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Marine Mammal Monitoring on Navy Ranges (M3R) for Beaked Whales on the Southern California Anti-Submarine Warfare Range (SOAR) and the Pacific Missile Range Facility (PMRF), 2021

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14. ABSTRACT
In the Pacific the Marine Mammal Monitoring on Navy Ranges (M3R) program maintains systems that automatically detect, classify and localize marine mammals in real-time on the U.S. Navy's deep-water Southern California Antisubmarine Warfare Range (SOAR) in Southern California and Pacific Missile Range Facility (PMRF) off Hawai'i. Long-term archive data collected on these ranges allows for numerous types of studies on species inhabiting the ranges, including the monitoring of abundance and distribution, behavioral responses to naval activities, and habitat usage. They also provide the opportunity to study ambient noise and soundscapes.
In FY21 the M3R program had four areas of focus for SOAR and PMRF:
1. Long-term data collection and the evaluation of the distribution and abundance of Cuvier's beaked whales at SOAR and Blainville's and Cuvier's beaked whales at PMRF. Data from 2010-2021 was evaluated at SOAR and data from 2011-2021 at PMRF. Distribution was analyzed using beaked whale Group Vocal Periods (GVPs) detected on range, and the GVPs were converted to number of animals to estimate abundance. The Cuvier's beaked whales at SOAR exhibit a clear seasonal pattern, with the highest numbers in May, followed by the December/January timeframe. The numbers are lowest in September, followed by a less pronounced drop in March. A trend analysis shows that the sample mean number of GVPs per hour and sample mean abundance per hour has significantly dropped ($p < 2.2e-16$) between the periods of 2011-2013 ($\mu GVP = 4.02$, $\mu Abund=45.8$) and 2018-2020 ($\mu GVP = 3.11$, $\mu Abund=35.4$), though

the mean # GVPs (μGVP = 1.72) and mean abundance (μAbund=19.5) in 2015 is lower than either of these time periods. At PMRF, the seasonal distribution of Blainville's beaked whales peaks in January and May through July, while it is lowest in September, with another dip in March. Cuvier's beaked whales, however, peak in March, during one of the low points for Blainville's beaked whales, and then the numbers drop through to September, when they are lowest. They then start to increase until reaching the March peak. Though both species reach peaks at different times, their numbers are both lowest in September. The trend analysis for Blainville's beaked whales at PMRF shows that the sample mean number of GVPs per hour and sample mean abundance per hour has significantly increased (p < 2.2e-16) between the periods of 2012-2014 (μGVP = 0.37, μAbund=8.0) and 2018-2020 (μGVP = 0.76, μAbund=18.8). Similarly, the sample mean number of Cuvier's beaked whale GVPs per hour has significantly increased (p < 2.2e-16) between the periods of 2012-2014 (μGVP = 0.04) and 2018-2020 (μGVP = 0.26). Note that the detection statistics have not yet been applied to the GVPs at SOAR or PMRF, and detection statistics for Cuvier's beaked whales have not yet been calculated at PMRF. Calculating Cuvier's beaked whale detection statistics at PMRF and improving the existing detection statistics at PMRF (for Blainville's) and SOAR (for Cuvier's) should provide more accurate estimates.

2. Accuracy analysis of the M3R low-frequency detector algorithm at SOAR in coordination with the Naval Information Warfare Center (NIWC). The accuracy of localizations of low-frequency (LF) calls automatically generated by the M3R system installed at the SOAR was analyzed by comparing LF localizations extracted from M3R archive files to fin whale detections and localizations generated by researchers at the Naval Information Warfare Center (NIWC), San Diego through their post-processing of whole range acoustic recordings (M3R packet recorder data) for select days. The initial comparisons between the M3R and NIWC localizations were disappointing, but they identified a processor loading problem within the M3R cluster at SOAR caused by a large amount of dolphin vocal activity, particularly at night. Reprocessing of just the M3R LF spectrogram data (alone) through the LF association/localization code produced tens of thousands of LF posits, resulting in closer parity between NIWC fin tracks and M3R LF tracks. When overlaid, the M3R posits exhibit more scatter than the NIWC localizations, likely because the timing resolution of the M3R LF detector (170.67 ms) is much coarser than the timing resolution of the NIWC fin detector. The results demonstrate that M3R's LF localization routine can effectively localize calls from several baleen species, and identified steps that can be taken to improve the accuracy of the M3R LF detection and localization.

3. Validation of the "sprinkle analysis" method to extract ambient noise from M3R archives by comparison with broadband recordings analyzed by NIWC. A method has been developed to automatically extract ambient noise curves from M3R binary Fast Fourier Transform (FFT) archive files by averaging "single-bin" detections (detections with just a single bin above threshold) over time. This method was validated in collaboration with researchers from NIWC by comparison of the ambient curves generated by the M3R sprinkle analysis with ambient noise curves derived by NIWC from analysis of broadband recordings. Correction factors were empirically derived to align the shapes of the overlaid curves, resulting in close matches between the two. The results validate the sprinkle analysis method, though future work should include determination of system transfer functions to convert the output of the sprinkle analysis to received levels. The sprinkle analysis will provide a straightforward way to leverage years of M3R archive files collected on the ranges to analyze the spatio-temporal distribution and long-term trends of the ambient noise on the Navy's undersea ranges.

4. Support of on-site field exercises at SOAR and PMRF with real-time monitoring using the M3R system. In FY21 M3R conducted two field tests at SOAR (October, 2020 and September, 2021) in collaboration with Marine Ecology and Telemetry Research (MarEcoTel), and one field test at PMRF (in August, 2021) with Robin Baird of the Cascadia Research Collective. During these field exercises M3R team members use the M3R system to direct on-water researchers to the locations of animals, where they collect photos for photo-ID catalogs, behavioral data, biopsy data, and potentially place satellite tags on animals. At SOAR, additional planned efforts were cancelled due to COVID related travel restrictions. The focus at SOAR was on Cuvier's beaked whales and fin whales, and during the two field tests both species were acoustically detected, along with blue whales, common dolphins, and unidentified dolphins and baleen whales. The Cuvier's beaked whales, fin whales, and blue whale were all visually verified. At PMRF the following species were acoustically detected: Blainville's and Cuvier's beaked whales, sperm whales, melon-headed whales, short-finned pilot whales, false killer whales, bottlenose dolphins, rough-toothed dolphins, Risso's dolphins, Fraser's dolphins, and unidentified dolphins and baleen whales. The Blainville's, beaked and melon-headed whales, and bottlenose and rough-toothed dolphins were visually verified, and a total of eight satellite tags were placed on four different species. M3R archive data and broadband recordings are also collected during the field tests.

15. SUBJECT TERMS

Acoustic monitoring, marine mammals, beaked whales, Southern California Anti-Submarine Warfare Range, Pacific Missile Range Facility, Hawaii Range Complex, Southern California Range Complex

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Executive Summary

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In FY21 the M3R program had four areas of focus for SOAR and PMRF:

1. *Long-term data collection and the evaluation of the distribution and abundance of Cuvier's beaked whales at SOAR and Blainville's and Cuvier's beaked whales at PMRF.* Data from 2010-2021 was evaluated at SOAR and data from 2011-2021 at PMRF. Distribution was analyzed using beaked whale Group Vocal Periods (GVPs) detected on range, and the GVPs were converted to number of animals to estimate abundance. The Cuvier's beaked whales at SOAR exhibit a clear seasonal pattern, with the highest numbers in May, followed by the December/January timeframe. The numbers are lowest in September, followed by a less pronounced drop in March. A trend analysis shows that the sample mean number of GVPs per hour and sample mean abundance per hour has significantly dropped ($p < 2.2e\text{-}16$) between the periods of 2011-2013 ($\mu_{GVP} = 4.02$, $\mu_{Abund}=45.8$) and 2018-2020 ($\mu_{GVP} = 3.11$, $\mu_{Abund}=35.4$), though the mean # GVPs ($\mu_{GVP} = 1.72$) and mean abundance ($\mu_{Abund}=19.5$) in 2015 is lower than either of these time periods. At PMRF, the seasonal distribution of Blainville's beaked whales peaks in January and May through July, while it is lowest in September, with another dip in March. Cuvier's beaked whales, however, peak in March, during one of the low points for Blainville's beaked whales, and then the numbers drop through to September, when they are lowest. They then start to increase until reaching the March peak. Though both species reach peaks at different times, their numbers are both lowest in September. The trend analysis for Blainville's beaked whales at PMRF shows that the sample mean number of GVPs per hour and sample mean abundance per hour has significantly increased ($p < 2.2e\text{-}16$) between the periods of 2012-2014 ($\mu_{GVP} = 0.37$, $\mu_{Abund}=8.0$) and 2018-2020 ($\mu_{GVP} = 0.76$, $\mu_{Abund}=18.8$). Similarly, the sample mean number of Cuvier's beaked whale GVPs per hour has significantly increased ($p < 2.2e\text{-}16$) between the periods of 2012-2014 ($\mu_{GVP} = 0.04$) and 2018-2020 ($\mu_{GVP} = 0.26$). Note that the detection statistics have not yet been applied to the GVPs at SOAR or PMRF, and detection statistics for Cuvier's beaked whales have not yet been calculated at PMRF. Calculating Cuvier's beaked whale detection statistics at PMRF and improving the existing detection statistics at PMRF (for Blainville's) and SOAR (for Cuvier's) should provide more accurate estimates.
2. *Accuracy analysis of the M3R low-frequency detector algorithm at SOAR in coordination with the Naval Information Warfare Center (NIWC).* The accuracy of localizations of low-frequency (LF) calls automatically generated by the M3R system installed at the SOAR was analyzed by comparing LF localizations extracted from M3R archive files to fin whale detections and localizations generated by researchers at the Naval Information Warfare Center (NIWC), San Diego through their post-processing of whole range acoustic recordings (M3R packet recorder data) for select days. The initial comparisons between the M3R and NIWC localizations were disappointing, but they identified a processor loading problem within the M3R cluster at SOAR

