localizations by examining the geometry between hydrophones on which calls are detected). As expected, no minke whale presence occurred in the previously unreported FY20 decimated data from June-August 2020 since those data occur outside of their seasonal presence.



- 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 classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

Figure 3. The maximum number of minke whales detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 ranged from one (light blue) to ten (dark red) which was artificially inflated due to spurious and duplicate tracks being generated.

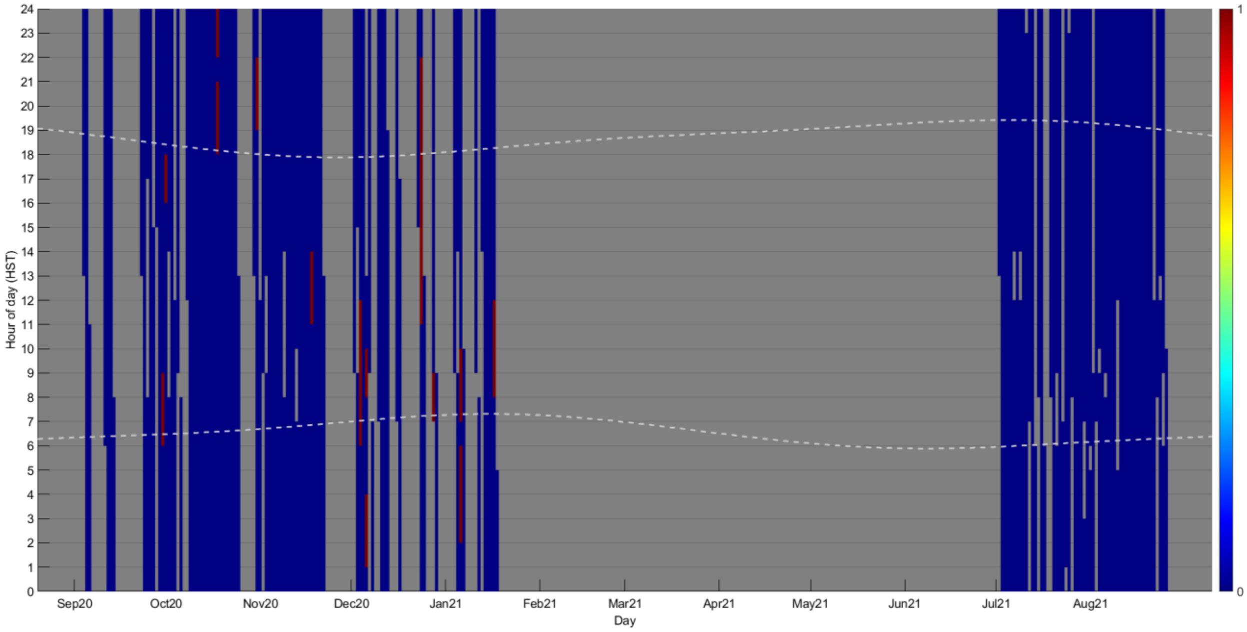
3.2.1.2 Minke Whale Calling Rates

Minke whales have a strong bimodal call rate with a more common “nominal” rate that averages one call every 7 min and a more “rapid” rate averaging 0.6 min. Thompson and Friedl (1982) were the first to hypothesize that the call rate increased when two whales were in close proximity to each other using limited encounters recorded off Oʻahu. The WARP Laboratory began to explore this topic in Martin et al. (2019) and Martin et al. (2020), and in recent efforts analyzed 509 validated individual minke whale tracks composed of 36,033 calls that occurred at PMRF between August 2012 and July 2017. Hidden Markov Models were utilized to quantify the relationship between call rate and the distance to the nearest calling minke whale. Overall, the probability that the rapid call rate would occur increased as the distance to the nearest minke whale decreased, and the probability of the nominal call rate occurring increased as the distance to the nearest minke whale increased. A draft manuscript documenting minke whale call rate as a function of distance to the nearest calling minke whale has been prepared and will be submitted for peer-reviewed publication in early CY22 (Martin et al. in prep).

3.2.2 Humpback Whales

3.2.2.1 Snapshot Tracks Sep 2020 to Aug 2021

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 2020 and August 2021 are shown in Figure 4. Between September 2020 and January 2021 there was a maximum of one acoustic humpback track (based on song) detected in a one-hour bin (Figure 4), which aligns with previously reported typical presence. These results utilized a small study area focused on the hydrophone array and include all decimated and full bandwidth data, including classified full bandwidth data recorded in August 2021. The start of humpback whale seasonal presence occurred in late September 2020. This is comparable to the winters of 2015 to 2018 (Martin et al. 2019) and 2019 (Martin et al. 2020), when humpback presence also started as early as September. Although not captured in the FY21 data set, we have previously reported the 2002-2020 whale seasons to last until April/May (Martin et al. 2020; 2021). As expected, no humpback whale presence occurred in the in the previously unreported FY20 decimated data from June-August 2020 since those data occur outside of their seasonal presence.



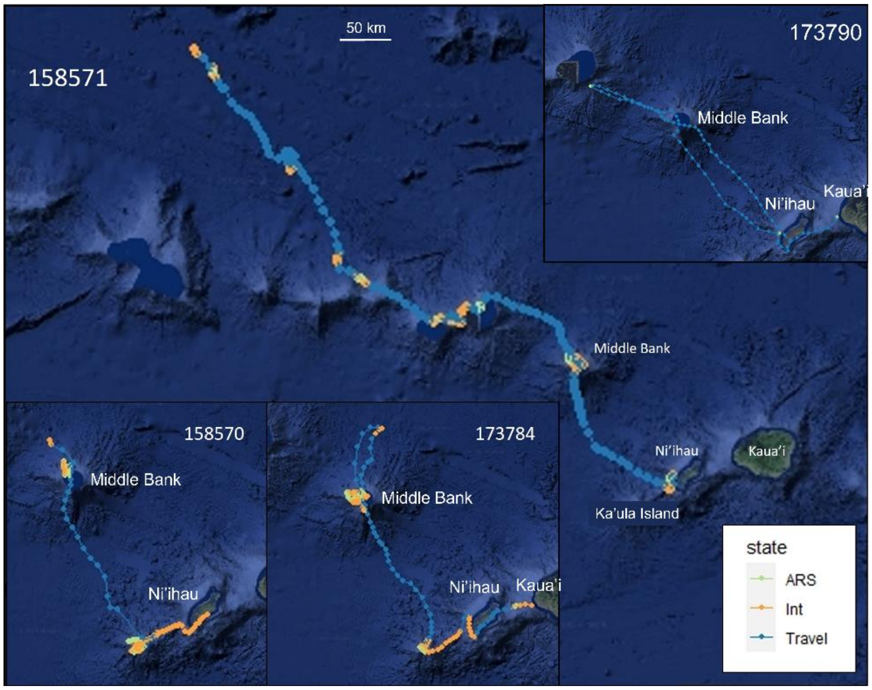
- Dark blue regions indicate periods of effort when acoustic recordings were collected and zero whale tracks were present. Results are from decimated and full bandwidth data collections, including classified data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

Figure 4. The maximum number of humpback whales detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 was one (dark red).

3.2.2.2 Humpback whale satellite tagging

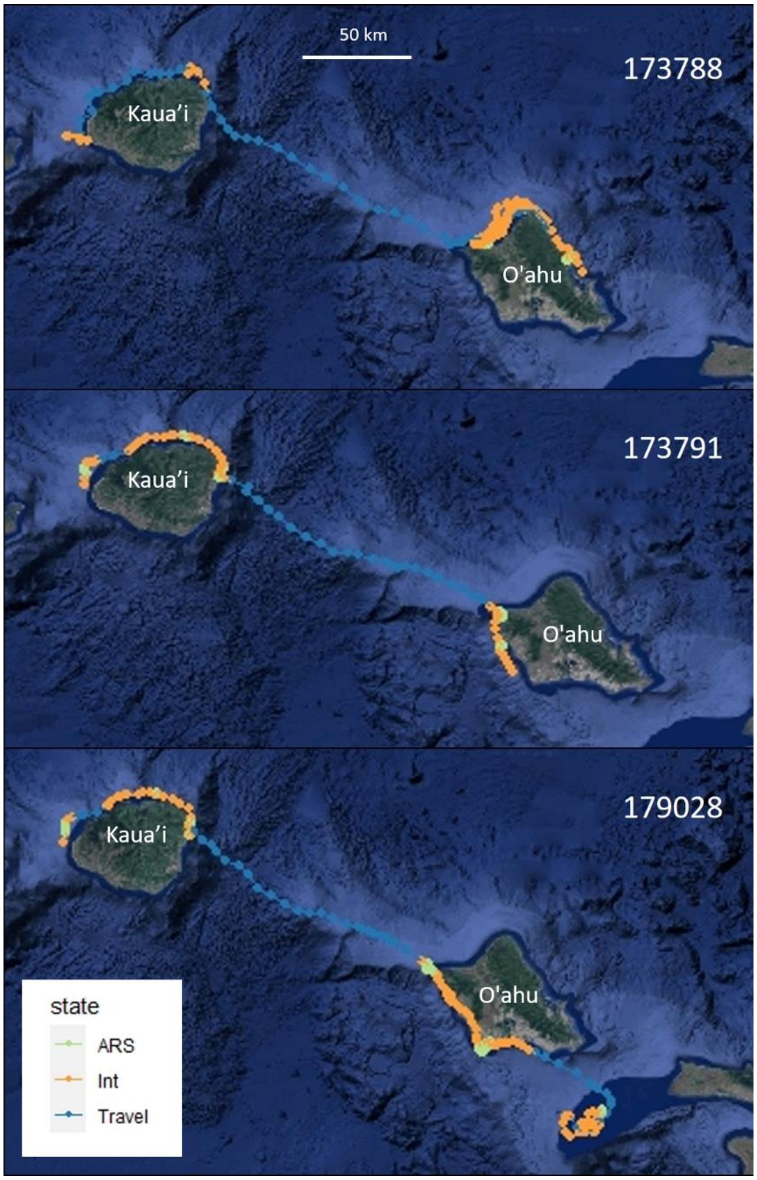
From 2017 to 2019, nineteen humpback whales were tagged off Kaua‘i with satellite-monitored, location-dive tags (Wildlife Computers SPLASH10 F-333) in the Low-Impact Minimally Percutaneous External electronics Tag (LIMPET) configuration. Effort and analyses are described in detail in Henderson et al. (2022). Briefly, locations were filtered first with a Kalman filtering algorithm then a Douglas-Argos Filter available in Movebank (www.movebank.org); a final manual filtering was conducted to remove erroneous positions on land or those outside of nominal humpback whale swim speeds (up to 15 km/hr). The filtered locations were then fitted with a correlated random walk to smooth the track and interpolate the positions every hour using the R program package *crawl* (Johnson et al. 2008, Johnson & London 2018, R Core Team 2019). A discrete-time HMM was then developed based on step length (distance between interpolated positions) and turning angle between interpolated hourly smoothed locations using the package momentuHMM (McClintock & Michelot 2018). Three behavioral states were modeled: 1) Area-Restricted Search (ARS), which typically indicates milling or foraging but may also be indicative of social behavior, 2) an intermediate behavior (a transition state between ARS and travel); and 3) directed travel. Dive behavior was analyzed using the package *diveMove* (Luque, 2007), and generalized estimating equations (GEEs) were fit to the resulting dive data, including dive depth, duration, descent and ascent rate, and bathymetric depth at each dive, as well as hour of day, dive shape, diel period, and whether the dive occurred inshore or offshore of 50 km. Palacios et al. (2019) determined that 50 km from shore was the approximate distance that humpback whales transitioned from breeding behavior to migration, so that value was used in this study as well to investigate behavior within and outside of that boundary.

The movement behavior models determined that the intermediate behavior was the most common behavior overall, while ARS and the intermediate behavior were the most common inshore behaviors, and directed travel was the dominant behavior offshore of 50 km. There was a low likelihood of transitioning from directed travel into ARS or vice versa; most transitions occurred via the intermediate state. The whales would transition from intermediate behavior into directed travel when moving between islands into deeper water, and from directed travel to intermediate when approaching shallower water near an island or seamount. Movement behavior and travel routes were very similar across all three years in humpback whales traveling northwest beyond Niʻihau along islands and seamounts (Figure 5) as well as among the whales traveling east to Oʻahu (Figure 6).



- Tracks 158570 and 158571 are from 2017, track 173784 is from 2018, and track 173790 is from 2019. (Figure taken from Henderson et al. 2022).

Figure 5. One-hour interpolated tracks fitted with the crawl model and movement behavior determined by HMMs, demonstrating the similarities in movement behavior and travel routes across individuals and years.

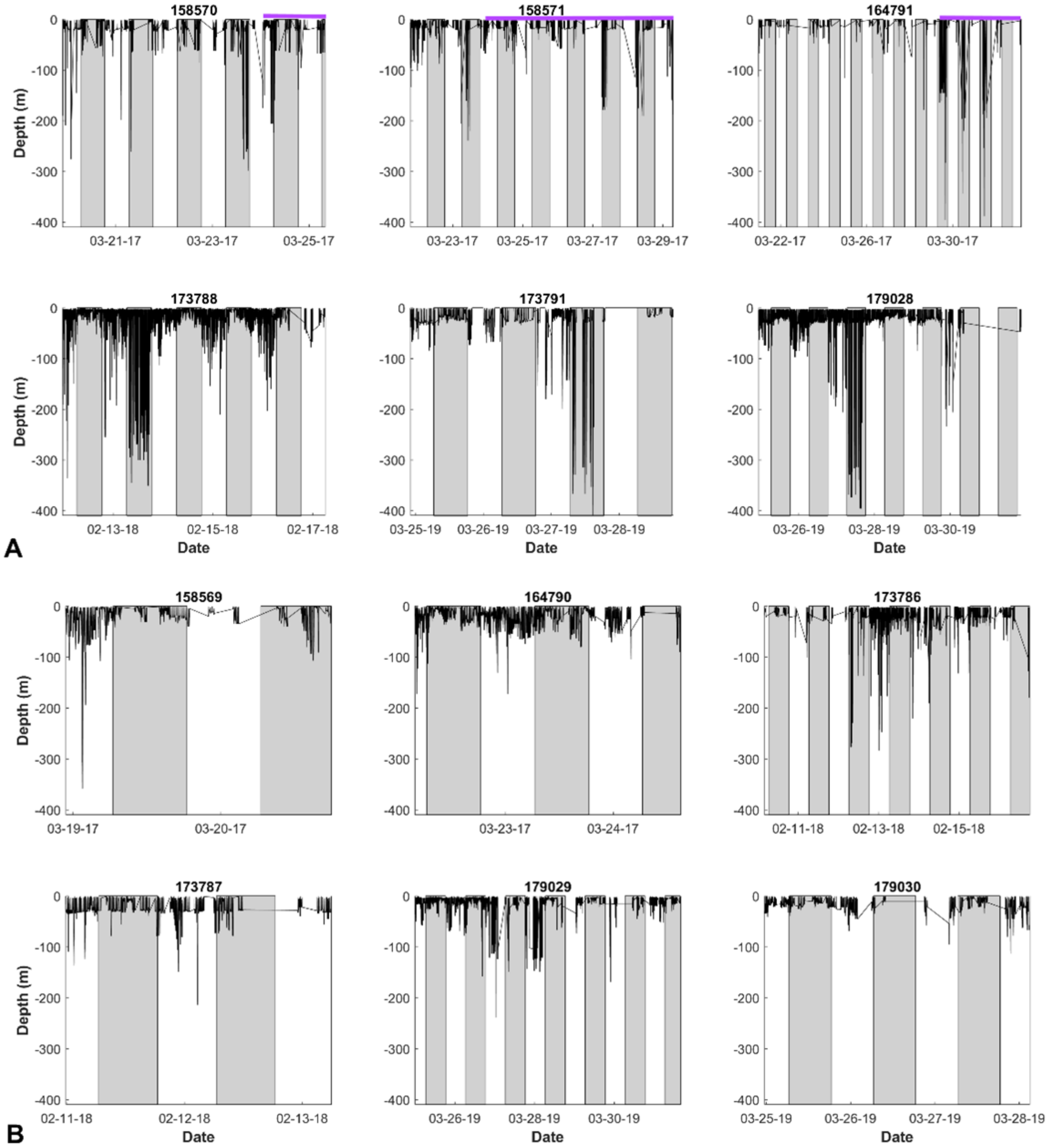


- Track 173788 was from 2018, while Track 173791 and 179028 were both from 2019, and actually appear to have remained together for four days as they traveled to O'ahu (Henderson et al. 2021). (Figure taken from Henderson et al. 2022).

Figure 6. One-hour interpolated tracks fitted with the crawl model and movement behavior determined by HMMs, demonstrating the similarities in both movement behavior and route utilized by the three humpback whales that traveled east to O‘ahu.

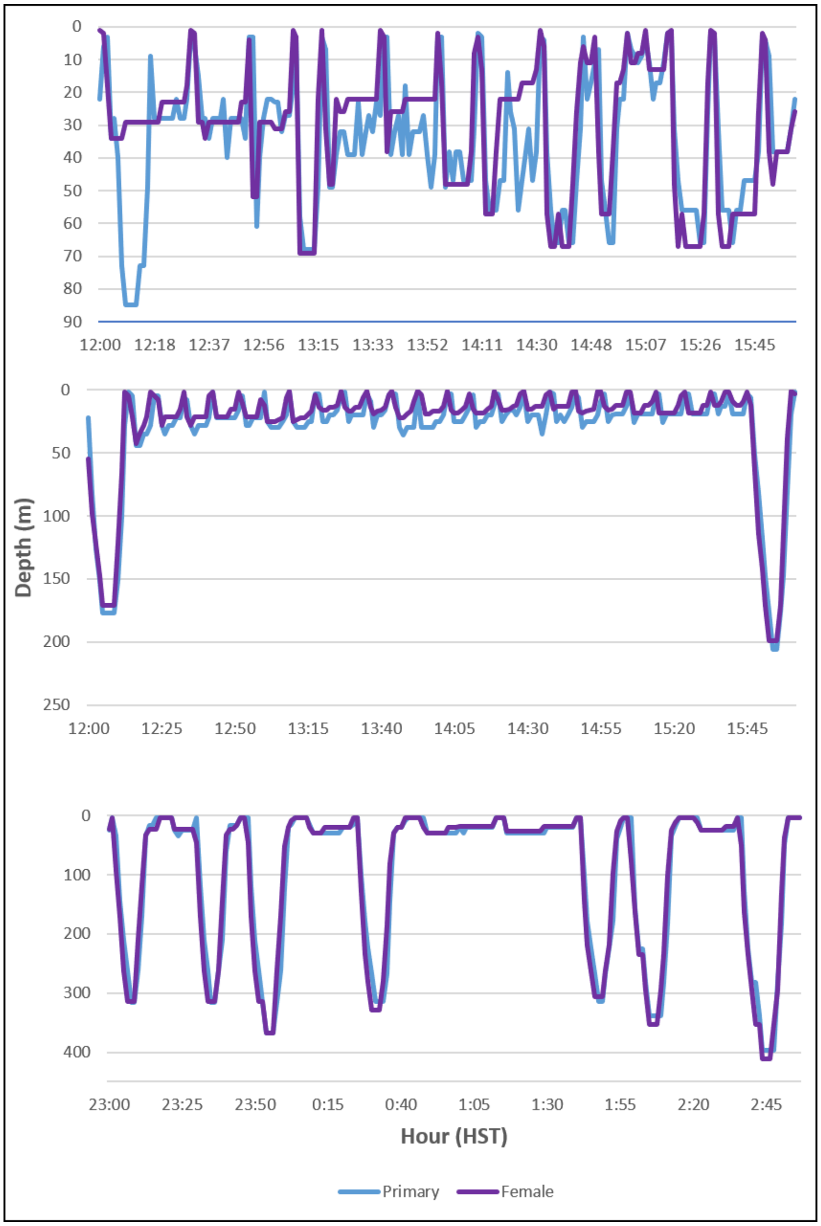
Most humpback whale dives were shallower than 50 m (82.2% of 5314 recorded dives), while only a small percentage of dives were greater than 100 m (5.9%). However, dives deeper than 100 m occurred more frequently at night during directed travel in deeper water depths, and occurred more frequently in offshore waters than shallow dives (Figure 7). In fact, humpback whales transiting between islands or seamounts offshore of the 50 km buffer (and including whales crossing between Kaua‘i and O‘ahu) conducted repeated series of long, deep dives (> 100 m) that occurred only at night (Figure 7). The GEE determined that dive durations were longer with deeper dives, while descent and ascent rates increased with deeper dives. Further, maximum dive depths were correlated with bathymetric depth, so that deeper dives were conducted in deeper waters and shallower dives in nearshore waters, where dives often extended close to the bottom. As described above, series of deeper dives tended to occur at night, but only in offshore waters during directed travel.

In addition to these general findings, four of the humpback whales were tagged in the same competitive pod: the female, primary escort, and two secondary escorts (Henderson et al. 2021). For the first hour of the three-hour encounter, the dive behavior of the primary escort and female were highly correlated. Then during two periods of 48 and 55 minutes respectively, the dive behavior of the primary escort was correlated with the two tagged secondary escorts as they each attempted to challenge the primary escort and were chased away. After this encounter, the primary escort and female remained together for at least four additional days while they circumnavigated the northern side of Kauaʻi and then traveled together to Oʻahu. During this period their movement and dive behavior was again highly correlated, with coordinated transitions between ARS, intermediate behavior, and directed travel, and very synchronous dives throughout their tag records (e.g. Figure 8). Periods of asynchronous diving occurred during ARS and could represent additional instances of the formation of competitive groups, although more work would need to be done to support that hypothesis.



- Dive time series are indicated by black lines and nighttime hours are marked by gray bars. Horizontal or diagonal lines connecting dives indicate periods of missing data. A) Individuals that moved outside the 50 km buffer and likely began their migration (top three, with purple lines indicating the offshore period) or crossed from Kaua‘ i to O‘ ahu within the buffer (bottom three); all of these animals conducted a series of long, deep dives exclusively at night when in deep water. B) Individuals that remained in the 50 km buffer near Kaua‘ i and Ni‘ ihau. Note that the depths are different for each plot. (Figure taken from Henderson et al. 2022).

Figure 7. Dive time series from tagged humpback whales across all three years.

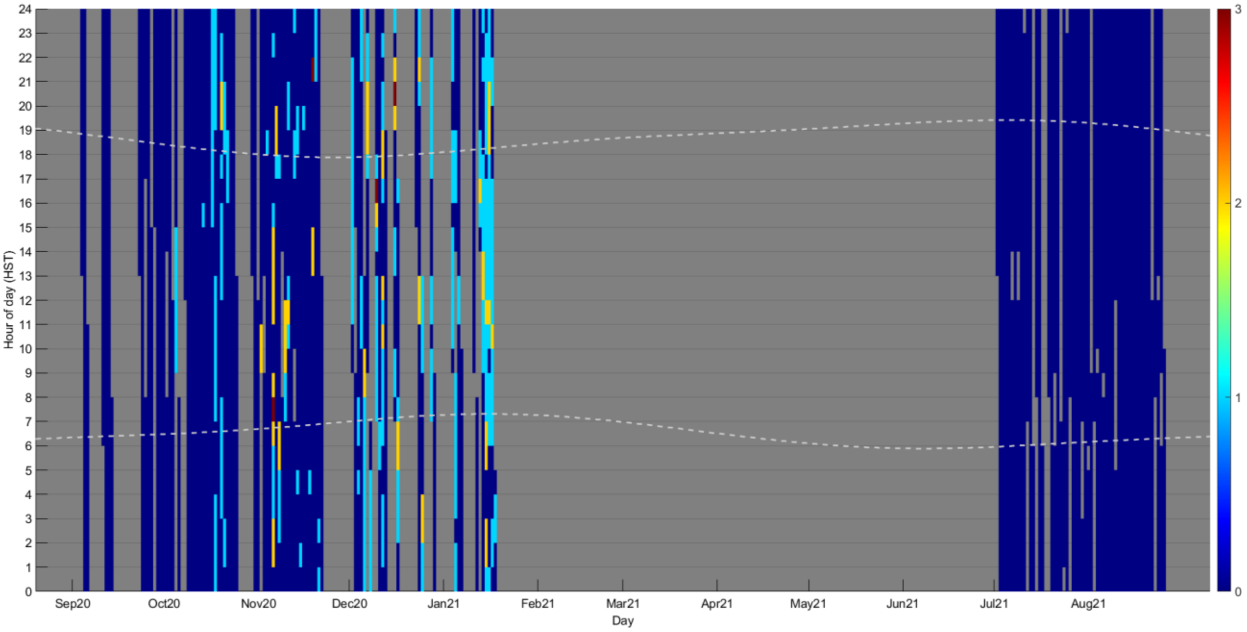


- The top plot spans the period from 12:00 to 16:00 on 26 March; the whales begin this period in ARS and then transition to the intermediary behavior state around 14:00. The middle plot spans the period from 12:00 to 16:00 on 27 March; here the dive behavior is more similar between both animals, although the male consistently dives deeper and with more movement at depth than the female. The bottom plot spans the period 27 March 23:00 to 28 March 3:00; these deep dives occur as the animals transited between islands and were highly synchronized. In both the middle and bottom plots the whales were in directed travel and had moved into the channel between Kaua‘ i and O‘ ahu; however, the middle plot takes place during the middle of the day while the bottom plot takes place at night. Note than in all of these examples, the male always surfaces with the female. (Figure taken from Henderson et al. 2021).

Figure 8. Dive behavior comparison for the female and primary escort for portions of the four-day period the animals spent together.

3.2.3 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 2020 to August 2021 are shown in Figure 9. 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 collected in August 2021. Results in Figure 9 are from the C++ detection and localization algorithms described in Section 2.2.1 compared to the fin, sei, and Bryde's results from the Matlab GPL algorithm in Section 3.2.3.1. These results are included for historical comparison with results in prior annual reports. The maximum number of low-frequency baleen whales present in a one-hour bin ranged from one to three whales between October 2020 and January 2021. Instances when the maximum was three occurred in a total of four separate one-hour bins between November and December 2020. Previously unreported FY20 results from June to August 2020 did not indicate presence of low-frequency baleen whales. FY21 results from July to August 2021 also indicated that low-frequency baleen whales were not present.



- 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 classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

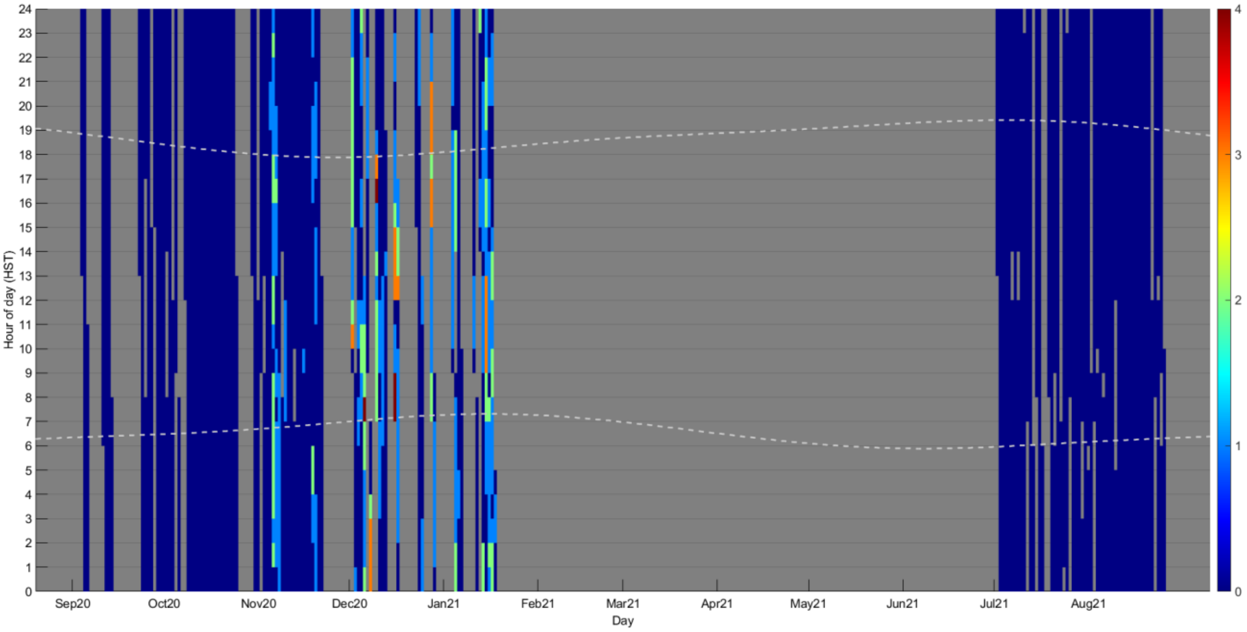
Figure 9. The maximum number of low-frequency baleen whales detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 ranged from one (light blue) to three (dark red).

3.2.3.1 Bryde's, Fin, and Sei Whales

As in last year's report (Martin et al. 2021), custom Matlab algorithms were used separately from the C++ algorithms above to detect low-frequency whales using specific localization arrays, group localizations into tracks using a large study area spanning about one degree of latitude and longitude centered on the PMRF array, and further classify tracks to species. Possible classifications included 1) fin whales, 2) Bryde's whales, 3) sei whales, 4) 40-Hz downsweeps unattributed to a single species (but may be produced by fin or sei whales), or 5) unknown (those that do not match previously identified call types). All automatic classifications of tracks were then manually validated and corrected if needed using tracked call spectrograms.