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Abbreviations and Acronyms

Acronym	Definition
AIST	Advanced Instrumentation Systems Technology
ASW	Anti-Submarine Warfare
AUTEC	Atlantic Undersea Test and Evaluation Center
BARSTUR	Barking Sands Tactical Underwater Range
BSURE	Barking Sands Underwater Range Expansion
CI	Confidence Interval
CRC	Cascadia Research Collective
CS-SVM	Class-Specific Support Vector Machine classifier
CTP	Click Train Processor
CV	Coefficient of Variation
DCL	Detection, Classification and Localization
FFT	Fast Fourier Transform
GVP	Group Vocal Period
FP	False Positive
HARP	High Frequency Recording Package
Hrs	Hours
ICI	Inter-Click Interval
IQR	Inter-Quartile Range
kHz	kilohertz
LF	Low-frequency
LIMPET	Low Impact Minimally Percutaneous Electronic Transmitter
LMR	Living Marine Resources
M3R	Marine Mammal Monitoring on Navy Ranges
MarEcoTel	Marine Ecology and Telemetry Research
METEOR	Marine Mammal Effects of Test and Evaluation on Ocean Ranges
MFAS	Mid-Frequency Active Sonar
Min	Minutes
MMAMMAL	Marine Mammal Monitoring And Localization
NIWC	Naval Information Warfare Center
NVT	Noise Variable Threshold
PD	Probability of Detection
PMRF	Pacific Missile Range Facility
RHIB	Rigid Hull Inflatable Boat
RL_{rms}	Received Level root mean squared
RMS	Root mean squared
SCORE	Southern California Offshore Range
SES	Shore Electronics System
SOAR	Southern California Anti-Submarine Warfare Range
SWTR	Shallow Water Training Range
T	Time
TDOA	Time difference of arrival
USWTR	Undersea Warfare Training Range
V_{rms}	Volts root mean squared
Whdetect	Whale Detection algorithm

1 Introduction

1.1 Background

The Marine Mammal Monitoring on Navy Ranges (M3R) program utilizes the U.S. Navy's instrumented hydrophone ranges for passive acoustic detection of marine species (Jarvis et al. 2014). This important resource allows for long-term monitoring of certain populations of interest, and provides data for answering key questions regarding basic biology, habitat usage, and behavioral responses to Navy training and testing activities. This report presents the results of annual baseline monitoring on two ranges managed by Commander, U.S. Pacific Fleet; the Southern California Anti-Submarine Warfare Range (SOAR) located off San Clemente Island, California, and the Pacific Missile Range Facility (PMRF), located off Kauai, Hawaii.

1.2 Study Goals

The goals of the FY21 monitoring effort included the following:

1. Collect M3R archives at both SOAR and PMRF to inform long-term distribution and abundance estimates for Cuvier's beaked whales (*Ziphius cavirostris, Zc*) and Blainville's beaked whales (*Mesoplodon densirostris, Md*)
2. Analyze the accuracy of the installed low-frequency detector algorithm at SOAR in coordination with the Naval Information Warfare Center (NIWC).
3. Validate the "sprinkle analysis" method for ambient noise calculation using the Fast Fourier Transform (FFT)-based archives by comparison to ambient noise calculated from broadband recordings by NIWC
4. Support real-time monitoring of on-water tagging operations at SOAR and PMRF

1.3 Study Sites

SOAR is located in the San Nicolas Basin west of San Clemente Island, CA (Figure 1). San Clemente Island is one of the Channel Islands in the southern California Bight. SOAR is an Anti-submarine Warfare (ASW) training range on which sound sources, including mid-frequency active sonar, are routinely used, and beaked whales are regularly detected acoustically and visually, displaying a high level of site fidelity to the area (Falcone et al. 2009, Schorr et al. 2014, Schorr et al., 2020Schorr et al., 2020). The SOAR range consists of an array of 177 bottom-mounted hydrophones covering an area of about 2200 square kilometers (km^2). The SOAR hydrophone baselines range from about 2.5 to 6.5 kilometers (km), and are at average depths of 1600-1800 meters (m). The 88 original, or legacy, hydrophones have a bandwidth of ~8 to 40 kilohertz (kHz), while the newer refurbished 89 hydrophones have a bandwidth of ~50 Hz to 48 kHz [4].

PMRF is located off the northwest coast of Kauai, HI (Figure 2). The range consists of the three distinct areas, known as the Barking Sands Tactical Underwater Tracking Range (BARSTUR), the Barking Sands Underwater Range Expansion (BSURE) and the Shallow Water Training Range (SWTR). BARSTUR consists of 42 hydrophones with a bandwidth of approximately 8-45 kHz, with six broadband hydrophones that cover a bandwidth of approximately 20 Hz to 45 kHz. BSURE has 41 newer hydrophones (BSURE refurb) with a bandwidth of 50 Hz to 45 kHz, and the original 18 hydrophones with a bandwidth of 50 Hz to 18 kHz. All hydrophones aside from strings A, B and H were used in this analysis. Note that over this period of time the hydrophone configuration has changed as a result of certain hydrophones becoming nonfunctional, and this variation in spatial effort has not yet been accounted for in the analysis.

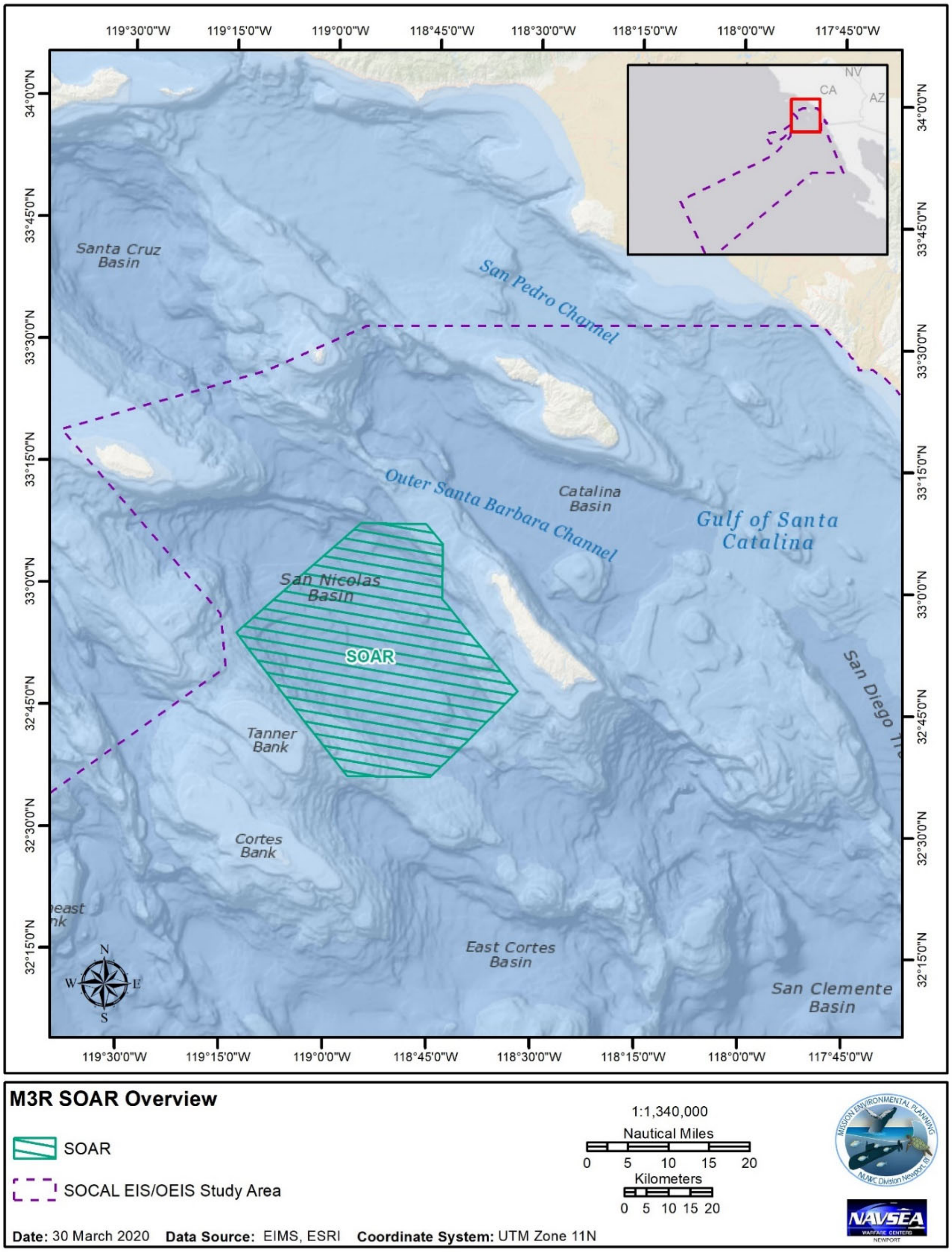

Figure 1. Location of SOAR hydrophone range, west of San Clemente Island off southern California.