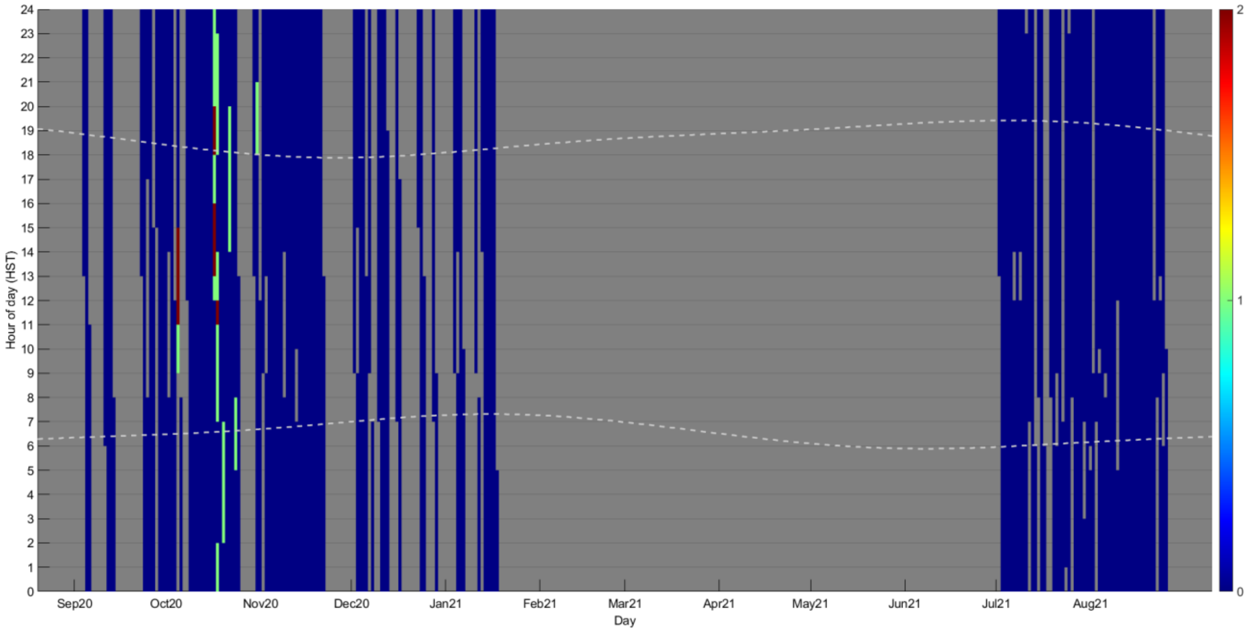
The maximum number of automatically tracked individuals detected in a 10-minute snapshot period for each hour of the day for each species category present in the recorded data from September 2020 to August 2021 are shown in Figure 10 through Figure 13. As in the C++ general low-frequency baleen results (3.2.3), previously unreported FY20 results from June to August 2020 did not indicate presence of any of the five call categories investigated here, so that effort is not displayed in the figures. The FY21 summer months also have no detections, but this period is displayed for consistency across all reported whale species. This agrees with general knowledge and the long-term seasonal patterns found in last year's report (Martin et al. 2021). The only baleen whale known to potentially call in the area year-round is the Bryde's whale, which this FY was only present in October. Furthermore, no tracks could be certainly attributed to sei whales, so they are excluded from the following results, but could potentially be represented by either the 40-Hz and unknown tracks.

Fin whales were detected throughout November, December, and January, peaking in December with a maximum of four fin whales tracked in a total of four separate one-hour bins during that month (Figure 10). As already mentioned, confirmed Bryde's whale calls were only present in October, peaking at two simultaneous tracks in a 10-min snapshot, which occurred during ten one-hour bins (Figure 11). Downswept 40-Hz calls, potentially attributable to fin or sei whales, were less frequent and peaked in the winter months, which is consistent with WARP's historical data (Martin et al. 2021). No more than one individual track consisting of 40 Hz calls was ever detected in a 10-min snapshot (Figure 12). Finally, very few tracks (seven total) consisted of unknown call types, spanning October and November 2020. Again, no more than one individual track consisting of unknown calls was ever detected in a 10-min snapshot (Figure 13). Due to the archival nature of WARP data storage and constant processing updates, tracks classified as these latter two categories are available for potential future reclassification to species pending new literature and additional investigation.



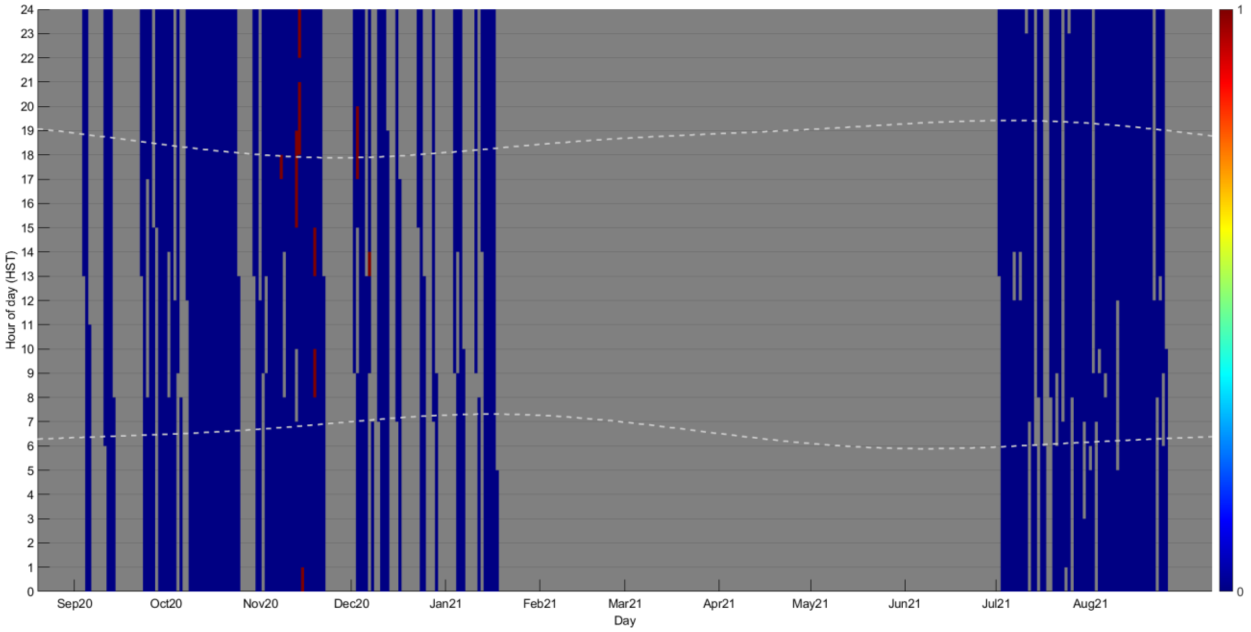
- Dark blue regions indicate periods of effort when acoustic recordings were collected and no whale tracks were present. Results are from decimated and full bandwidth data collections, including classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

Figure 10. The maximum number of manually confirmed fin whales detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 ranged from one (light blue) to four (dark red).



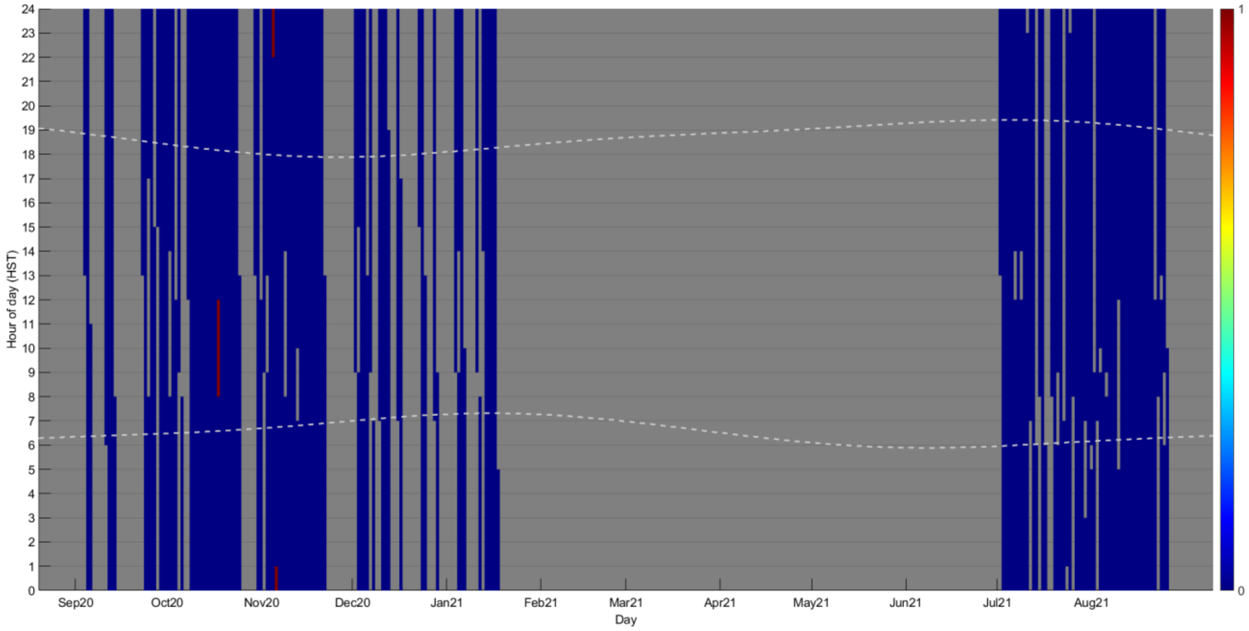
- Dark blue regions indicate periods of effort when acoustic recordings were collected and no whale tracks were present. Results are from decimated and full bandwidth data collections, including classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

Figure 11. The maximum number of manually confirmed Bryde’s whales detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 ranged from one (light green) to two (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 classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

Figure 12. The maximum number of manually confirmed tracks comprised of 40-Hz downsweeps (suspected to be either fin or sei whales) detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 never exceeded one (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 classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

Figure 13. The maximum number of manually confirmed tracks comprised of unknown low-frequency baleen calls detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 never exceeded one (dark red).

3.2.4 Blue Whales

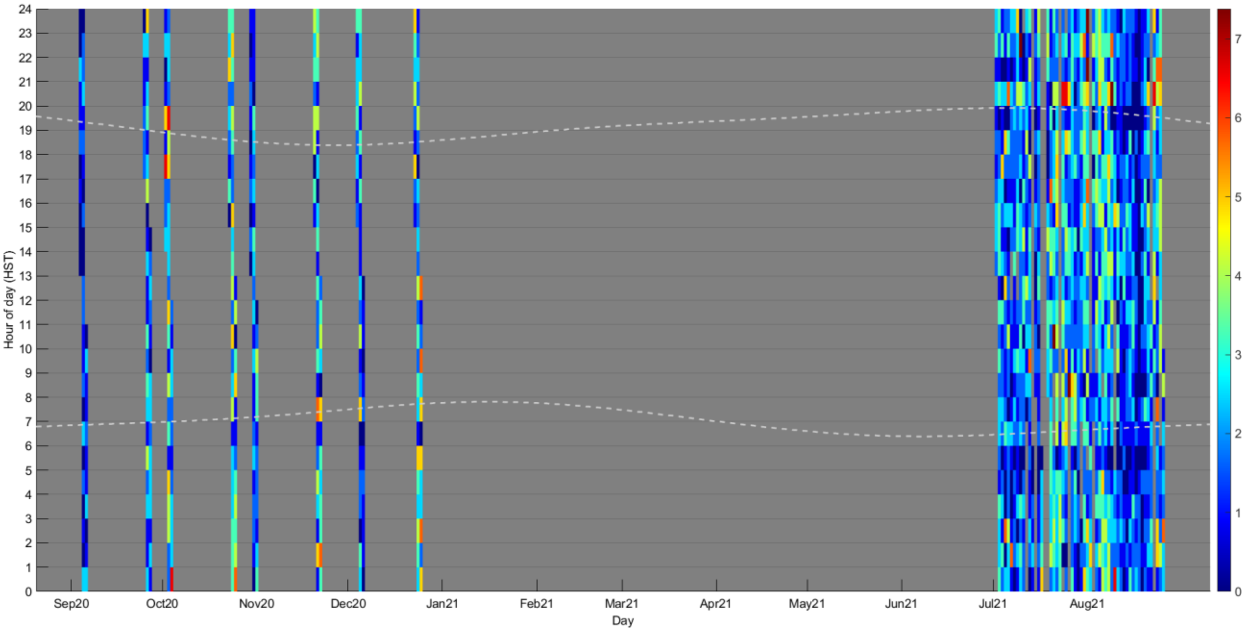
As in Martin et al. (2020), blue whale calls were automatically detected and localizations attempted using custom Matlab algorithms. Datasets with at least 20 automatic localizations were manually validated to confirm calling blue whale presence, which at PMRF is infrequent. Due to the low frequency of their calls, blue whale vocalizations can propagate long distances, but due to the flatness and long duration of blue whale calls and their tendency to occur well offshore (north and west) of the range, localizations tend to have low accuracy (high least squared error [LSQ] scores). Two blue whale call types are known to occur in the PMRF data. These have been identified and described by Stafford et al. (2001) and spectrograms of both call types as seen in PMRF data can be found in Martin et al. (2020).

This year, several northwestern Pacific calls (as described by Stafford et al. [2001]) were detected on the PMRF range in three datasets. In the December 10, 2020 dataset, several of the calls were identifiable mainly by harmonics at 38 and 54 Hz rather than the fundamental frequency at about 18 Hz. In the December 16, 2020 and January 14, 2021 datasets, the 18 Hz frequency was stronger than harmonics in almost all detections. In all three cases, localizations placed the calling animal in the northern part of the range.

The only instances of northeastern Pacific calls (see again Stafford et al. 2001) were five calls detected and localized well off-range (significantly lowering the localization accuracy) to the north and west in the January 11, 2021 dataset. In this instance, the calls were identified by the harmonic at approximately 44 Hz. For northeastern Pacific blue whale calls, the low-frequency roll-off of the PMRF hydrophones tends to make the fundamental frequency at 15 Hz difficult to detect.

3.2.5 Blainville's Beaked Whales

Since beaked whale detections are limited to full bandwidth data collections, potential coverage for beaked whale detections is limited to September through December 2020 and July and August 2021. Five baseline datasets from FY21 recordings with Blainville's beaked whale GVPs were randomly selected for manual validation. Echolocation clicks were automatically detected and combined into GVPs which were manually validated by systematically reviewing click spectrograms, spectra, and inter-click intervals (ICI) to meet known Blainville's beaked whale echolocation click characteristics. The five FY21 manually validated recordings contained 517 validated true positive GVPs (91% true positive rate) and 52 false positive GVPs (9% 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 BWC beaked whales). FY21 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 the manual sample validation of five baseline FY21 recordings, causing GVP estimates to be fractional. Two GVP metrics are calculated for all beaked whales; hourly dive rates as the total number of dives with start times in each one-hour bin of effort (as depicted in Figure 14), and monthly dive rates as the total number of dives with start times in a month over the total hours of effort for a month (as presented in Table 2). The maximum number of GVPs that began within an hour bin was 7.38 and occurred in multiple datasets from July and August 2021 (Figure 14). The normalized monthly dive rate per hour of effort ranged from 1.39 dives/hr (September 2020) to 2.47 dives/hr (July 2021), and the average monthly dive rate for FY21 recordings was 2.08 dives/hr in 2020 and 2.44 dives/hr in 2021 (Table 2).



- The total number of GVPs in a one-hour bin ranged from 0.82 (medium blue) to 7.38 (red). Results are from full bandwidth data collections, including classified full bandwidth data collected in August 2021. Gray areas indicate periods when full bandwidth data were not available. The gray dashed line indicates sunrise and sunset times.

Figure 14. The total number of Blainville's beaked whale GVPs per hour corrected using manually validated dives from five datasets between September to August 2021 (no full bandwidth data was available between January to June 2021).

Table 2. FY21 Blainville's beaked whale GVP summary.

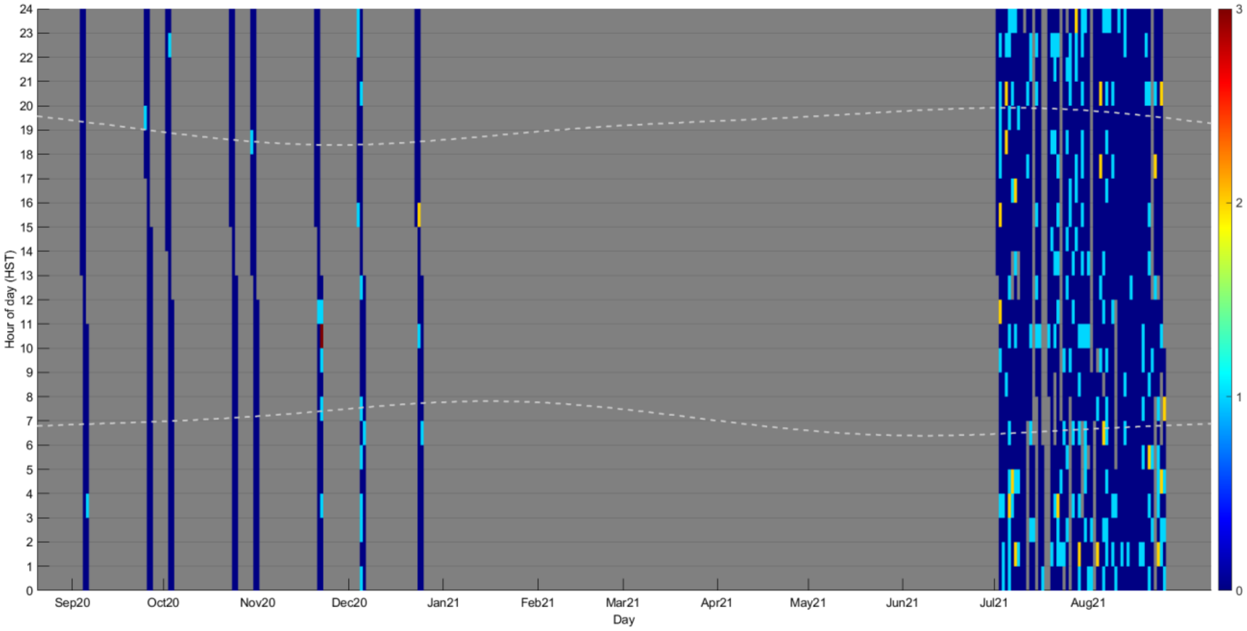
Date	Sum of Dives	Hours of Effort	Dives/hr
2020	**767.52**	**369**	**2.08**
Sep	127.92	92	1.39
Oct	276.34	117	2.36
Nov	160.72	68	2.36
Dec	202.54	92	2.20
2021	**2778.36**	**1139**	**2.44**
Jul	1418.18	575	2.47
Aug	1360.18	564	2.41

3.2.6 Cuvier's Beaked Whales

Autogrouping for Cuvier's beaked whales is performed in a similar manner as for the other beaked whales (see Section 2.2.1) with one small difference. Due to the high false positive rate for individual Cuvier's beaked whale clicks in the beaked whale click classifier, clicks associated into GVPs by the autogrouper were further filtered, requiring Cuvier's beaked GVPs to have a peak ICI (defined as the ICI associated with the maximum from a histogram of that dive's ICIs) between 0.3 and 0.6 seconds. This helped exclude some of the most common false positive GVPs from delphinids. The remaining GVPs that met this criterion were all manually validated.

This FY, there were 221 true positive and 71 false positive GVPs, corresponding to a 76% true positive rate and 24% false positive rate for the year. The Cuvier's beaked whale classifier is currently being further refined in parallel with the Longman's beaked whale classifier (see Section 3.2.8). Figure 15 shows the total number of fully validated Cuvier's beaked whale GVPs with start times in each hour bin of effort. The total number of Cuvier's beaked whale dives detected in an hour bin did not often exceed one, but a peak of three did occur once in November 2020. As is consistent with established literature and historical results from WARP for Cuvier's beaked whales, there appeared to be no strong diel foraging pattern and they were present year-round. However, in the summer recordings, for which there was high recording effort due to the installation of the new recorder, instances when there were two detected GVPs in an hour bin seemed more likely to occur at night. Hopefully with increased recording coverage in the coming years and improvements to the Cuvier's beaked whale classifier, this apparent trend can be analyzed for statistical significance.

Table 3 gives the total number of fully validated Cuvier's beaked whale GVPs with start times in each month with effort, the hours of recording effort for that month, and the resulting metric of GVPs per hour of recording. The normalized monthly dive rate per hour of effort ranged from 0.02 dives/hr in both September and October 2020 to a peak of 0.23 dives/hr in July 2021. The average monthly dive rate for FY21 recordings was 0.07 dives/hr in 2020 and 0.19 dives/hr in 2021.



- Results are from full bandwidth data collections, including classified full bandwidth data collected in August 2021. The total number of GVPs 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.

Figure 15. The total number of manually validated Cuvier's beaked whale GVPs per hour from September 2020 to August 2021.

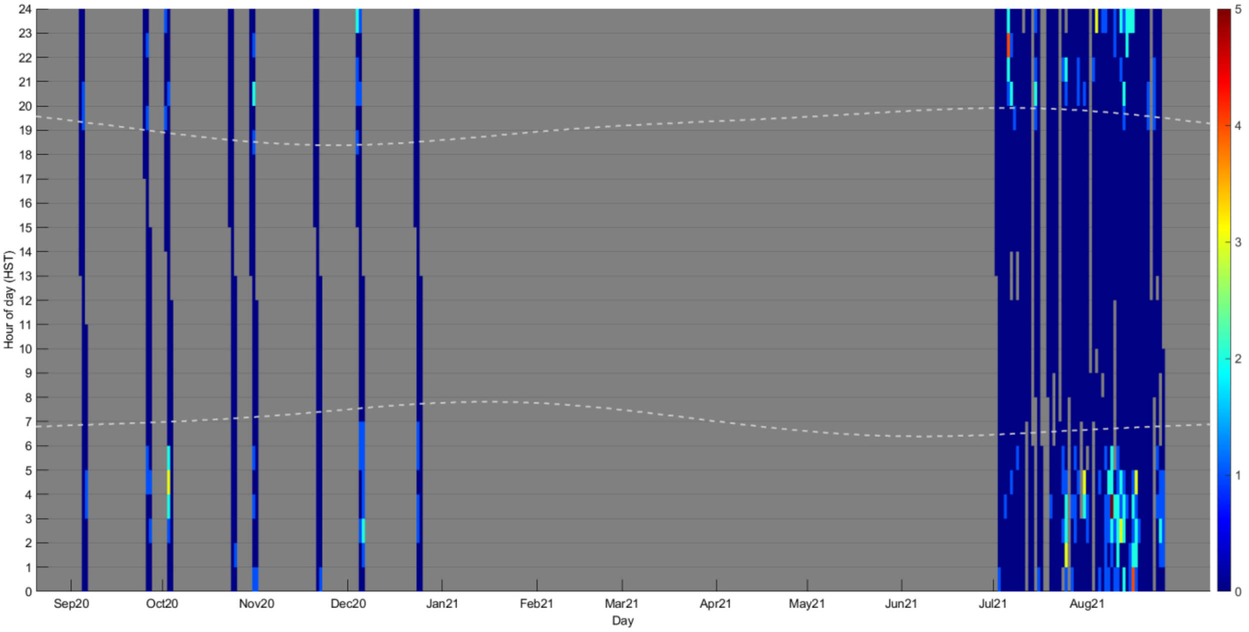
Table 3. FY21 Cuvier's beaked whale manually validated GVP summary.

Date	Sum of Dives	Hours of Effort	Dives/hr
2020	27	369	0.07
Sep	2	92	0.02
Oct	2	117	0.02
Nov	8	68	0.12
Dec	15	92	0.16
2021	**221**	**1139**	**0.19**
Jul	132	575	0.23
Aug	89	564	0.16

3.2.7 Cross Seamount Beaked Whales

Cross seamount beaked whale clicks were automatically detected and grouped, then fully manually validated by systemically reviewing click spectrograms, spectra, and ICIs to meet known BWC beaked whale echolocation click characteristics. The FY21 dataset utilized full bandwidth data from September to December 2020 and July to August 2021, including classified full bandwidth data recorded during the August SCC. The BWC results contained 197 validated true positive dives (26% true positive rate) and 480 validated false positive dives (74% false positive rate). Work on the BWC click classifier continues to improve performance to reduce misclassification of BWC beaked whale clicks.

The maximum number of GVPs that began in an hour bin of effort was five and occurred in August 2021 (Figure 16). Monthly dive rates are the total number of dives with start times in a month over the total hours of effort for a month. The normalized monthly dive rate per hour of effort ranged from 0.09 dives/hr (November 2020 and July 2021) to 0.23 dives/hr (December 2020), and the average monthly dive rate for FY21 recordings was 0.14 dives/hr in 2020 and 0.15 dives/hr in 2021 (Table 4).



- The total number of GVPs in a one-hour bin ranged from one (medium blue) to 5 (red). Results are from full bandwidth data collections, including classified full bandwidth data collected in August 2021. Gray areas indicate periods when full bandwidth data were not available. The gray dashed line indicates sunrise and sunset times.

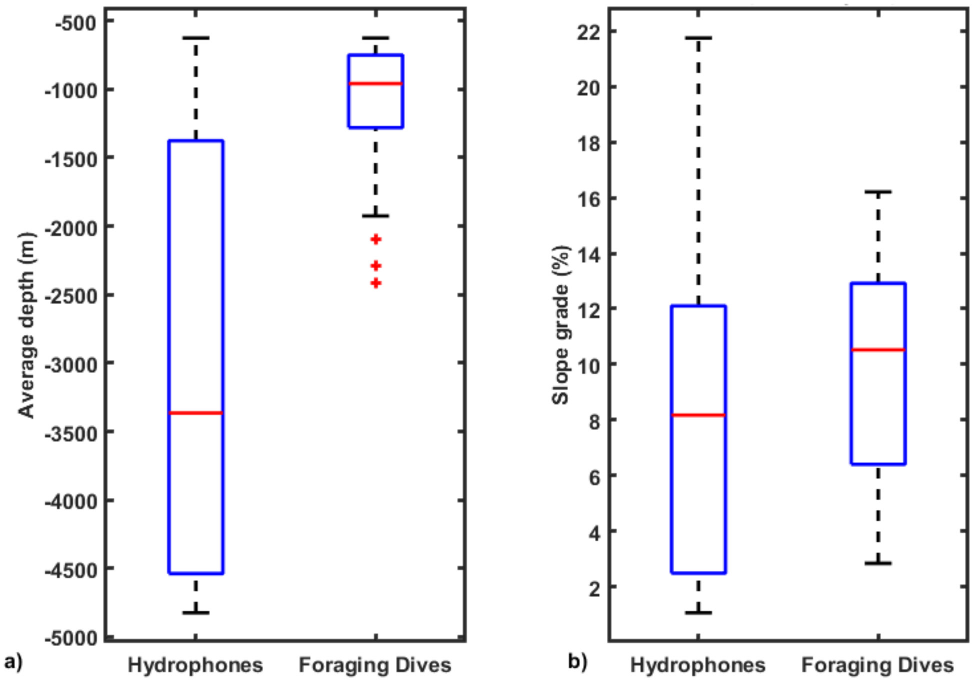
Figure 16. The total number of BWC beaked whale GVPs per hour corrected using manually validated dives between September to August 2021 (no full bandwidth data was available between January to June 2021).

Table 4. FY21 Cross Seamount beaked whale manually validated GVP summary.

Date	Sum of Dives	Hours of Effort	Dives/hr
2020	**52**	**369**	**0.14**
Sep	10	92	0.11
Oct	15	117	0.13
Nov	6	68	0.09
Dec	21	92	0.23
2021	**168**	**1139**	**0.15**
Jul	53	575	0.09
Aug	115	564	0.20

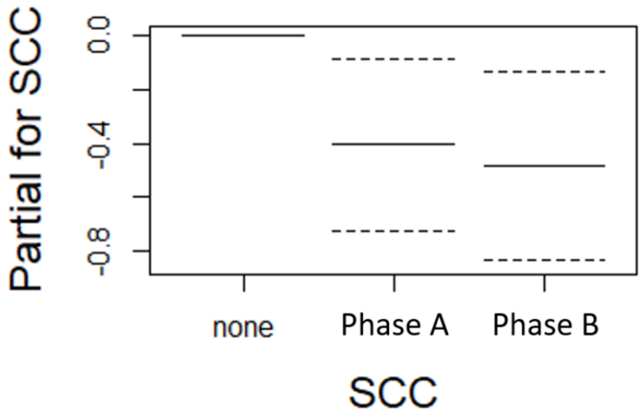
3.2.7.1 Long-Term Analysis of BWC Beaked Whales

Manzano-Roth et al. (submitted) analyzed detected BWC beaked whale GVPs at PMRF in data collected from 2007 to 2019. Chi-squared tests and generalized additive models (GAMs) were used to determine foraging dive rates, foraging dive patterns (with respect to local time, seasons, months, and lunar cycle), and depth and slope preferences across thirteen years of data. The study found that the average BWC foraging dive rate was 0.11 dives/hr and all foraging dives occurred at night. A majority of detections occurred on shallow depth hydrophones (< 1000 m depth) and a bathymetric slope of around 10% (Figure 17). Foraging dive rates and dive characteristics during SCC training events were compared against baseline periods. The combined average foraging dive rates decreased from 0.26 dives/hr to 0.083 dives/hr in February SCCs and 0.14 dives/hr to 0.012 dives/hr in August SCCs and returned to baseline levels a few days after the SCC ended. These findings were supported by the GAM that demonstrated reduced dives during both Phases of the SCCs (during Phase A there is training activity but no surface ship hull-mounted MFAS is used, while in Phase B the training includes surface ship hull-mounted MFAS use; Figure 18). Cross Seamount beaked whale foraging dive characteristics were compared against a previous long-term study of Blainville’s beaked whale foraging dives from Henderson et al. (2016). Different dive behaviors were identified between the species, such as Blainville’s beaked whales foraging consistently over the 24-hr day and preferring to dive during the full moon phase, while BWC foraging dives were only detected at night and they preferred to dive during the new moon phase.



- The median depth of all the hydrophones recording was 3365 m and the median depth of hydrophones with detections was 959 m. The median slope of all the hydrophones recording was 8.2% gradient and the average slope of hydrophones with detections was 10.52% gradient. The red line is the median value and the edges of the blue box are the 25th and 75th percentiles. (Figure from Manzano-Roth et al. submitted).