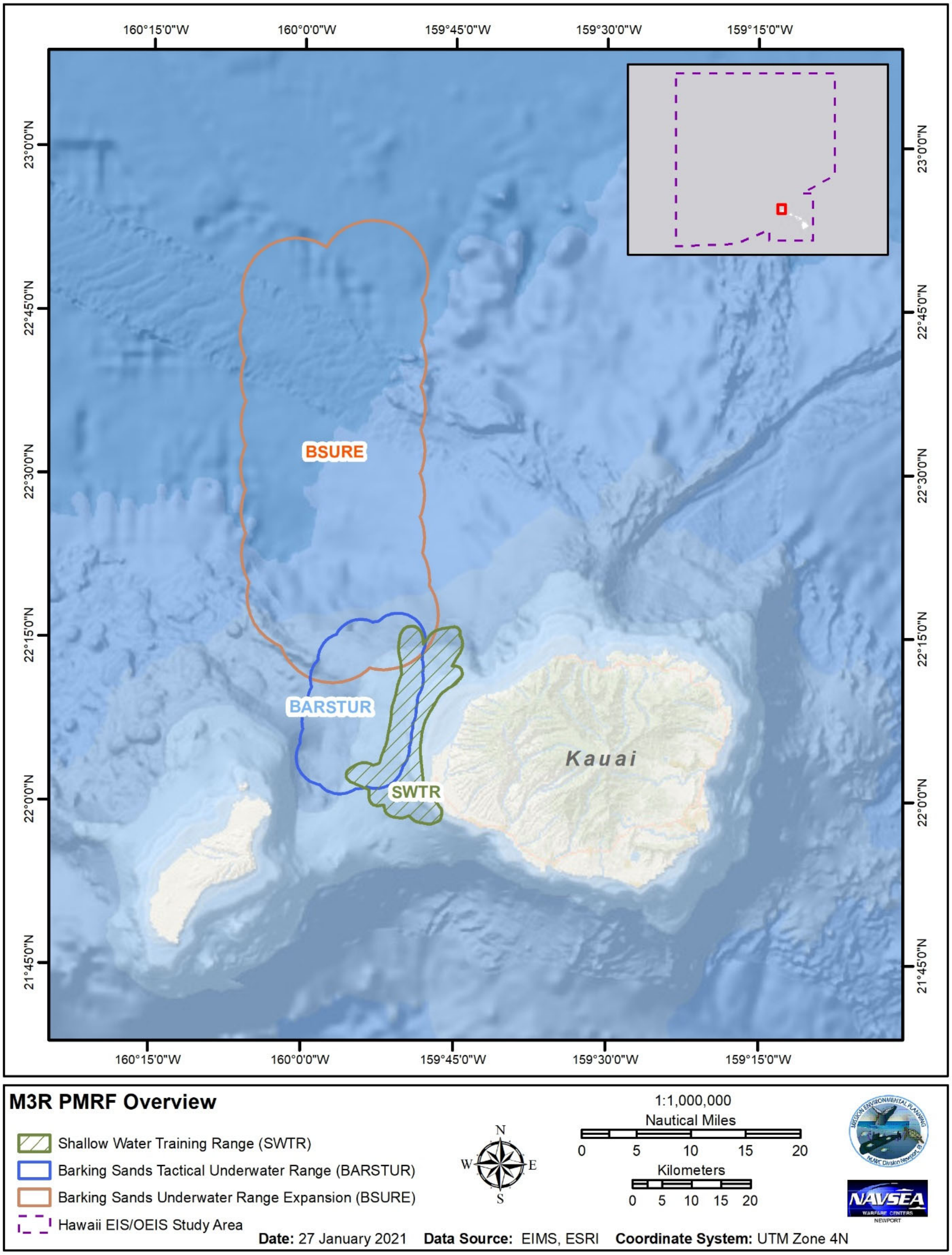

Figure 2. Location of PMRF hydrophone range, west of Kauai, Hawaii

1.4 Data Collection

The M3R system runs nearly continuously year-round, archiving data from all range hydrophones simultaneously in real-time, when there are no range activities that would preclude its operation. Detection, classification, and localization (DCL) reports are stored to binary archive files for later playback and analysis.

The M3R system employs three detector/classifiers: a Fast Fourier Transform (FFT)-based detector, a Class-Specific Support Vector Machine (CS-SVM) detector/classifier, and a Blainville's beaked whale foraging click matched filter (Jarvis et al. 2008). The CS-SVM classifier currently has four classes at SOAR: Cuvier's beaked whale foraging and buzz clicks, sperm whale clicks, and 'generalized dolphin' clicks. At PMRF there are six CS-SVM classes: Blainville's beaked whale foraging and buzz clicks, Cuvier's beaked whale foraging and buzz clicks, sperm whale clicks, and 'generalized dolphin' clicks.

Archives which included FFT-based detections were first collected at SOAR in 2006, when the system was first installed (Table 1). The CS-SVM detector was implemented in May 2010, and the analyses of Cuvier's beaked whale distribution and abundance use the CS-SVM output; thus, they cover the time period from May 2010 through September 2021. The plus (+) sign in September 2021 indicates that data are still being collected, but have not yet been retrieved from the range.

Table 1. Number of days per month for which M3R detection archives have been collected at SOAR. CS-SVM archives were first collected in May, 2010 (indicated in blue).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006							6	11	0	0	0	0
2007	0	0	0	12	0	0	0	0	0	9	0	0
2008	0	0	0	0	0	0	4	19	7	16	12	0
2009	0	0	30	15	0	1	22	30	22	0	12	0
2010	3	0	0	0	**7**	0	0	9	30	29	22	23
2011	22	27	8	3	13	0	6	28	30	31	22	31
2012	27	23	18	30	15	6	1	4	0	17	13	10
2013	0	0	0	0	17	30	24	31	30	6	2	12
2014	31	22	28	29	28	17	14	17	28	14	4	31
2015	31	28	24	25	31	15	22	21	15	30	15	11
2016	31	27	31	25	18	7	16	31	27	0	26	22
2017	15	0	13	17	2	0	11	31	24	17	29	27
2018	27	14	4	17	28	30	21	31	30	31	30	22
2019	28	28	31	30	30	28	29	20	8	26	29	31
2020	28	19	0	4	0	0	0	0	0	27	22	0
2021	7	9	31	30	9	20	16	28	8+			

Archives that included FFT-based detections were first collected at PMRF in January, 2011 when the system was installed, but the CS-SVM detector was incorporated in in May of 2011 (Table 2). Distribution and abundance of Blainville's and Cuvier's beaked whales at PMRF were analyzed using the CS-SVM detections, which covers the period from May 28, 2011 through August 11, 2021. The plus (+) sign in September 2021 indicates that data are still being collected, but have not yet been retrieved from the range. These results were for the BSURE and BARSTUR PMRF range hydrophones, excluding strings A, B, which have an upper frequency limit of 20 kHz, and excluding the shallow SWTR hydrophones.

Table 2. Number of days per month for which M3R detection archives have been collected at PMRF. CS-SVM archives were first collected in May, 2011 (indicated in blue).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	11	27	15	0	1	2	13	1	0	0	0	0
2012	12	0	0	0	0	18	2	0	0	0	0	0
2013	0	9	0	0	0	0	7	19	0	0	0	0
2014	1	27	15	0	5	30	31	20	0	11	0	0
2015	0	22	31	17	0	0	0	0	26	1	0	0
2016	0	11	0	0	0	0	0	11	0	0	0	0
2017	0	27	31	30	31	30	31	30	30	30	30	31
2018	31	28	31	12	7	13	31	22	11	31	25	0
2019	3	16	31	30	31	30	22	0	0	0	29	24
2020	26	29	31	30	31	30	23	29	30	31	30	16
2021	21	28	31	30	7	0	3	12+				

2 Distribution & Abundance of Cuvier's and Blainville's beaked whales

2.1 Introduction

The long-term detection archives recorded at SOAR and PMRF allow for analysis of trends in detections over time. Changes in relative detections could indicate changes in foraging behavior, changes in prey quality or density, or changes in animal abundance. Passive acoustic methods of calculating abundance allow for the relatively low-cost collection of archive data to provide insights on populations of species on Navy ranges.

2.2 Methods

2.2.1 Overview

The distribution and abundance of Cuvier's beaked whales at SOAR and for Blainville's and Cuvier's beaked whales at PMRF are assessed. In order to examine the temporal distribution of beaked whale foraging groups, their Group Vocal Periods (GVPs) are evaluated. A beaked whale group will typically ensonify at least one, and often several hydrophones in a given location while echolocating during deep foraging dives. The clicks detected on these hydrophones are referred to as a GVP, and are considered to represent a group of foraging beaked whales. The duration of the GVP is the time between the first and last detected click from the group. Temporal distribution is presented in terms of the number of GVPs detected on range, while the abundance, or number of animals detected, is derived from the GVPs and is reviewed separately.

The GVPs are automatically generated through several software processing steps. Cuvier's or Blainville's beaked whale foraging clicks detected with the CS-SVM classifier are each first combined into click trains on a per-hydrophone basis, then click trains are used to form groups, and the resulting group data are filtered and post-processed in R.