Figure 17. a) Box plot of median hydrophone depths at PMRF and hydrophones with BWC foraging dive detections. b) Median hydrophone slope gradients at PMRF and hydrophones with BWC foraging dive detections.



- The baseline level was held as the reference level. The dashed lines represent the standard error about the mean. Dives were reduced during both Phase A and Phase B (p = 0.012 and 0.006 respectively). (Figure from Manzano-Roth et al. submitted).

Figure 18. Partial effects of the parametric model component of SCC Phase (None/Baseline, Phase A, Phase B) on the likelihood of BWC dive occurrence.

3.2.8 Longman's Beaked Whales

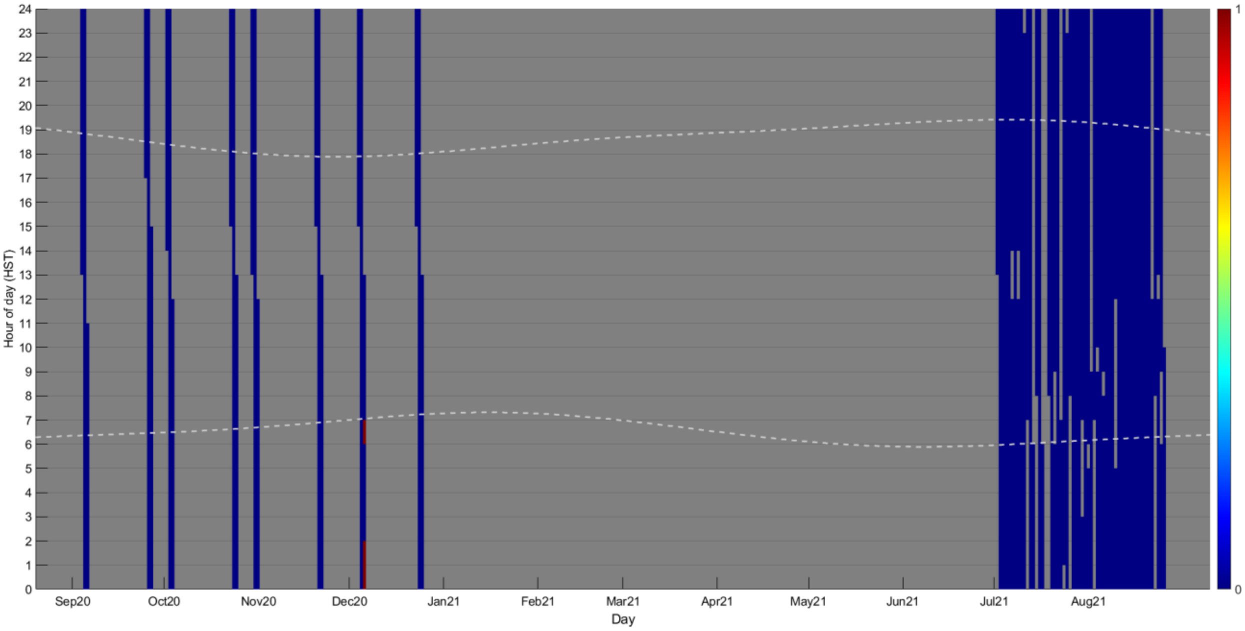
As mentioned in last year's report (Martin et al. 2021), attempts are ongoing to add Longman's beaked whales to the beaked whale classifier component of NARWHAL, while simultaneously improving the false negative rates of the Cuvier's and BWC beaked whale classifiers. A preliminary version was developed using a single dataset known to exhibit all four beaked whale clicks (September 7, 2019) but requires further testing on more datasets and in various conditions (different times of year, during other marine mammal activity, during anthropogenic activity, etc.). As Longman’s beaked whales are relatively rare at PMRF, the compilation of enough data to support a detector is a continuing process.

3.2.9 Killer Whales

As with beaked whales, killer whale HFM calls (see Simonis et al. 2012, Samarra et al. 2010) are automatically associated into groups (see Section 2.2.1), but due to their rare occurrence and a high false positive rate due to other high-frequency whistling delphinids, all groups are fully manually validated. Two groups of confirmed HFM calls were detected in FY21 – one in the December 24, 2020 dataset and the other in the July 26, 2021 dataset. Consistent with a trend noted in previous reports (Martin et al. 2020, 2021), in both instances the HFM calls only occurred during daylight hours. In previous years, HFM calls occasionally occurred at night, but only when the moon was over three-quarters full.

3.2.10 Sperm Whales

The maximum number of automatically-tracked, individual calling sperm whales detected in a 10-minute snapshot period for each hour of the day from recordings made between September 2020 and August 2021 are shown in Figure 19. These results utilized the smaller study area focused on the hydrophone array and include all full bandwidth data, including classified full bandwidth data recorded in August 2021 (although the sperm whale detector has not yet been validated to assess potential false positives in those data, in this case no automatic tracks were generated). The maximum number of sperm whale tracks detected in a one-hour bin was one, in the earlier December 2020 recording (dark red) (Figure 19). For comparison, sperm whale tracks were detected in only nine one-hour bins from September 2019 to September 2020, and there was a maximum of one sperm whale track in 78% of those one-hour bins (Martin et al., 2021). The previously unreported FY20 decimated data from June-August 2020 were not processed for sperm whales since they are only detectable in full bandwidth data sets.



- Dark blue regions indicate periods of effort when acoustic recordings were collected and zero whale tracks were present. Results are from full bandwidth data collections only, including classified full bandwidth data collected in August 2021. Gray shaded regions indicate periods of no recorded data. The light gray dotted lines indicate sunrise and sunset times.

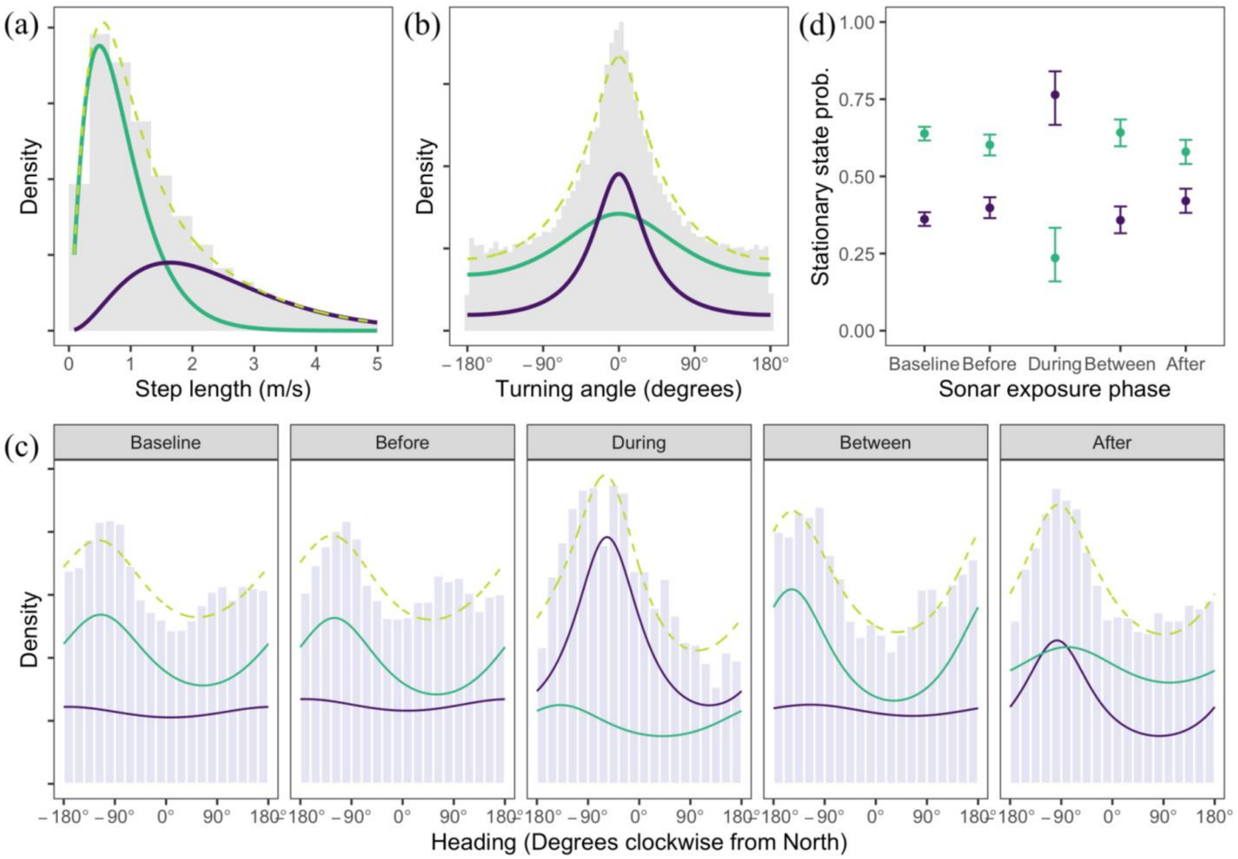
Figure 19. The maximum number of sperm whales detected in a 10-minute snapshot period for each hour of the day from September 2020 to August 2021 was a maximum of one (dark red).

3.3 DISTURBANCE ANALYSIS

3.3.1 Transition of BREVE Processes

The R language code developed by co-investigators at the University of St. Andrews Centre for Research into Ecological and Environmental Modelling (CREEM) (Durbach et al. 2021) for statistical analysis of minke whale tracks during the BREVE effort has been transitioned to NIWC Pacific/National Marine Mammal Foundation (NMMF). The code utilized 627 minke whale tracks for Baseline, Before, During MFAS, Between MFAS, and After periods around the February 2014, 2015, and 2017 SCC MFAS training events. The input data to the provided R code includes: information on detected, classified, and localized whale calls; localization association tracks (Klay et al. 2015); and multiple hypothesis tracks (Baggenstoss 2015). Also included is detailed information for call dates/times and estimated call locations (with details for each hydrophone contributing to the localization) and various estimates of detection features, such as speeds and headings. R code is also utilized for behavioral change point analyses to smooth the whale's estimated headings rather than using location to location headings.

These smoothed data are processed for correlated random walk tracking (*crawl* package in R; Johnson et al. 2008, Johnson & London 2018) of the call association tracks and two-state HMM analyses (faster more directed movement and slower less directed movement akin to traveling and milling) using the R package *momentuHMM* (McClintock & Michelot 2018). Both single and multiple imputation methods are utilized. Data are pooled and considered by exposure phase (baseline [>1 week preceding the first MFAS transmission], before [within 1 week preceding the first MFAS transmission], during sonar blocks, between sonar blocks, and after [starting 24 hrs following the last MFAS transmission). Sonar blocks are bouts of MFAS PAM detections consisting of multiple MFAS pings and end after a delay of 30 minutes past the last ping. Figure 20 (from Durbach et al. 2021) provides plots for the HMM analysis on the five-minute binned data showing a faster, more directed, movement state (fast state for brevity) and the slower, less directed movement state (slow state). The slower state was preferred for all exposure phases except the During sonar blocks phase, when the preferred state switched to a fast state. The whale heading covariate with regard to sonar exposure phase also showed a strong heading preference in the During phase to the NW, which was found in Durbach et al. (2021) to be consistent with movement away from MFAS ships. Figure 21 demonstrates results obtained by WARP for successful multiple imputations of the full classified dataset as of November 2021 (18 out of 60 attempted imputations), which are very similar to those of Durbach et al. (2021) as seen compared to Figure 20. Subsequent processing includes assigning each location to its most likely state using the Viterbi algorithm, determining whale headings relative to ship locations, model checking, and showing cessation of calling as a response to MFAS activity.



- Density values are uninformative and so suppressed. One state (green) comprises slow, undirected movement, most commonly with a heading between south-east and north-west (i.e. a positive slope is commonly between +135° to +180° and -45° to -180°). A second state (purple) involves faster, more directed travel which, during sonar exposure, is also characterized by more northerly headings that would typically take the whale away from the range of ship activity. Whales are much more likely to be observed in the second state during sonar exposure. Observed data is shown as gray histograms; the marginal distribution (dashed lime-green line) shows the sum of the state-dependent densities. Heading densities in (c) are standardized within each sonar exposure phase to facilitate comparison between the phases, which have very different sample sizes.

Figure 20. From Durbach et al. 2021 Figure 3: Estimated state-dependent densities for (a) speed, (b) turning angle, and (c) whale heading relative to North, and (d) the effect of sonar exposure phase on the probability that a location is found in a given state.

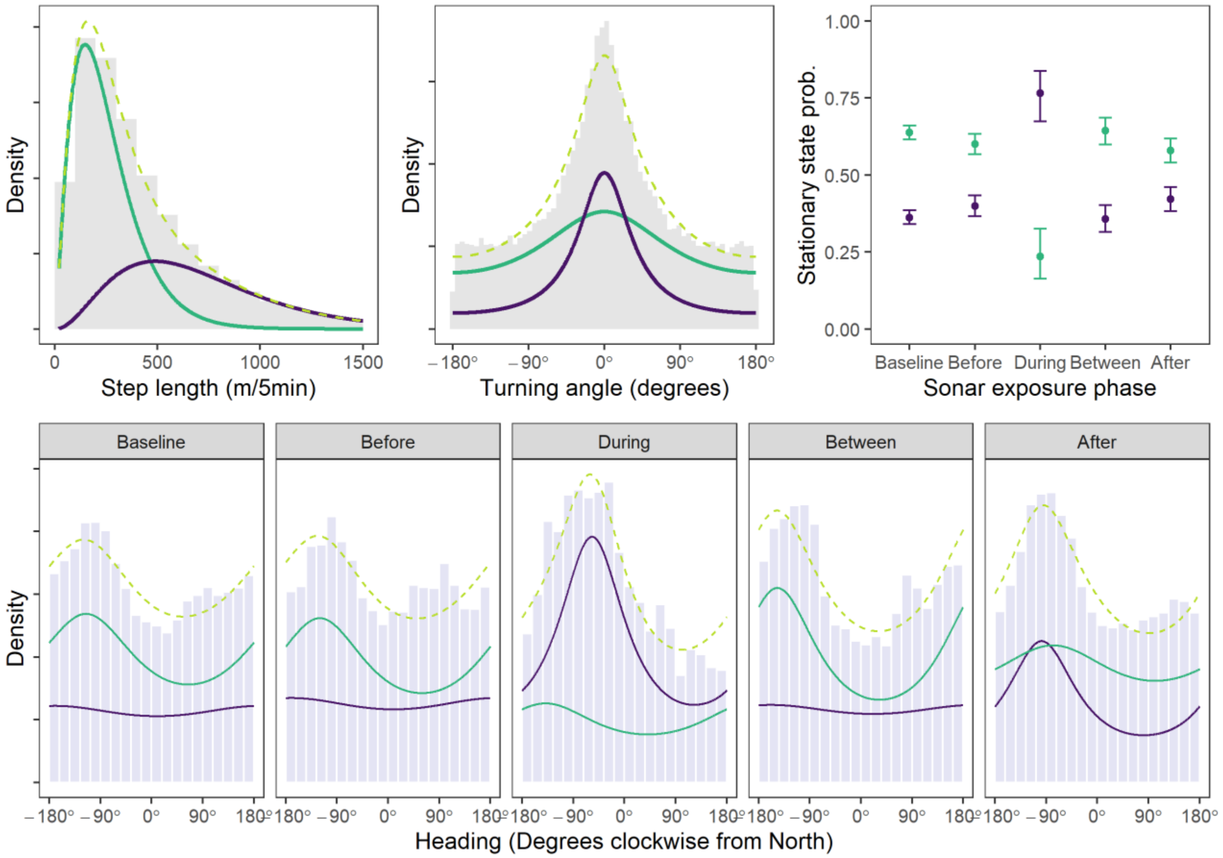


Figure 21. Results replicating BREVE two-state HMM showing very similar results to that in Durbach et al. (2021) with the same descriptors for each set of plots as in Figure 20.

3.3.2 August 2021 Disturbance Analysis

In FY21, exposure data were collected during a unit-level training event (ULT) in early August and during the August SCC. The number of Blainville's, BWC, and Cuvier's beaked whale GVPs per hour of effort during non-training phases (i.e. Pre-ULT, Post-ULT/Pre-SCC, Between, and Post-SCC phases), and during training events (i.e. ULT [includes surface ship hull mounted MFS], Phase A [does not include surface ship hull-mounted MFAS] and Phase B [includes surface ship hull mounted MFAS]) are shown in Table 5 through Table 7.

Blainville's beaked whale dives during non-training phases were adjusted by the baseline subset validated true positive rate of 91%, and false positive rate of 9%. Due to the presence of anthropogenic sound sources during exposure phases, the true positive and false positive rates may be different than the baseline rates. As a result, Blainville's beaked whale dives during the ULT were fully validated and had a true positive rate of 100%. Results from one dataset during the SCC were examined to derive a subset validated true positive rate of 97%, and a false positive rate of 3% for adjusting dives during the SCC. Dive detection and grouping performance during the SCC was thus slightly higher than performance during baseline conditions. Based on the dives per hour metric in Table 5, there was an apparent reduction in dives per hour between the Pre-ULT (2.09) and ULT (1.7) phases; however, there were also fewer hours of recording effort in the ULT phase. Although the dive per hour metric is intended to normalize results so they are comparable, the dive frequency is not likely constant over time and especially may change between baseline and exposure phases. In this case, only collecting 5.3 hours of effort during the ULT (compared to 99.4 hours Pre-ULT) can limit the number of dives we can detect. Dives per hour in the Post-ULT/Pre-SCC phase increased to 2.37 and exceeded dives per hour in the Pre-ULT phase (2.09). When compared to the Post-ULT/Pre-SCC phase, there was a decrease during Phase A to 1.26 dives/hr. 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, dives per hour slightly increased to 1.45, then had an apparent reduction in Phase B that was 71% lower than Phase A. In the Post-SCC phase, dives per hour increased to levels similar to the Pre-ULT phase. These results also follow the long-term trend from Martin et al. (2020) in which dives per hour decreased from before the SCC to Phase A, were lower in Phase B compared to Phase A, and increased after the SCC.

Table 5. Blainville's beaked whale dives and hours of effort during baseline and exposure conditions in August 2021.

Phase	Start date	End date	Duration (hrs)	Dives	Dives/hr
Pre-ULT	7/30/21 17:33	8/3/21 20:57	99.4	207.46	2.09
ULT	8/3/21 21:27	8/4/21 2:42	5.3	9.00	1.71
Post-ULT/Pre-SCC	8/4/21 2:45	8/12/21 3:59	193.2	458.38	2.37
Phase A	8/12/21 4:00	8/13/21 20:20	40.3	50.76	1.26
Between	8/13/21 20:21	8/17/21 14:59	90.6	131.2	1.45
Phase B	8/17/21 15:00	8/20/21 0:30	57.5	34.78	0.60
Post-SCC	8/20/21 0:31	8/26/21 19:24	162.9	311.6	1.91

BWC beaked whale dives in Table 6 were fully validated. Results during the SCC had a 26% true positive rate 74% false positive rate, which was the same as performance during baseline conditions (Section 3.2.7). Compared to Blainville's beaked whale results in Table 5, BWC beaked whale GVPs had a relatively lower abundance. In the ULT phase, dives decreased to zero likely due to a combination of fewer hours of effort, low species abundance, and MFAS use. It is interesting to note that from the Post-ULT/Pre-SCC phase into Phase A dives per hour increased by 54%. In the Between phase there was a slight decrease to 0.38 dives/hr, followed by an apparent decrease to 0.02 dives/hr in Phase B. Comparison of rates between Phase A and Phase B indicates a stronger response of reduced diving during Phase B. From Phase B to the Post-SCC phase, dives per hour increased to 0.10, which was slightly higher than levels in the Pre-ULT phase.

Table 6. Cross Seamount beaked whale dives and hours of effort during baseline and exposure conditions in August 2021.

Phase	Start date	End date	Duration (hrs)	Dives	Dives/hr
Pre-ULT	7/30/21 17:33	8/3/21 20:57	99.4	8	0.08
ULT	8/3/21 21:27	8/4/21 2:42	5.3	0	0.00
Post-ULT/Pre-SCC	8/4/21 2:45	8/12/21 3:59	193.2	45	0.23
Phase A	8/12/21 4:00	8/13/21 20:20	40.3	16	0.40
Between	8/13/21 20:21	8/17/21 14:59	90.6	34	0.38
Phase B	8/17/21 15:00	8/20/21 0:30	57.5	1	0.02
Post-SCC	8/20/21 0:31	8/26/21 19:24	162.9	16	0.10

Cuvier’s beaked whale dives in Table 7 were also fully validated and also had a lower abundance than Blainville’s beaked whales (Table 5). Results during the SCC had a 66% true positive rate and a 34% false positive rate. Dive detection and grouping performance during the SCC was slightly lower than performance during baseline conditions, which had a true positive rate of 70% and a false positive rate of 30% (Section 3.2.6). Similar to BWC beaked whales, Cuvier’s beaked whale GVPs in the ULT phase decreased to zero, which was also likely due to a combination of fewer hours of effort, low species abundance, proximity of ships to whales, and MFAS use. Dives per hour during the Post-ULT/Pre-SCC phase increased to levels that were nearly the same as the Pre-ULT phase, then decreased in Phase A. It is interesting to note that dives per hour continued to decrease in the Between phase when no training occurred, similar to the trend that also occurred for BWC beaked whales. In comparison, Blainville’s beaked whale GVPs increased from Phase A to the Between phase. This may be a result of lower species abundances or indicate a relatively slower recovery time for Cuvier’s and BWC beaked whales. Dives per hour in Phase B for Cuvier’s beaked whales were the same as in Phase A, and dives per hour increased from the Between phase to Phase B. This trend was not observed in Blainville’s or BWC beaked whale dives and will be further investigated. As expected, dives per hour in the Post-SCC phase increased and exceeded levels in the Pre-ULT and Post-ULT/Pre-SCC phases.

Table 7. Cuvier's beaked whale dives and hours of effort during baseline and exposure conditions in August 2021.

Phase	Start date	End date	Duration (hrs)	Dives	Dives/hr
Pre-ULT	7/30/21 17:33	8/3/21 20:57	99.4	19	0.19
ULT	8/3/21 21:27	8/4/21 2:42	5.3	0	0.00
Post-ULT/Pre-SCC	8/4/21 2:45	8/12/21 3:59	193.2	34	0.18
Phase A	8/12/21 4:00	8/13/21 20:20	40.3	4	0.10
Between	8/13/21 20:21	8/17/21 14:59	90.6	4	0.04
Phase B	8/17/21 15:00	8/20/21 0:30	57.5	6	0.10
Post-SCC	8/20/21 0:31	8/26/21 19:24	162.9	35	0.21

3.4 NOISE ANALYSIS

3.4.1 FY20 Anthropause Acoustic Analysis

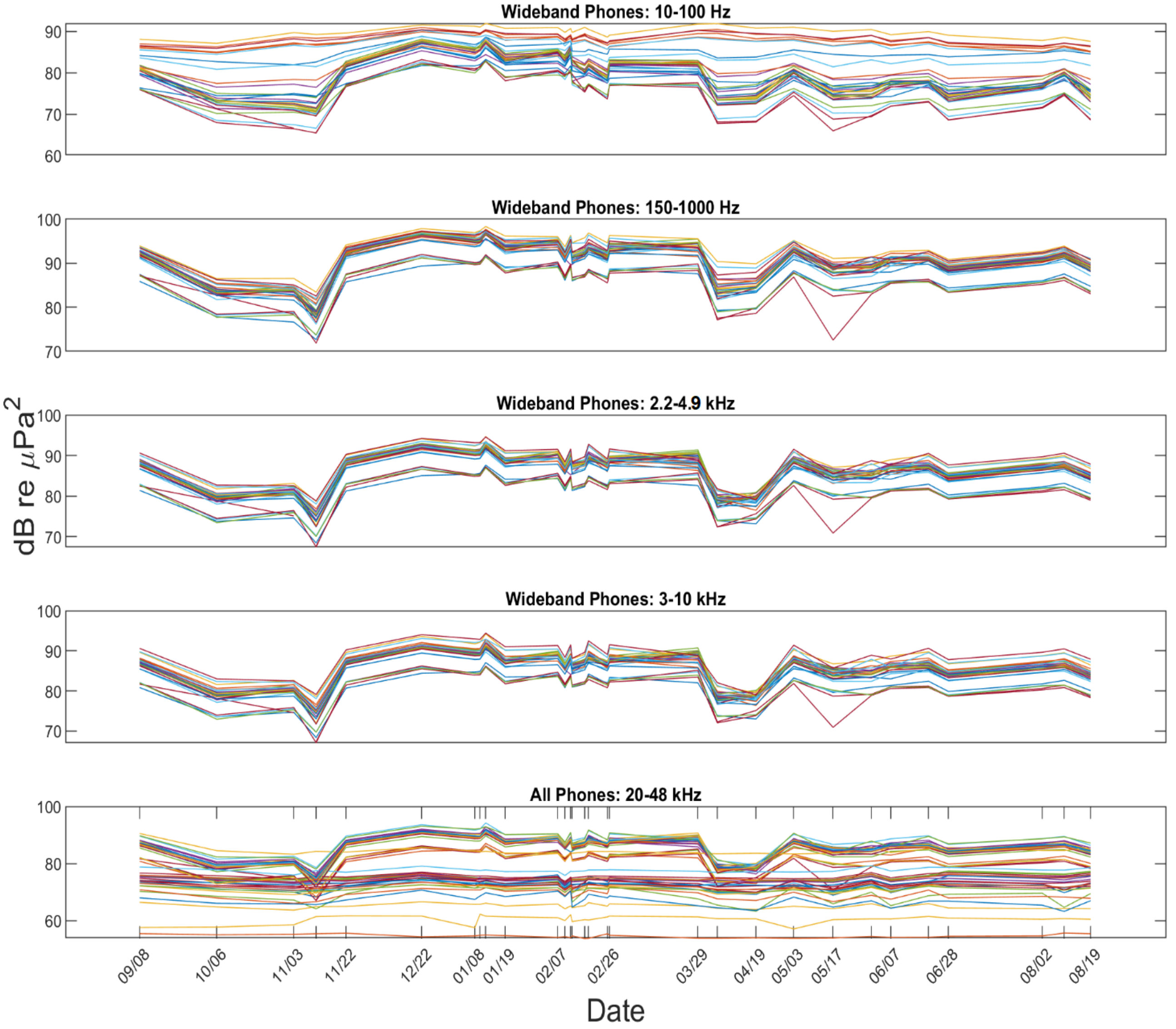
The period of reduced human activity during the first few months of the COVID-19 pandemic has been termed the "anthropause" (Rutz et al 2020). On PMRF, all range activity was canceled from the start of March 2020 through July 2020. In addition, the Department of Land and Natural Resources (DLNR) of Hawaiʻi curtailed all commercial and recreational boat activity from March 2020 through April 2021, although fishermen and small boat owners could go out with their families. This has provided the opportunity to conduct a natural experiment on the PMRF range to determine if noise levels associated with anthropogenic activities on the range were reduced, and if levels associated with biological activity might have increased. In order to investigate this, full-band spectral densities up to 48 kHz (in dB re $\mu Pa^2/Hz$) were obtained for every minute of recorded data from September 8, 2019 – August 19, 2020. Additionally, integrated spectral densities (in dB re μPa^2) were calculated across frequency bands of interest, including 10 – 100 Hz (where fin and blue whale vocalizations occur but also a main band for ship noise), 150 – 1000 Hz (another band for ship noise but also humpback whales), 2.2 – 4.9 kHz (the primary band for MFAS), 3 – 10 kHz (the remainder of the MFAS bandwidth), and 20 – 48 kHz (the band for beaked whale and other odontocete click detections). The means of these values were taken across each dataset to capture a snapshot value of noise levels that could be compared statistically.

First, a two-way analysis of variants (ANOVA) of hydrophone, date, and the interaction between the two variables was tested on the integrated spectral density values for the five bands of interest to determine if there was both a spatial and temporal shift in noise levels. Most recreational boating activity occurs close to shore and would likely only be detected on the most inshore of the Barking Sands Tactical Underwater Range (BARSTUR) hydrophones, while most range activity, particularly that including MFAS, occurs towards the middle of the range. Therefore, any detected spatial changes in activity could reflect the different schedules by Navy and commercial/recreational boats in their resumption of activity. However, this test was inconclusive as all resulting F-values were not a number (NaN), likely due to the high number of possible combinations in this test (62 hydrophones plus 28 usable datasets). Therefore, a second ANOVA was tested using only the date as the test variable. In this case, while the results were significant for all five bands of interest (Table 8), they were difficult to interpret due to the natural variability in noise levels already inherent in the data.

In all five bands there was a strong drop in noise levels from March into April that could be due to the sharp decline in anthropogenic activity; however, this drop also is evident on the 20-48 kHz band, where an increase in noise levels would be expected if beaked whales and other odontocetes were reacting favorably to the quieter environment (Figure 22). In addition, there were three datasets in the fall of 2019 (from October through early November) that had noise levels equally as low, or lower, than the levels observed in April 2020. Furthermore, the noise levels from late November through March 2020 were generally higher in all of the low- and mid-frequency bands tested than the noise levels from April through July. Noise levels began to increase again in August, which is consistent with when range activities resumed. While the levels were statistically significantly different for the 20-48 kHz band as well across this year, it was the least significant ($p = 0.034$) and levels were more consistent across the year. Additionally, the high-pass phones included in the 20-48 kHz band don't reflect the dips in noise levels in November and March as strongly as the wide-band hydrophones. Finally, the elevated levels from December through February may reflect the arrival of baleen whales, particularly humpback whales, on their breeding grounds causing elevated background levels across all frequency bands. Therefore, separating out any quieting that may have occurred from reduced anthropogenic activity may be confounded by those elevated levels that occurred prior to the anthropause.

Table 8. ANOVA results for integrated spectral densities across all dates for five bandwidths of interest.