Cuvier's and Blainville's beaked whale clicks are detected and classified using a CS-SVM algorithm (Jarvis 2012). A Java-based click train processor (CTP) program next forms the click detections for a particular class into click trains on a per hydrophone basis. A click train is initiated when a click is detected, and clicks are added to the click train until at least three minutes pass without detections. At this point if the click train has at least five clicks a click train report is generated; otherwise the click train is discarded. A Matlab-based Autogrouper program then uses a set of rules based on time and location of the click trains to associate the CTP click trains into GVPs. For Cuvier's beaked whales only click trains with an inter-click interval (ICI) greater than or equal to 0.35 sec and an ICI less than or equal to 0.75 sec, and with duration greater than 1 min and less than 60 min, are used in the grouping process. Blainville's beaked whale click trains with an ICI between 0.23 and 0.4 sec are used. Locations are based on the hydrophone locations, with the beaked whale group center being the hydrophone with the highest click density (number of clicks per min). To form a GVP the click trains must be within 9.75 km of the group center. Post-processing in R generates summary data for each group after filtering the GVPs based on duration and total number of clicks. For Cuvier's beaked whales GVPs with fewer than 300 clicks or more than 43,400 clicks are removed, and for Blainville's beaked whales the GVPs must contain between 360 and 64,800 clicks. For Cuvier's beaked whales the filtering on the number of clicks is based on a minimum of one animal clicking for 2.5 min and a maximum of six animals clicking for 60 min, at a click rate of two clicks per sec. For Blainville's beaked whales the click rate is three clicks per sec, the minimum is one animal clicking for 2 min, and the maximum is six animals clicking for 60 min. GVPs less than 5 min or greater than 90 min are also removed.

2.2.2 Beaked Whale Distribution

2.2.2.1 GVP Data Processing

GVPs are generated by processing click train output through the Autogrouper program. The Autogrouper output lists each click train associated with a group, and can contain either very short or very long duration GVPs, potentially triggered by dolphin clicks misclassified as beaked whales on some hydrophones in the group; thus further filtering is conducted in R. After combining all the data for a year, and filtering and summarizing the Autogrouper GVP output in R, the data consists of the following fields (Figure 3):

GpID – Identifier for the group

grp_clkcnt – sum of all clicks detected on all hydrophones associated with a group

maxhyd – the hydrophone in the group with the most clicks

maxclk – the number of clicks detected on maxhyd

nhyds – the number of hydrophones associated with the group

grp_start – start date and time of the GVP

grp_end – end date and time of the GVP

as.numeric.gvp – GVP duration in minutes

MON.start – month start of the GVP

DAY.start – day start of the GVP

YYYY.start – year start of the GVP

HR.start – hour start of the GVP

MM.start – minute start of te GVP

SS.start – second start of the GVP

MON.end – month end of the GVP

DAY.end – day end of the GVP

YYYY.end – year end of the GVP

HR.end – hour end of the GVP

MM.end – minute end of the GVP

SS.end – second end of the GVP

edge_only – indicates if the group consists solely of hydrophones located on the edge of the range (0/1)

JD_start – Julian day start of the GVP

JD_end – Julian day end of the GVP

Dec_hr_start – Decimal hour start of the GVP

Dec_hr_end – Decimal hour end of the GVP

Julian_hr_start – Hour of the year start of the GVP

Julian_hr_end – Hour of the year end of the GVP

```
> head(filtered_groups_2015_ne)
   GpID grp_clkcnt maxhyd maxclk nhyds            grp_strt             grp_end as.numeric.gvp.
7     3       1030    908    727     4 2015-01-01 00:04:27 2015-01-01 00:38:05        33.63333
9     5        874    509    867     2 2015-01-01 00:09:41 2015-01-01 00:44:01        34.33333
18   12        578    208    578     1 2015-01-01 00:40:35 2015-01-01 00:52:16        11.68333
19   13       4068    906   3978     2 2015-01-01 00:55:27 2015-01-01 01:30:27        35.00000
22   14       4481    205   4409     3 2015-01-01 00:58:40 2015-01-01 01:55:43        57.05000
28   16       5172    705   3518     4 2015-01-01 01:47:48 2015-01-01 02:23:50        36.03333
   MON.start. DAY.start. YYYY.start. HR.start. MM.start. SS.start. MON.end. DAY.end. YYYY.end. HR.end.
7           1          1        2015         0         4        27        1        1      2015       0
9           1          1        2015         0         9        41        1        1      2015       0
18          1          1        2015         0        40        35        1        1      2015       0
19          1          1        2015         0        55        27        1        1      2015       1
22          1          1        2015         0        58        40        1        1      2015       1
28          1          1        2015         1        47        48        1        1      2015       2
   MM.end. SS.end. edge_only JD_strt JD_end Dec_hr_strt Dec_hr_end Julian_hr_strt Julian_hr_end
7       38       5         0       0      0  0.07416667  0.6347222     0.07416667     0.6347222
9       44       1         0       0      0  0.16138889  0.7336111     0.16138889     0.7336111
18      52      16         0       0      0  0.67638889  0.8711111     0.67638889     0.8711111
19      30      27         0       0      0  0.92416667  1.5075000     0.92416667     1.5075000
22      55      43         0       0      0  0.97777778  1.9286111     0.97777778     1.9286111
28      23      50         0       0      0  1.79666667  2.3972222     1.79666667     2.3972222
```

Figure 3. Example of filtered Autogrouper output at SOAR for 2015.

For each year matrices are then created for both effort (with each entry either 1 or NA) and number of GVPs per hydrophone and hour of the year (matrix sizes 178 x 8784 for SOAR and 83x8784 for PMRF). For the effort, hours with partial effort are set to NA. For the GVP matrix, the "center hydrophone", or hydrophone in the group with the most clicks (maxhyd) is used to represent the GVP. Therefore the entry in this matrix is the total number of times maxhyd is detected in a given hour and on a given hydrophone. Typically this number is zero or possibly one. The highest number per hydrophone and hour at SOAR has been four, which occurred in 2011. Finally a matrix of number of GVPs per hydrophone and hour of effort is generated by dividing the GVP matrix by the effort matrix.

The percent effort per hour for each year (array size 1x8784) is calculated by adding the effort over all hydrophones in each hour and dividing by the number of hydrophones being evaluated (178 for SOAR and 83 for PMRF). Similarly the number of GVPs per hour for each year is obtained by summing over the hydrophones for each hour, and the number of GVPs per hour effort for each year is generated by dividing the GVP arrays by the percent effort arrays.

Effort per day (array sizes 1x365/366) come from adding the effort from all hydrophones and hours in a day. Dividing the effort per day by the number of hydrophones multiplied by the number of hours in a day (178x24=4272 for SOAR) produces the percent effort per day. In the statistical model the log of the number of hours of effort per day (and not the log of the percent) is used as an offset. The number of GVPs per day, which is used in the model, is the total number of GVPs over all hydrophones and hours in a day.

2.2.2.2 Statistical Modelling

A Generalized Additive Model (GAM) with a Poisson distribution and log link function was used to model the number of GVPs per day on range (GVP) (mcgv 1.8-31 package built under R version 3.5.3). This approach was chosen as the response GVP is not normally distributed, and the Poisson distribution with the canonical link function was used as the data contain counts for both SOAR (between 0 and 213) and PMRF (0 to 65 for Blainville's and 0 to 56 for Cuvier's). For each year a matrix is generated, using only the center hydrophone to represent a GVP, of the number of GVPs detected per hydrophone and per hour of the year. The number of GVPs per day used in the model is derived by adding all the GVPs in this matrix over all the hydrophones and hours in a day. The log of the effort per day is used as an offset in the model. Here the effort per day is the sum of effort over all hours and hydrophones in a day, where each hour-hydrophone entry is either a 1 or NA.

To examine the long-term trend the sequential years over the analysis time period (Year: 2010-2021 for SOAR, 2011-2021 for PMRF) was used as a predictor. Cyclic days (JDay: 1-365/366) was used as a predictor for seasonal variation, and the log of the effort was used as an offset to account for the spatial variation in effort (i.e. the fact that at times data were not obtained from particular hydrophones):

(1) *SOAR:* GVP_JDay_Yr_mcgv.gam = gam(GVP ~ s(JDay) + s(Year) + offset(log_effort_2010_2021), family=poisson(link="log"),data=GVP_JDay_Yr)

(2) *PMRF:* MdGVP_JDay_Yr_mcgv.gam1 = gam(Md_GVP ~ s(JDay) + s(Year) + offset(log_effort_2011_2021), family=poisson(link="log"),data=MdGVP_JDay_Yr)

(3) *PMRF:* ZcGVP_JDay_Yr_mcgv.gam1 = gam(Zc_GVP ~ s(JDay) + s(Year) + offset(log_effort_2011_2021), family=poisson(link="log"),data=ZcGVP_JDay_Yr)

2.2.3 Beaked Whale Abundance

Moretti et al. (2010) described a passive acoustic method for determining Blainville's beaked whale density and abundance at the U.S. Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) using a dive counting method. This method uses the start of a deep foraging dive, as indicated by the first detected click, as the cue for determining density and abundance. As Blainville's and Cuvier's beaked whales have similar dive behavior, both consisting of small groups that conduct deep foraging dives synchronously, and produce echolocation clicks at depth, a modified version of this method has been applied to derive beaked whale abundance on the SOAR and PMRF ranges. The equation for animal abundance (N) presented by Moretti, et al. (2010) was:

(8) $N = \frac{n_d\, s}{r_d\, T}$

where n_d is the total number of dive starts (or GVPs), s is the average group size, r_d is the dive rate (dives/unit time), and T is the time period over which the measurement was made.