Bandwidth	Sum of Squares	Degrees of Freedom	Mean Square	F-statistic	Probability
10 - 100 Hz	9689.4	29	334.12	14.83	<0.001
150 – 1000 Hz	14722.4	29	507.67	89.64	<0.001
2.2 – 4.9 kHz	14202.2	29	589.73	86.39	<0.001
3 – 10 kHz	13113.1	29	452.17	79.33	<0.001
20 – 48 kHz	499.58	29	17.23	1.55	0.034



- The lowest four bands were measured on the wide-band hydrophones only, while the highest frequency band (20-48 kHz) was measured on both the wide-band and high-pass hydrophones. The colored lines represent individual hydrophones.

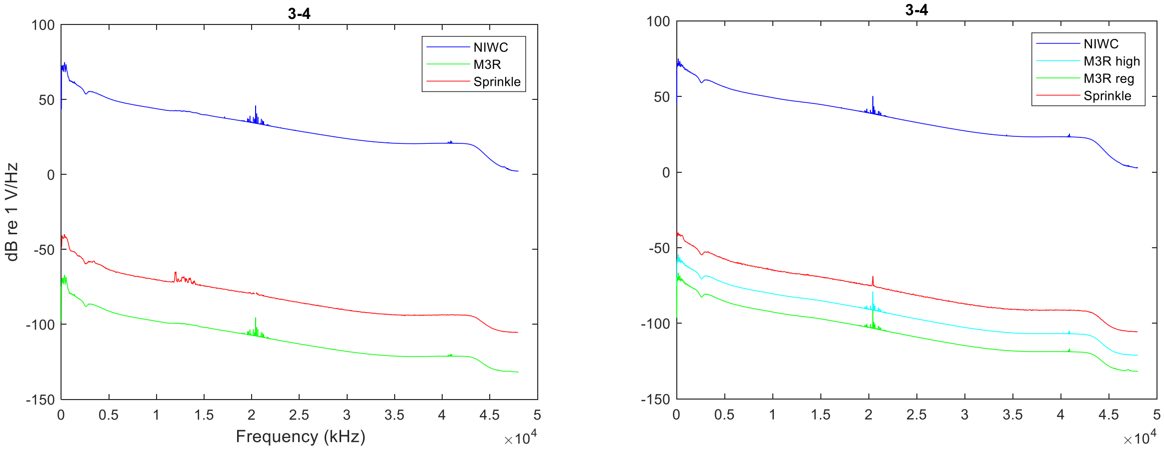
Figure 22. Averaged integrated spectral density values for all five frequency bands of interest from September 2019 through August 2020.

3.4.2 Comparison of Ambient Noise Analyses

At PMRF, three sources of ambient noise data were compared: data from the NIWC Pacific legacy recorder, data from the NUWC Newport M3R packet recorder, and archived binary spectrogram data from the M3R system. Across both organizations it was determined that there were five periods where all three data streams had been recorded for at least four hours. These included 15 March and 21 June 2019, and 8 January, 10 January, and 17 January 2020. Unfortunately, it turned out that the data from 21 June 2019 included previously recorded data that the range plays back for analysis purposes and could not be used, however, the other four periods were analyzed. In addition, the M3R Packet data on 8 and 10 January were recorded at two gain settings due to a test between the two systems; both sets of data were analyzed here. Figure 23 depicts the ambient noise spectral density curves for hydrophone 3-4 from each of the three systems before they were aligned from 15 March

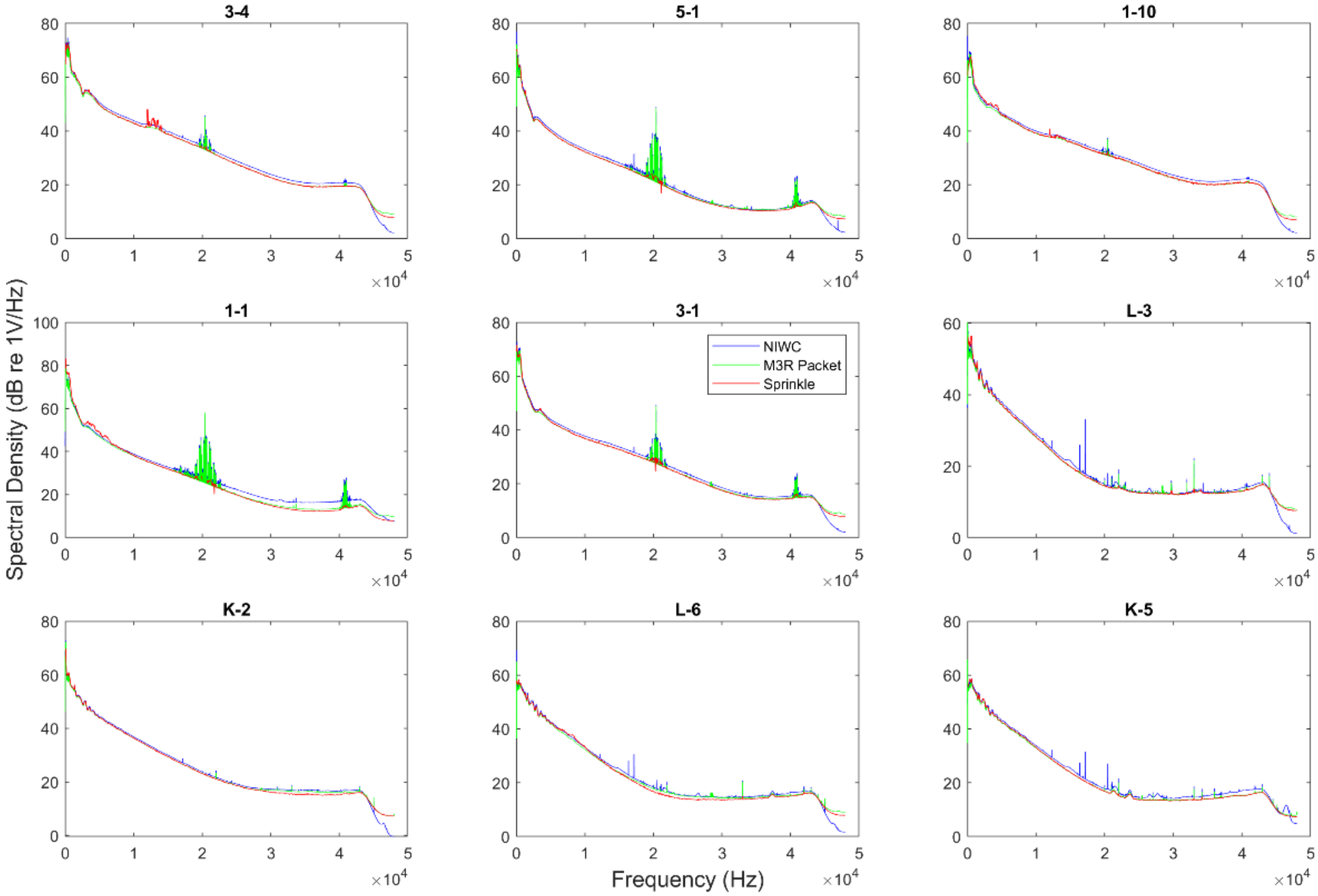
2019 (left) and 10 January 2020 (right). Figure 24 depicts the spectral density curves on nine hydrophones (data from 17 January 2020) after they have all been aligned with the levels on the NIWC Pacific legacy recorder.

The calculated offset values for the four datasets are given in Table 9. These were initially calculated separately for the wide-band Barking Sands Underwater Range Expansion (BSURE) and BARSTUR hydrophones and the high-pass BARSTUR hydrophones (only comparing the data above 10 kHz for those hydrophones), but the differences were less than 1 dB so the data were combined into a single offset value between systems. Unexpectedly, the offset values differed between the 17 January and the 15 March recordings. This was explained when the normal versus high gain data from 8 and 10 January were compared; it became clear that the M3R packet data from 17 January had been recorded at the higher gain level.



- Results are from the NIWC Pacific legacy recorder (blue), the NUWC Newport M3R packet recorder (at both the regular gain setting in green, and the high gain setting in the right plot in cyan), and the NUWC Newport M3R binary FFT sprinkle analysis (red). The left plot is from 15 March 2019, the right plot is from 10 January 2020.

Figure 23. Spectral density curves of ambient noise levels on hydrophone 3-4 at PMRF.



- Shown for BSURE replacement phones and BARSTUR broadband hydrophones after they were aligned with offset values (in dB re 1 V/Hz) to the spectral density levels of the NIWC Pacific legacy recorder. These data are from 15 March 2019.

Figure 24. Spectral density values for the three systems recorded at PMRF on nine hydrophones.

Table 9. Mean offset values calculated between the different recording systems at PMRF when estimating ambient noise levels, with ranges of values given in parentheses.

Dataset date	NIWC-M3R offset value (regular gain)	NIWC-M3R offset value (high gain)	M3R recorder-FFT offset value (regular gain)	M3R recorder-FFT offset value (high gain)
15 March 2019	138.9 (132.7 – 148.6)	NA	-27.0 (-28.9 - -24.4)	NA
8 January 2020	141.0 (135.9 – 150.9)	129.3 (125.3 – 138.9)	-27.7 (-18.2 - -34.6)	-15.9 (-6.2 - -22.7)
10 January 2020	140.8 (135.7 – 150.9)	129.0 (125.3 – 138.8)	-27.6 (-19.2 - -29.8)	-15.8 (-7.3 - -18.2)
17 January 2020	NA	129.5 (123.3 – 130.7)	NA	-15.6 (-12.0 - -16.6)

- As these values were calculated from the full-band spectral density data but without the application of a transfer function, the units are in dB re 1 V/Hz.

At SOAR, four hours of data from 1/2/2019 were compared in a similar manner and an offset value of 94.5 dB re 1 µPa^2/Hz was found between the M3R packet data and the sprinkle analysis data (Figure 25). Different averaging techniques were also tested, with a per hydrophone averaged offset value compared against an overall averaged value (Figure 26; DiMarzio et al. 2022).

While these results are preliminary at both ranges, and additional statistical analyses need to be conducted to derive statistical metrics for each hydrophone, these initial offset values can now be used by NUWC Newport moving forward with their sprinkle analysis of the binary spectrogram data to estimate calibrated ambient noise levels at both PMRF and SOAR. System transfer functions should also be applied to these data in order to get precise units in addition to the statistical metrics. These steps will be taken in the next phase of this analysis.

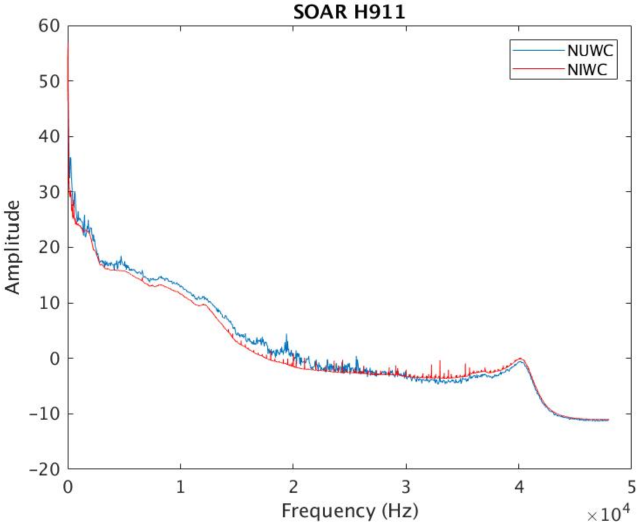
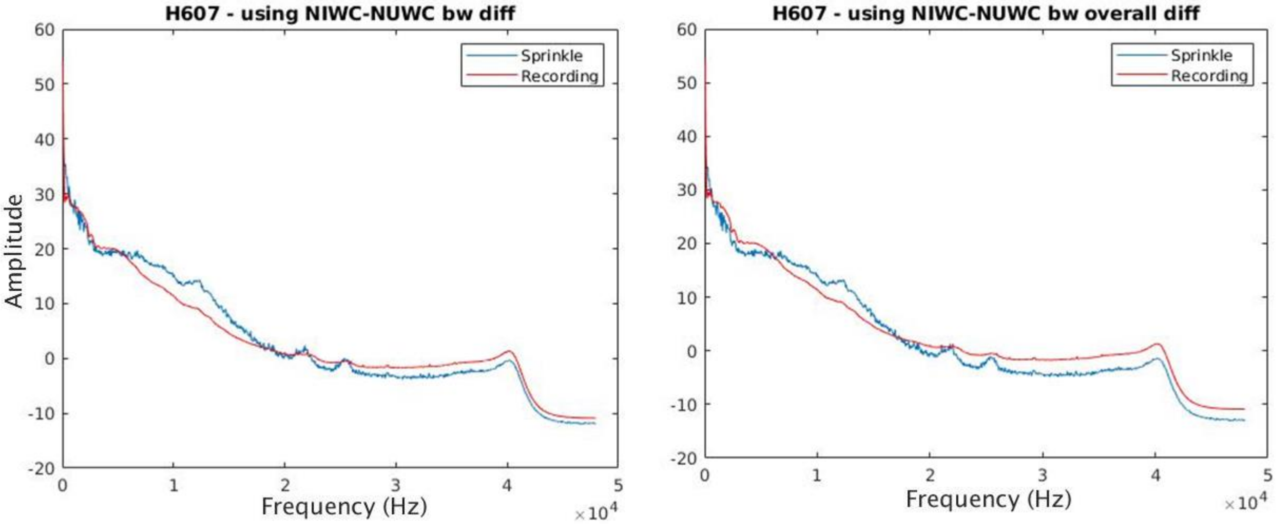


Figure 25. Ambient noise curve from a hydrophone at SOAR calculated using the NARWHAL algorithm on M3R packet data (“NIWC”) and aligned with the NUWC sprinkle analysis results (“NUWC”). Figure from N. DiMarzio, NUWC Newport.

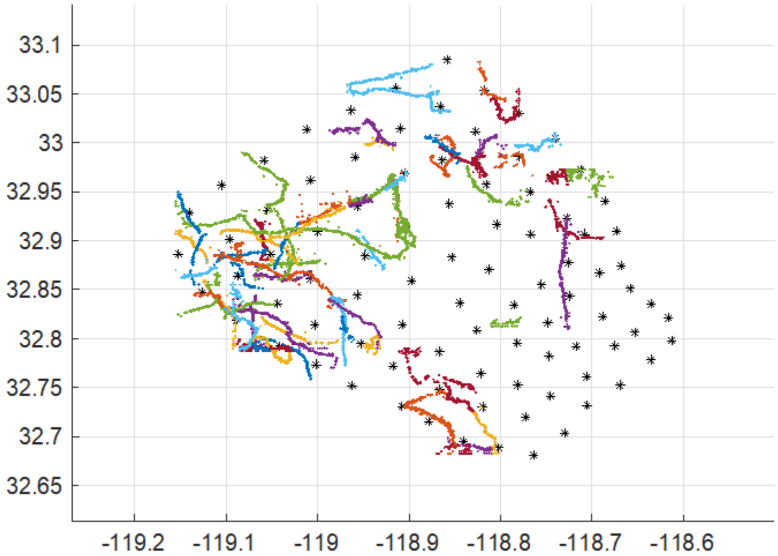


- The left plot demonstrates applying the offset as averaged by hydrophone, while the right plot demonstrates applying the overall average as the offset. Figure from N. DiMarzio, NUWC Newport.