For the Moretti et al. (2010) estimate, data were obtained over a relatively short time period (approximately six days around a multi-ship sonar exercise) and the data were manually reviewed. It was therefore assumed that the probability of detection was 1, and that there were no false positives. However, at SOAR there is a much higher density of marine mammals, and in particular delphinids, than at the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas. Also, this analysis is conducted over long time periods (years) with automated tools, as opposed to the manual analysis carried out at AUTEC; thus, the abundance equation is modified to account for both the probability of detection and the proportion of false positives. The equation used for abundance in this analysis is:

(9) $N = \frac{n_d \, s \, (1-c)}{r_d \, T \, PD}$

where n_d is the total number of dive starts (or GVPs), s is the average group size, r_d is the dive rate (dives/unit time), T is the time period over which the measurement was made, c is the proportion of false positive detections, and PD is the probability of detection. Values used in the calculations are given in Table 3. Note that detection statistics have not yet been calculated for Cuvier's beaked whales at PMRF, so for this analysis the detection statistics for PMRF's Blainville's beaked whales were used for its Cuvier's beaked whales.

Table 3. Variables used in abundance calculations

	SOAR		***PMRF***	
Variable	***Value (CV)***	***Reference***	***Value***	***Reference***
s	3.18 (0.62)	E. Falcone, pers. comm., December 06, 2017	3.6 (*Md*) / 2.6 (*Zc*)	Baird et al. 2006
r_d	0.3 (0.17)	Schorr et al. 2014	0.42 (*Md*) / 0.40 (*Zc*)	Baird et al. 2008
C	0.185 (0.32)	Calculated	0.188 (*Md*)	Calculated
PD	0.76 (0.05)	Calculated	0.283 (*Md*)	Calculated

2.3 Results

2.3.1 SOAR

2.3.1.1 SOAR: Cuvier's beaked whale temporal distribution

2.3.1.1.1 GVP data

Cuvier's beaked whale temporal distribution was analyzed using SOAR archives from May 2010 through September 2021. After removing partial hours of effort (setting them to NA) and scaling by the number of hydrophones per hour on which data were collected, a total of 36,065 hours of data were processed, with the number of hours per year varying from a low of 1109 hours in 2010 to a high of 6172 hours in 2018 (Table 4).

Table 4. SOAR: Total number of hours of effort per year analyzed for 2010-2021.

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1109	2361	1382	1770	2946	2885	3163	3912	6172	6160	2215	3099

GVPs were calculated on an hourly basis, since this time scale is approximately the same as the deep foraging dive mean duration of 67.4 min (Schorr, et al., 2014). After accounting for effort, the average number of GVPs on any hydrophone in any hour varies from 0.01 to 0.03, and the maximum number of GVPs is of 4 in 2011 (Table 5).

Table 5. SOAR: Statistics on the number of *Zc* GVPs per hydrophone-hour effort from 2010-2021.

Year	Hours of effort	*Zc* GVPs per hydrophone per hour of effort				
		min	max	mean	median	stdev
2010	1,109	0	2	0.02	0	0.13
2011	2,361	0	4	0.02	0	0.14
2012	1,382	0	2	0.03	0	0.17
2013	1,770	0	3	0.02	0	0.15
2014	2,946	0	3	0.03	0	0.16
2015	5,985	0	3	0.01	0	0.10
2016	3,163	0	2	0.02	0	0.16
2017	3,912	0	3	0.02	0	0.13
2018	6,172	0	3	0.02	0	0.13
2019	7,214	0	3	0.02	0	0.12
2020	2,215	0	3	0.03	0	0.17
2021	3,099	0	3	0.02	0	0.14

The average number of GVPs in any hour across the whole range varies from 1.72 to 4.98, with a maximum of almost 30 GVPs per hour in 2012 (Table 6; Figure 4, left). Note that these values are not yet corrected with the detection statistics.

Table 6. Statistics on the number of *Zc* GVPs per hour effort across SOAR from 2010 to 2021.

Year	Hours of effort	Zc GVPs per hour of effort				
		min	max	mean	median	stdev
2010	1,109	0.00	22.82	3.19	2.00	3.78
2011	2,361	0.00	24.00	3.30	2.00	3.86
2012	1,382	0.00	29.67	4.98	4.00	4.69
2013	1,770	0.00	26.00	4.11	2.00	4.30
2014	2,946	0.00	26.00	4.45	4.00	3.94
2015	5,985	0.00	12.00	1.72	1.00	1.67
2016	3,163	0.00	24.78	4.44	4.00	3.69
2017	3,912	0.00	15.22	3.14	2.34	2.57
2018	6,172	0.00	15.22	2.93	2.34	2.58
2019	7,214	0.00	14.00	2.71	2.00	2.29
2020	2,215	0.00	23.42	4.81	4.68	3.57
2021	3,099	0.00	14.05	3.41	3.51	2.30

A trend analysis was conducted for Cuvier's beaked whales at SOAR and both Blainville's and Cuvier's beaked whales at PMRF by comparing the mean number of GVPs detected in three of the earlier years in the series (2011-2013 for SOAR, 2012-2014 for PMRF) with three of the later years (2018-2020 for SOAR and PMRF). Note, however, that the CS-SVM classes were updated in 2014, and any effects from the updates are not accounted for here.

In order to determine if there is a significant long-term trend in the number of Cuvier's beaked whale GVPs detected per hour of effort at SOAR, the following procedure was used:

1. Discounting the years at the ends of the series (2010, 2021), datasets of the number of GVPs per hour effort were created for the first three and last three years of the series (gvp_per_hr_eff_perc_2011_2013 and gvp_per_hr_eff_perc_2018_2020).
2. 1000 bootstrap sample means were generated for the earlier (gvp_per_hr_eff_perc_2011_2013) and later (gvp_per_hr_eff_perc_2018_2020) data series by randomly drawing samples (of 1000 data points each) with replacement from each series, and calculating the means.
3. Statistics were generated for the earlier and later bootstrap mean samples, and a Welch two sample t-test was used to determine if there was a significant difference in the means (Table 7; Figure 4, right).

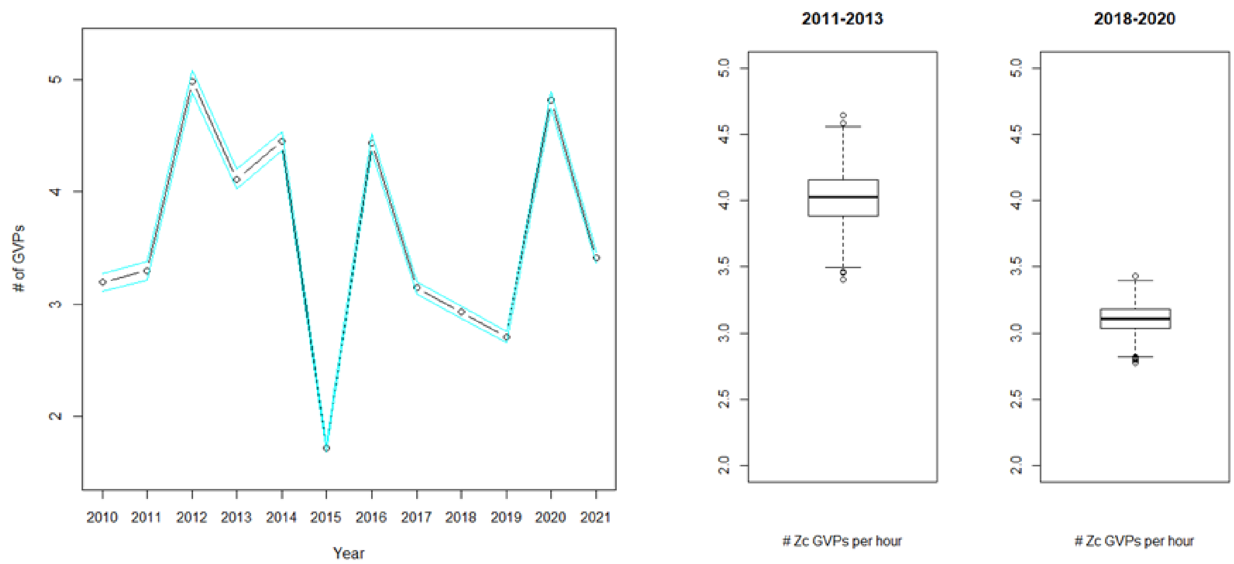

Figure 4. Mean number of *Zc* GVPs per hour of effort at SOAR.
Left: **For each year from 2010-2021; cyan lines indicate 95% confidence intervals.** ***Right:*** **Sample means from 1000 bootstrap samples for the periods 2011-2013 and 2018-2020.**

Table 7. SOAR: Statistics for *Zc* bootstrap sample mean GVPs per hour.

Series	Min	Max	Mean	Median	StdDev
2011-2013	3.41	4.64	4.02	4.03	0.21
2018-2020	2.77	3.43	3.11	3.12	0.11

The Welch two sample t-test found a significant difference ($p < 2.2e-16$) in the bootstrap sample means generated from the years 2011-2013 (μ=4.019686) and the years 2018-2020 (μ=3.108843), a drop of about 1 GVP per hour effort on range. Note, however, that the mean number of GVPs per hour effort in 2015 (μ =1.72) is lower than either of these bootstrap sample means, indicating either an outlier, or potentially that the bootstrap sample means are within the normal variation of *Zc* GVPs if a longer time series was evaluated.

2.3.1.1.2 Statistical Model

For the statistical modelling the mean number of GVPs per day after accounting for effort (per effort-day) were used. The number of GVPs per effort-day across the range between 2010 and 2021 varies from 0 to 336 (μ=89.7, median=82.6) (Figure 5, left). Figure 5, right shows the variation from year to year in the number of GVPs detected per effort-day across the SOAR range.

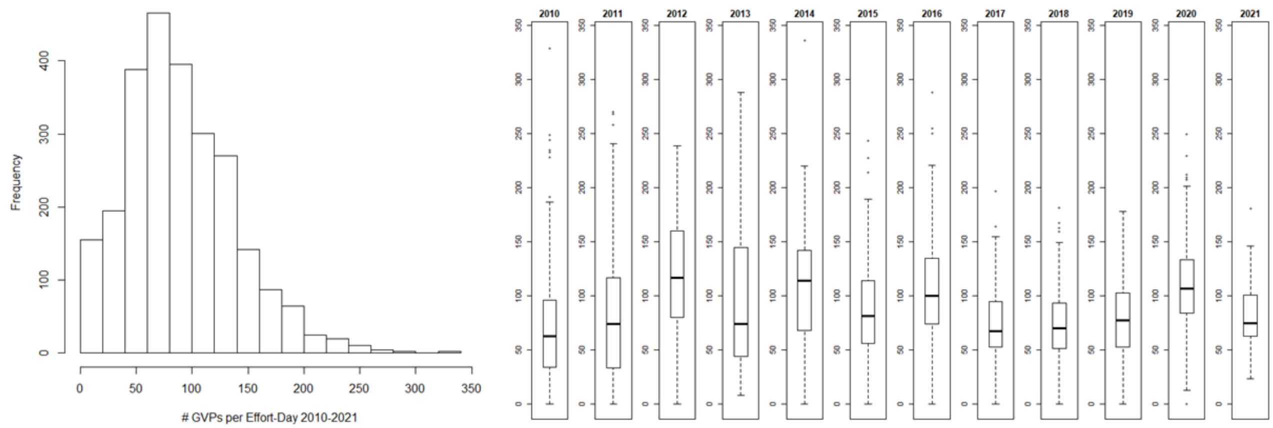

Figure 5. Number of *Zc* GVPs per day of effort on the SOAR range.
***Left:* Histogram of *Zc* GVPs for 2010 to 2021; *Right:* Boxplots for each year 2010 to 2021**

Both the JDay and Year predictors were very significant (p<2e-16) for determining the number of GVPs per day on the range (Table 8). The model had an R-squared value of 0.412 and only explained 29.7% of the deviance, indicating that other factors besides time are important in determining the number of Cuvier's beaked whale GVPs detected on range.

Table 8. Results of the gam in equation 1.

Parametric coefficients:				
	Estimate	Std Error	z value	Pr(>|z|)
(Intercept)	-3.92191	0.002914	-1346	<2e-16 ***
Approximate significance of smooth terms:				
	edf	Ref df	Chi sq	p-value
s(JDay)	8.982	9.000	8499	<2e-16 ***
s(Year)	8.966	9.000	2916	<2e-16 ***
Signif codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
R-sq (adj) = 0.412 Deviance explained = 29.7%				
UBRE = 10.623 Scale est = 1 n = 2526				

The smooths for each predictor, both without and with the residuals, are shown in Figure 6. They indicate the contribution of the predictor to the response, but are shown on the scale of the predictor, and not the response. The mean of the response is related to the linear combination of predictors through a link function. The response is represented by a Poisson distribution, and the link function is the log; so whereas the relationship between the response and predictors is nonlinear, the relationship on the link scale is linear, where the log of the mean response is equal to the linear combination of predictors (Wood, 2006; Qian, 2017; Mackenzie & Cox, 2010).

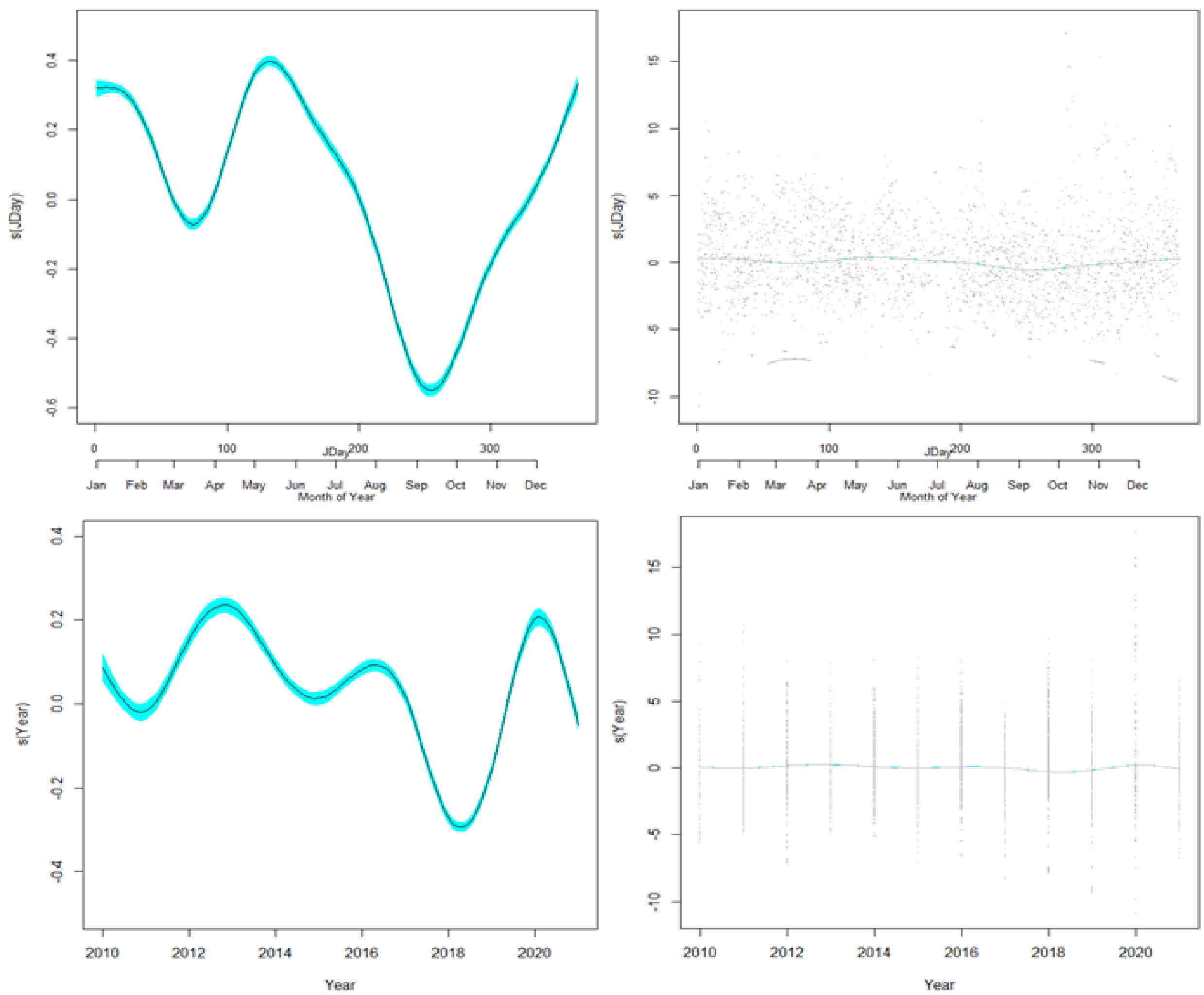

Figure 6. Smooths of the predictors for the number of Zc GVPs per day at SOAR for 2010-2021.
***Top:* Seasonal distribution – smooth of JDay on left, smooth of JDay with residuals on right; *Bottom:* Long-term trend – smooth of Year on left, smooth of Year with residuals on right**

If the other predictors are held constant at their median values, the contributions of predictors JDay and Year can be shown on the scale of the response variable, the number of GVPs per day on range (Figure 7). This gives a more intuitive view of the variation in the response both seasonally and over the twelve years.

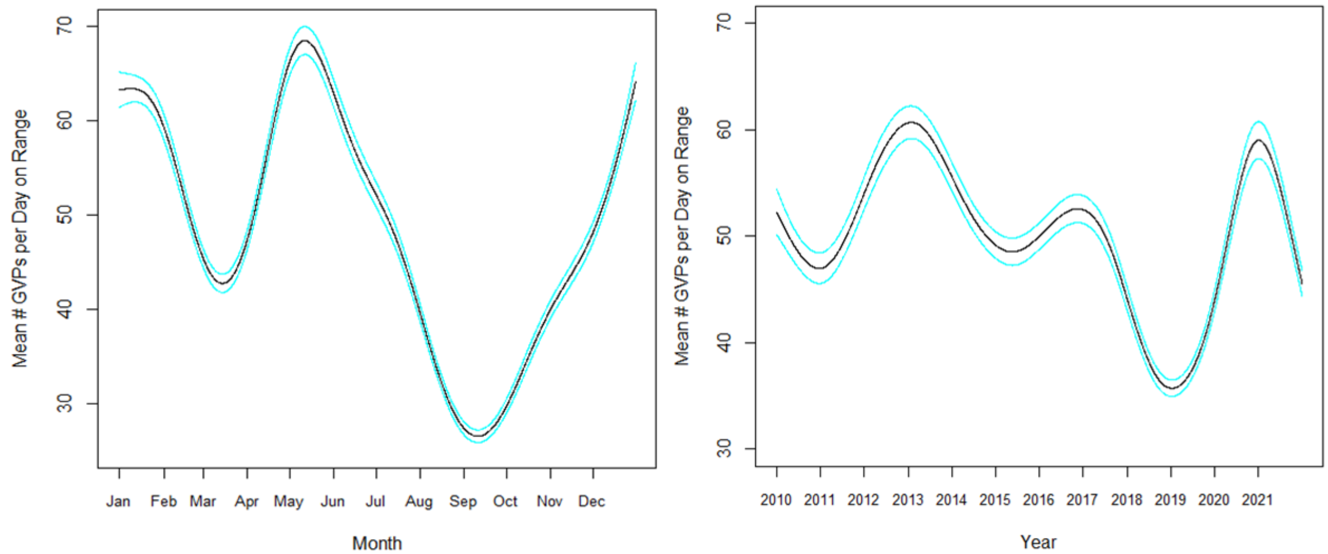

Figure 7. Contributions of the predictors (Month and Year) to the response (# GVPs per day on range) on the scale of the response when other predictors are held constant at their median values. *Left:* Month; *Right:* Year

There is a clear seasonal pattern to the Cuvier's beaked whale distribution on range, with the number of GVPs per day peaking in May and then again in December and January. The number of GVPs reach a low point in mid-September, with a smaller dip in numbers in March (Figure 7, left).