Figure 26. Comparison of averaging methods to apply the offset value on SOAR hydrophone data.

3.5 FIN WHALE TRACKING AT SOAR

Fin whale tracks at SOAR were computed for all datasets provided by NUWC Newport that were of sufficient duration to capture tracks (Table 10). Thousands of fin whale tracks were recorded, and a subset of these tracks were provided to NUWC Newport to validate/compare to the M3R localizer Example tracks obtained using the NARWHAL software suite on SOAR can be seen in Figure 27. A comparison of positions (or "posits") from the M3R locator can be seen overlaid with example positions from the NARWHAL software suite in Figure 28. Overall, it was noted that the M3R locator recorded fewer, more spurious positions when compared to NARWHAL. In addition, there were time periods with positions present in the NARWHAL output but missing from the M3R output. An investigation headed by NUWC Newport determined that the M3R locator was not as precise in determining positional information as NARWHAL, in part because of the more granular fast Fourier transform (FFT) settings used for determining the cross-correlation peak delay between hydrophones. Additional time-delay refinement tactics, such as interpolation of the cross-correlation results to compute more accurate time delays, are present in the NARWHAL software but not in the M3R software. These refinement techniques allow the NARWHAL software to more precisely filter by the LSQ score, and therefore subsequently filter more spurious (incorrect) localizations than the M3R system. The periods where no tracks were computed for M3R but were computed by NARWHAL were found to be during periods of high odontocete activity. It was determined that the M3R system can lag behind computationally (and subsequently drop detections and localizations) when activity increases in other detection bands, since the total system was designed to operate in real-time. Overall, the collaborative working group between NUWC Newport/NIWC Pacific determined that for post-processing, it made the most sense to eventually use the NARWHAL system once integrated into the Raven-X software package (FY22 new start LMR project). For processing in real-time, the NUWC Newport team can continue to compare results between NARWHAL and the M3R positions to refine real-time capabilities.



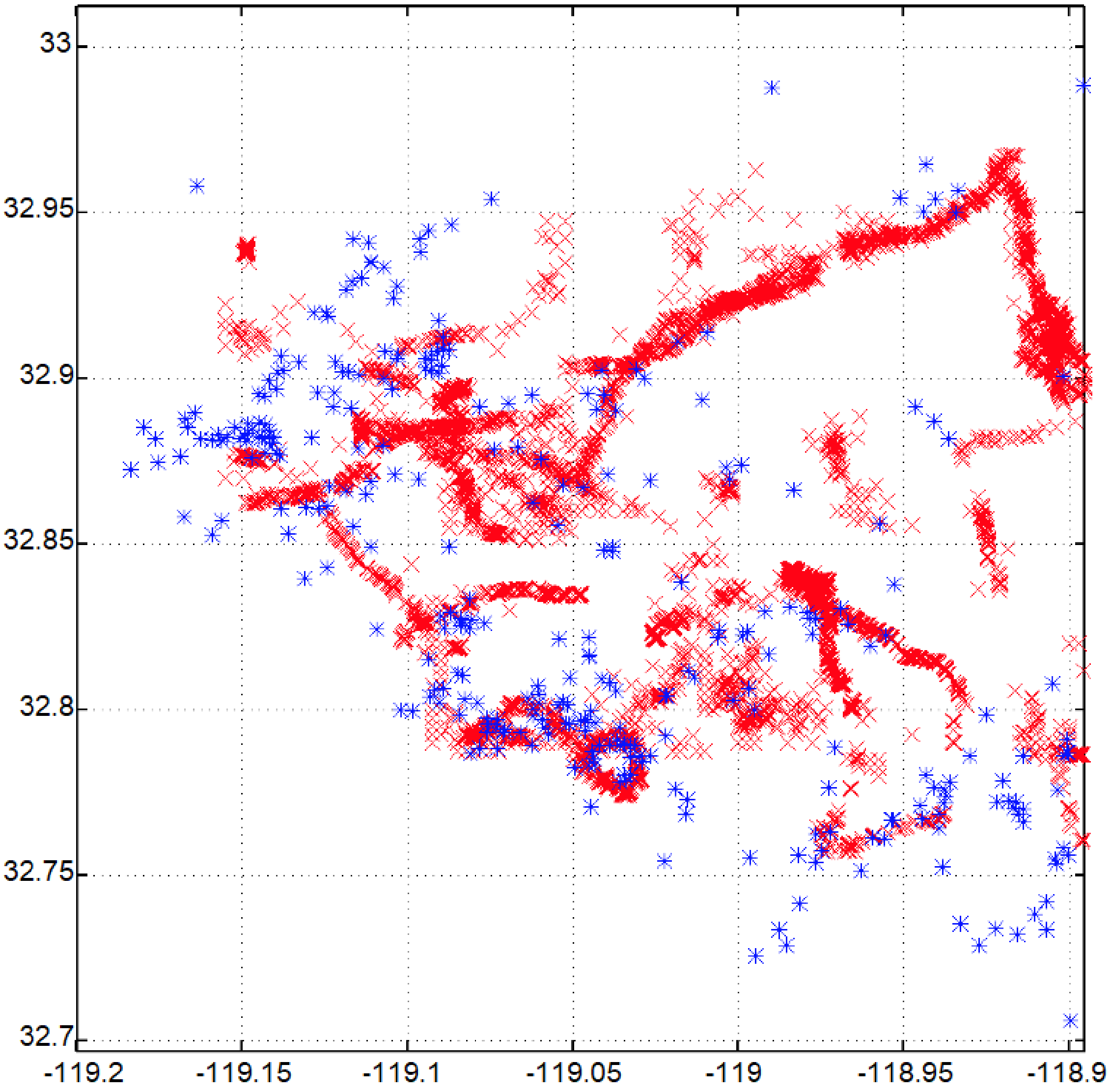
- Tracks occurred between Jan 2, 2019 21:59 GMT and Jan 5, 2019 19:46 GMT and were obtained using the NARWHAL algorithm suite. Colors reflect individual tracks.

Figure 27. Example Fin whale tracks at SOAR, where all tracks with at least 100 localizations are displayed and each track is a displayed as a single color.

Table 10. Summary of data from SOAR archives used for fin whale tracks and noise analyses.

Date	Start Time	Duration (hrs)	Max Tracks in a Snapshot
19 Oct 2012	15:56	23.02	6
05 Oct 2014	20:48	16.33	4
20 Mar 2015	13:28	54.61	2
04 May 2015	17:18	46.55	3
21 Dec 2015*	05:22	12.67	29
21 Dec 2015*	20:06	2.67	27
21 Dec 2015*	23:51	142.83	96
15 Jan 2016*	22:58	44.94	30
15 Jul 2016	19:48	28.36	0
12 Nov 2016	22:42	16.03	23
07 Jan 2017	00:04	14.40	36
11 Jan 2018	18:44	20.92	22
02 Jan 2019	21:58	69.87	40
05 Jan 2019	19:51	48.80	36
10 Jan 2019	18:16	19.84	46
12 Oct 2019	19:17	27.66	28
20 Nov 2019	00:45	21.97	13
20 Nov 2019	23:06	24.31	28

- “Max Tracks” is the maximum number of coexisting fin whale tracks in a 10-min snapshot taken every hour during the dataset. * indicates that only 79 out of 89 hydrophones were recorded for that dataset. Note that these tracks have not been validated and in some cases the numbers are likely inflated.



- Raw positions (before track grouping algorithms were run) were used to compare localization outputs between the two software packages.

Figure 28. Example comparison of M3R locator computed positions (blue) and NARWHAL computed positions (red), for a subset of time for the same Jan 2, 2019 dataset shown in Figure 27. (Image provided by NUWC).

4. CONCURRENT AND RELATED EFFORTS

4.1 ONR BREVE

The ONR funded BREVE effort began in August 2016 and was completed in July 2021. The effort was 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 analyses 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 also found that minke whales increase speed and their movements become more directed during periods of MFAS activities (Harris et al. 2018). The latest efforts utilized correlated random walk tracks with multiple imputation and HMMs with two states (faster more directed movement and slower, less directed movements) which reinforced that faster and more directed movements occur during MFAS activities and that whale movements were consistent with movement away from MFAS producing ships (Durbach et al. 2021).

4.2 SMART LOW SWARM

The Science, Mathematics, and Research for Transformation (SMART) Scholar Seed Grant (SEED) titled Low-frequency Sources with Whale Acoustic Reconnaissance for Mitigation (Low SWARM) is funding R. Guazzo to do collaborative research with the Marine Mammal Monitoring (M3) program at Naval Ocean Processing Facility (NOPF) Dam Neck. In order to maintain an active presence around the world, the U.S. Navy must conduct training and testing exercises. Active sonar, and especially low-frequency active (LFA) sonar, is an important system for Navy operations. Because LFA sonar encounters are rare, we are investigating the impact of airguns, which have a similar frequency range and intensity as LFA, albeit with very different durations. A seismic airgun survey was captured on a Navy passive acoustic monitoring system in the North Atlantic. During the time of the survey, 45 actively vocalizing whales of 3 species (19 fin whales, 11 humpback whales, and 15 sperm whales) were tracked swimming in the area of the seismic ship. Hidden Markov Models were used to study the behavior of the whales before, during, and after this seismic survey by modeling the speed and direction of whales as a function of distance to the ship, airgun activity, and species. This work is a necessary step to increase our knowledge about the impacts of low frequency impulsive noise sources on marine mammals.

4.3 ONR EBREVE

The ONR effort titled Environmentally-influenced Behavioral Response Evaluations (EBREVE) is focused on understanding the impact of environmental changes on baleen whale behavior at PMRF. Guazzo et al. (2021) described the swimming behavior of singing fin whales on PMRF. Male fin whales sing using 20 Hz pulses produced in regular patterns of inter-note intervals (INIs), but little is known about fin whale swimming behavior while they are singing. Even less is known about fin whales in Hawaiian waters because they have rarely been sighted during visual surveys and passive acoustic monitoring has been limited to sparse hydrophone systems that do not have localization capabilities. We hypothesized that fin whale kinematics may be related to their singing behavior, or external variables such as time and sea state. To investigate this hypothesis, we analyzed 115 tracks containing 50,034 unique notes generated from passive acoustic recordings on an array of 14 hydrophones from 2011 to 2017 at PMRF. Fin whales swam at an average speed of 1.1 m/s over relatively direct paths. The whales' speed and turning angle were incorporated into HMMs to identify different behavioral states based on the whales' movements. Fin whale kinematic behavioral state was found to be related to the vocalization rate (also known as cue rate) and time of day. When cue rate was higher, fin whales were more likely to swim slower and turn more. During the night, fin whales were also more likely to swim slower and turn more than during the day. In addition, GAMs were used to examine whether the presence of singing fin whales was related to time and sea state. Fin whale track presence was affected by day of the year and song season, and possibly also wind speed and wave height. Although the track kinematics from the fin whale tracks presented in this effort are limited to a subset of whales that are acoustically active, they provide some of the only detailed movements of fin whales in the region and can be compared against fin whale swim speeds in other regions. Understanding how fin whale swimming behavior varies based on their vocalization patterns, time, and environmental factors will help us to contextualize potential changes in whale behavior during Navy training and testing on the range (Guazzo et al., 2021).

4.4 LMR SONAR DETECTOR PROJECT

The LMR effort entitled “Standardizing Methods and Nomenclature for Automated Detection of Navy Sonar” began in 2019 and was extended through the end of 2022. Through this effort, a shallow neural net based generalized sonar detector was developed within RavenX. The detector can operate on windowed data or can be combined with existing first-stage detectors such as such as GPL or Silbido. In both scenarios, the operational performance is considerably higher than all previous sonar detectors tested based on receiver operating characteristic curves. This sonar detector will be tested and applied to NIWC Pacific’s stored historical SCC data. We will compare the results with the current hull-mounted MFAS detector in the NARWHAL algorithm suite and determine if the RavenX detector will be able to pull out other MFAS sources as well, including helo-dipping sonar, active sonobuoys, and torpedos. If so, NIWC Pacific can re-analyze the 10 years of SCC data for multiple sources of MFAS and couple the results with the BREVE behavioral disturbance models to conduct long-term disturbance analyses on multiple species of baleen whales and odontocetes at PMRF.

4.5 LMR BLAINVILLE’S BEAKED WHALE PHASE A BEHAVIORAL RESPONSE

The LMR effort entitled “A Blainville’s beaked whale behavioral risk function for Hawaiian populations” was a collaborative effort between NIWC Pacific, NUWC Newport, and University of St. Andrews CREEM, and worked to create a behavioral risk function for Blainville’s beaked whales in response to MFAS at PMRF. During the course of this analysis and model development, it was discovered that Blainville’s beaked whales were responding more strongly to the onset of Navy training activity during Phase A (when there are no surface ships using hull-mounted sonar present) than they were to the presence of ship hull-mounted MFAS during Phase B. After discussion with and support from members of the Navy community, including COMPACFLT, it was agreed that NIWC Pacific could share some generalized data on other sources of MFAS that occur during Phase A with the University of St. Andrews researchers in order to develop additional behavioral response models to these other sources and determine what may be causing this strong response in Blainville’s beaked whales. NIWC Pacific developed this dataset for the six SCCs that were initially examined and shared that data with the University of St. Andrews CREEM; those models are now in development.

4.6 TAGGING AT PMRF

Dr. Robin Baird is separately funded by COMPACFLT to tag marine mammals prior to the bi-annual SCC training events. Personnel from the NIWC Pacific WARP Laboratory supported the tagging effort by recording additional acoustic data and directing the tagging boat to areas where species of interest were acoustically detected. These data have been used in past analyses to estimate received levels of the tagged animals during periods of sonar use (e.g., Henderson et al. 2021).

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6. FY21 PRESENTATIONS

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Cameron R. Martin	Tyler A. Helble	Gabriela C. Alongi
E. Elizabeth Henderson	Roanne A. Manzano-Roth	Regina A. Guazzo
Stephen W. Martin	Brian M. Matsuyama	**NIWC Pacific**
NIWC Pacific	**NIWC Pacific**	

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NIWC Pacific
53560 Hull Street
San Diego, CA 92152–5001

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14. ABSTRACT

This report documents Naval Information Warfare Center Pacific (NIWC Pacific) marine mammal monitoring efforts in fiscal year (FY) 2021 for Commander, Pacific Fleet (COMPACFLT) at the Pacific Missile Range Facility (PMRF), Kauai, Hawaii.

This report includes our team's research of four areas:
(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 3203.7 hours of new data collected from September 4, 2020 to August 26, 2021.
(2) Abundance results for baleen whales from September 4, 2020 to August 26, 2021 including minke, humpback, and low-frequency baleen whales (Bryde's, fin, sei, and blue whales).
(3) Abundance results for odontocetes from September 4, 2020 to August 26, 2021 including Blainville's, Cross Seamount (CSM), Longman's, and Cuvier's beaked whales, sperm whales, and killer whales.
(4) Disturbance and noise analyses conducted at PMRF.

15. SUBJECT TERMS

Minke whale; humpback whale, low-frequency baleen whale, beaked whale; killer whale; sperm whale; passive acoustic monitoring; instrumented range; marine mammal monitoring; disturbance analysis; noise analysis

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