Over the past 12 years the number of GVPs per day has fluctuated, with peaks in 2013 and 2021 and a low point in 2019 (Figure 7, right). A trend analysis on the number of GVPs per hour effort was conducted earlier, in section 2.3.1.1.1.

2.3.1.2 SOAR: Cuvier's beaked whale abundance

The monthly Cuvier's beaked whale abundance was calculated using equation 9 in section 2.2.1.2. The mean monthly Cuvier's beaked whale abundance per hour for 2010 to 2021 peaks in January at 59.11 animals, followed by a peak in May of 59.08 animals. The mean abundance is lowest in September at 21.63 animals, with another smaller drop in abundance in March to 41.33 animals (Table 9; Figure 8, left). The drop in abundance in September is consistent with observations first reported from off range Navy funded passive acoustic monitoring for beaked whales [Baumann-Pickering, et al. 2014; Rice et al., 2018].

Table 9. Mean monthly Cuvier's beaked whale abundances at SOAR averaged from 2010 to 2021.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
upper CI	72.42	59.46	55.15	60.41	72.17	59.45	46.86	35.03	27.92	41.61	52.79	65.46
mean abundance	59.11	47.58	41.33	49.86	59.08	48.66	37.77	28.44	21.63	30.58	39.13	51.07
lower CI	45.80	35.70	27.52	39.31	45.98	37.87	28.68	21.84	15.34	19.54	25.48	36.68

Over the 12-year time period the mean abundance per hour in any month has varied from a high of 105 animals in May of 2013 to a low of 6 in March of 2018 (Table 10; Figure 8, right).

Table 10. Monthly SOAR Cuvier's beaked whale abundances 2010 - 2021.
NAs indicate periods without data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	NA	NA	NA	NA	NA	NA	NA	25.08	28.35	17.96	46.50	68.65
2011	80.48	43.89	45.10	68.31	75.57	NA	33.63	36.95	7.64	19.46	30.61	45.70
2012	70.86	72.12	71.82	52.33	63.22	NA	15.79	20.19	NA	42.30	29.28	19.65
2013	NA	NA	NA	NA	104.55	69.39	48.44	19.97	17.12	20.32	32.26	66.16
2014	58.81	48.18	58.10	65.87	66.78	59.33	27.05	28.64	20.42	30.79	90.96	59.89
2015	55.37	34.33	39.03	46.27	42.67	43.73	26.09	18.77	26.78	40.17	39.21	91.71
2016	81.42	59.42	47.77	61.38	52.80	52.63	48.10	33.71	25.65	NA	44.88	50.80
2017	53.52	NA	34.58	48.87	39.94	NA	31.99	30.76	22.89	21.79	26.41	49.99
2018	47.07	33.61	6.25	33.70	45.71	39.46	42.34	26.36	28.00	31.33	30.42	49.63
2019	43.33	38.96	31.07	41.53	58.98	46.06	39.54	32.65	13.86	16.95	26.43	27.47
2020	39.40	53.45	NA	48.82	NA	NA	NA	NA	NA	58.81	66.96	40.82
2021	63.58	47.57	49.77	42.64	36.17	28.99	34.54	29.38	27.30	NA	NA	NA

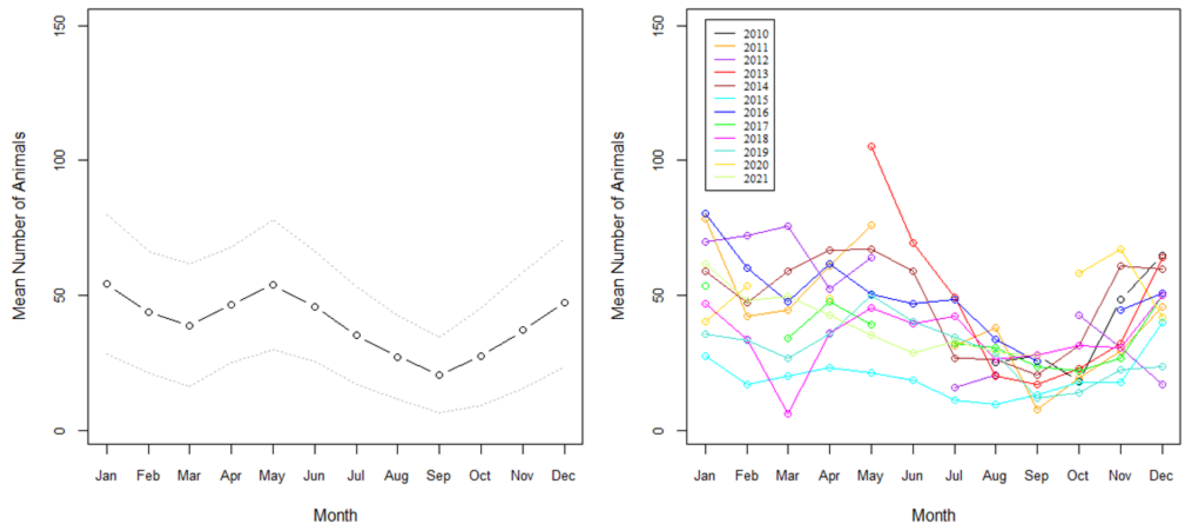

Figure 8. Mean monthly Cuvier's beaked whale abundance at SOAR.
Left: **mean of all years; dashed lines indicate 95% confidence intervals,** ***Right:*** **yearly means 2010 through 2021.**

Figure 9 indicates the mean number of *Zc* GVPs per hour of effort calculated for each year from 2011-2021. The trend in the Cuvier 's beaked whale abundance per hour at SOAR was determined in the same manner as described for Cuvier's beaked whales GVPs in section 2.3.1.1.1. Since abundance is proportional to the number of GVPs, similar trends are expected.

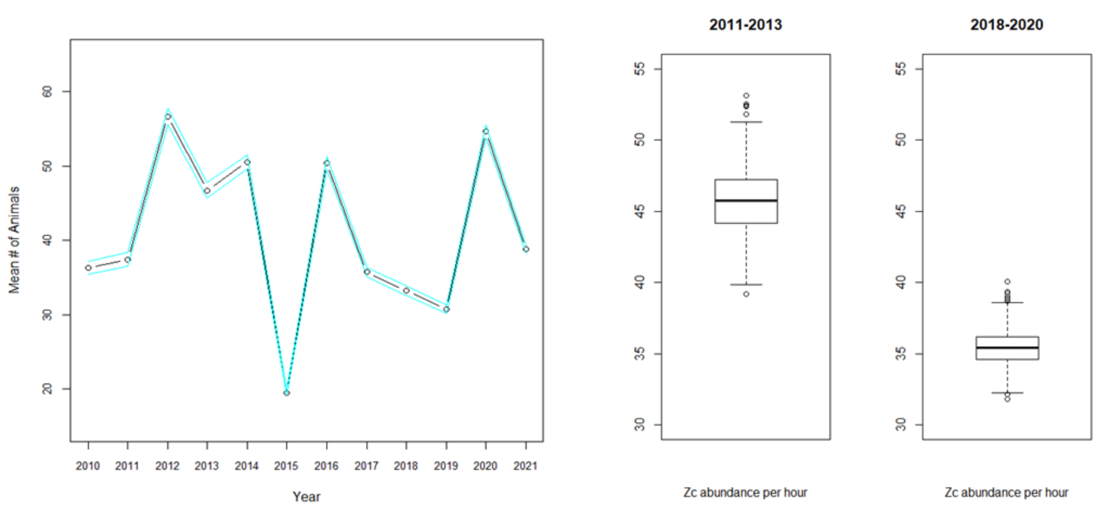

Figure 9. Mean abundance of *Zc* per hour of effort at SOAR.
Left: **For each year from 2010-2021; cyan lines indicate 95% confidence intervals.** ***Right:*** **Sample means from 1000 bootstrap samples for the periods 2011-2013 and 2018-2020.**

.

Table 11. SOAR: Statistics for *Zc* bootstrap sample mean GVPs per hour.

Series	Min	Max	Mean	Median	StdDev
2011-2013	39.22	53.14	45.75	45.75	2.25
2018-2020	31.82	40.07	35.41	35.44	1.20

The Welch two sample t-test found a significant difference ($p < 2.2e-16$) in the bootstrap sample means generated from the years 2011-2013 (μ= 45.74743) and the years 2018-2020 (μ= 35.41080), a drop of about 10 animals per hour effort on range. Note, however, that the mean number of animals per hour effort in 2015 is about 20, much lower than the sample means from either of these periods. This indicates that either this value is an outlier, or potentially that the bootstrap sample means are within the normal variation of *Zc* abundance if a longer time series was evaluated.

2.3.2 PMRF

2.3.2.1 Overview

Blainville's and Cuvier's beaked whale distribution and abundance were analyzed using PMRF CS-SVM archives from 2011 through 2021. After removing partial hours of effort and scaling by the number of hydrophones per hour on which data were collected, a total of 37,326 hours of data were processed, with the number of hours per year varying from a low of 106.4 hours in 2015 to a high of 7829 hours in 2017 (Table 12).

Table 12. PMRF: Total number of hours of effort per year of processed data.

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
266.5	3999.5	614.6	186.8	106.4	4592.8	7829.0	5650.0	4941.0	6753.3	2386.1

2.3.2.2 PMRF: Temporal Distribution

2.3.2.2.1 PMRF: Blainville's beaked whale temporal distribution

2.3.2.2.1.1 GVP Data

GVPs were calculated on the same hourly basis as was used for Cuvier's beaked whales at SOAR. After accounting for effort, the average number of GVPs on any hydrophone in any hour varies from 0.001 to 0.016 with a maximum of 3 in several years (Table 13).

Table 13. PMRF: Statistics on the number of *Md* GVPs per hydrophone-hour effort from 2011-2021.

Year	Hours of Effort	*Md* GVP per hydrophone per hour effort				
		min	max	mean	median	stdev
2011	267	0	2	0.016	0	0.13
2012	4000	0	2	0.003	0	0.05
2013	615	0	2	0.010	0	0.10
2014	187	0	2	0.011	0	0.11
2015	106	0	2	0.016	0	0.12
2016	4593	0	2	0.001	0	0.02
2017	7829	0	2	0.016	0	0.13
2018	5650	0	3	0.012	0	0.11
2019	4941	0	3	0.010	0	0.10
2020	6753	0	3	0.007	0	0.08
2021	2386	0	2	0.006	0	0.08

The average number of GVPs in any hour across the whole range varies from 0.04 to 1.33, with a maximum of 10 GVPs per hour in 2012 (Table 14; Figure 10, left). Note that these values are not yet corrected with the detection statistics.

Table 14. Statistics on the number of *Md* GVPs per hour effort at PMRF from 2011 to 2021.

Year	Hours of Effort	*Md* GVP per hour effort				
		min	max	mean	median	stdev
2011	267	0	5.25	1.33	1.05	1.20
2012	4000	0	9.46	0.21	0.00	0.66
2013	615	0	6.38	0.86	1.06	1.01
2014	187	0	4.37	0.93	1.09	0.98
2015	106	0	4.10	1.30	1.02	0.98
2016	4593	0	5.19	0.04	0.00	0.29
2017	7829	0	7.00	1.31	1.00	1.17
2018	5650	0	6.00	0.96	1.00	0.98
2019	4941	0	7.00	0.81	1.00	0.95
2020	6753	0	6.15	0.56	0.00	0.87
2021	2386	0	6.38	0.47	0.00	0.81

The trend in the number of Blainville's beaked whale GVPs per hour at PMRF was calculated in the same manner as described for Cuvier's beaked whales at SOAR in section 2.3.1.1.1, except that the period of earlier years was 2012-2014 rather than 2011-2013. Note the same caveat applies to PMRF, in that the CS-SVM classifiers were updated circa 2014, and any potential effects of the update has not yet been accounted for.

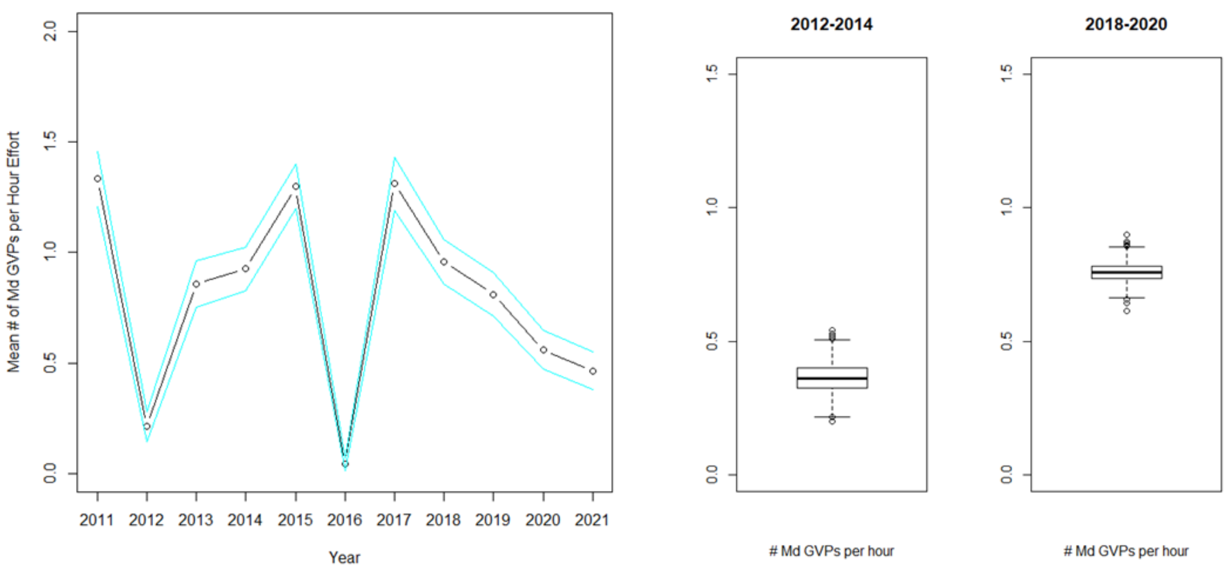

Figure 10. Mean number of *Md* GVPs per hour of effort at PMRF.
Left: **For each year from 2011-2021; cyan lines indicate 95% confidence intervals.** ***Right:*** **Sample means from 1000 bootstrap samples for the periods 2012-2014 and 2018-2020.**

Table 15. PMRF: Statistics for *Md* bootstrap sample mean GVPs per hour.

Series	Min	Max	Mean	Median	StdDev
2012-2014	0.20	0.54	0.37	0.36	0.54
2018-2020	0.61	0.9	0.76	0.76	0.37

The Welch two sample t-test found a significant difference (p < 2.2e-16) in the bootstrap sample means generated from the years 2012-2014 (μ= 0.3647587) and the years 2018-2020 (μ= 0.7581507), a gain of about twice the number of *Md* GVPs detected per hour on range. Note that the detection statistics have not yet been applied to the number of *Md* GVPs at PMRF.

2.3.2.2.1.1 Statistical Model

For the statistical modelling the mean number of GVPs per day after accounting for effort (per effort-day) were used. The number of *Md* GVPs per effort-day across the PMRF range between 2011 and 2021 varies from 0 to 65 (μ=17.2, median=17) (Figure 11, left). Figure 11, right shows the variation from year to year in the number of *Md* GVPs detected per effort-day across the PMRF range.

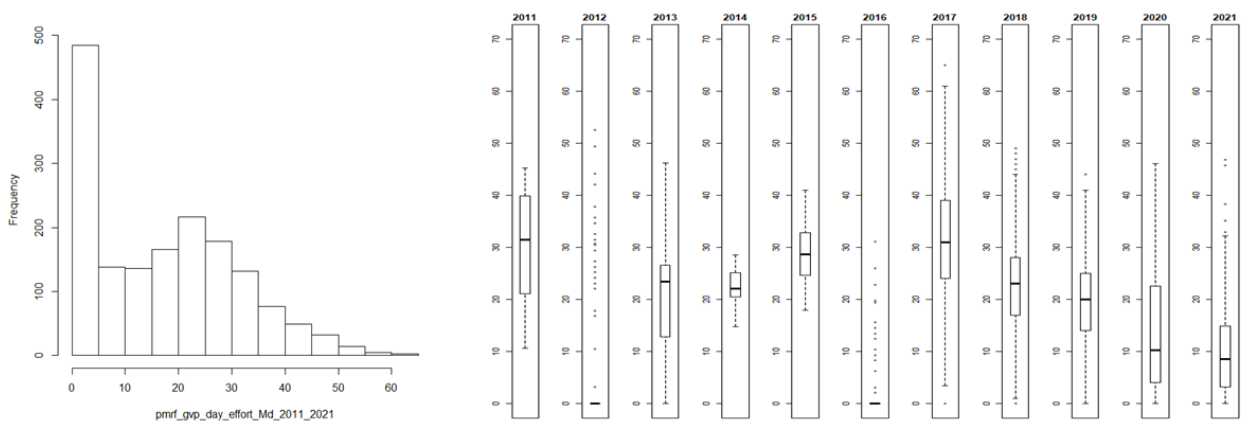

Figure 11. Number of *Md* GVPs per day of effort on the PMRF range.
Left: **Histogram of *Md* GVPs for 2011 to 2021;** ***Right:*** **Boxplots for each year 2011 to 2021**

Both the Julian day (JDay) and Year predictors were very significant ($p<2e^{-16}$) for determining the number of GVPs per day on the range (Table 16). The model had an R-squared value of 0.552 and explained 49% of the deviance, indicating that other factors besides time are important in determining the number of Blainville's beaked whale GVPs detected on range. The smooths for each predictor are shown in Figure 12.

Table 16. Results of the PMRF *Md* GAM in equation 2.

Parametric coefficients:				
	Estimate	Std Error	z value	Pr(>|z|)
(Intercept)	-5.06145	0.009298	544.4	<2e-16 ***
Approximate significance of smooth terms:				
	edf	Ref df	Chi sq	p-value
s(JDay)	8.926	8.998	778.1	<2e-16 ***
s(Year)	8.989	9.000	6939.3	<2e-16 ***
Signif codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
R-sq (adj) = 0.552 Deviance explained = 49%				
UBRE = 6.2074 Scale est = 1 n = 1629				

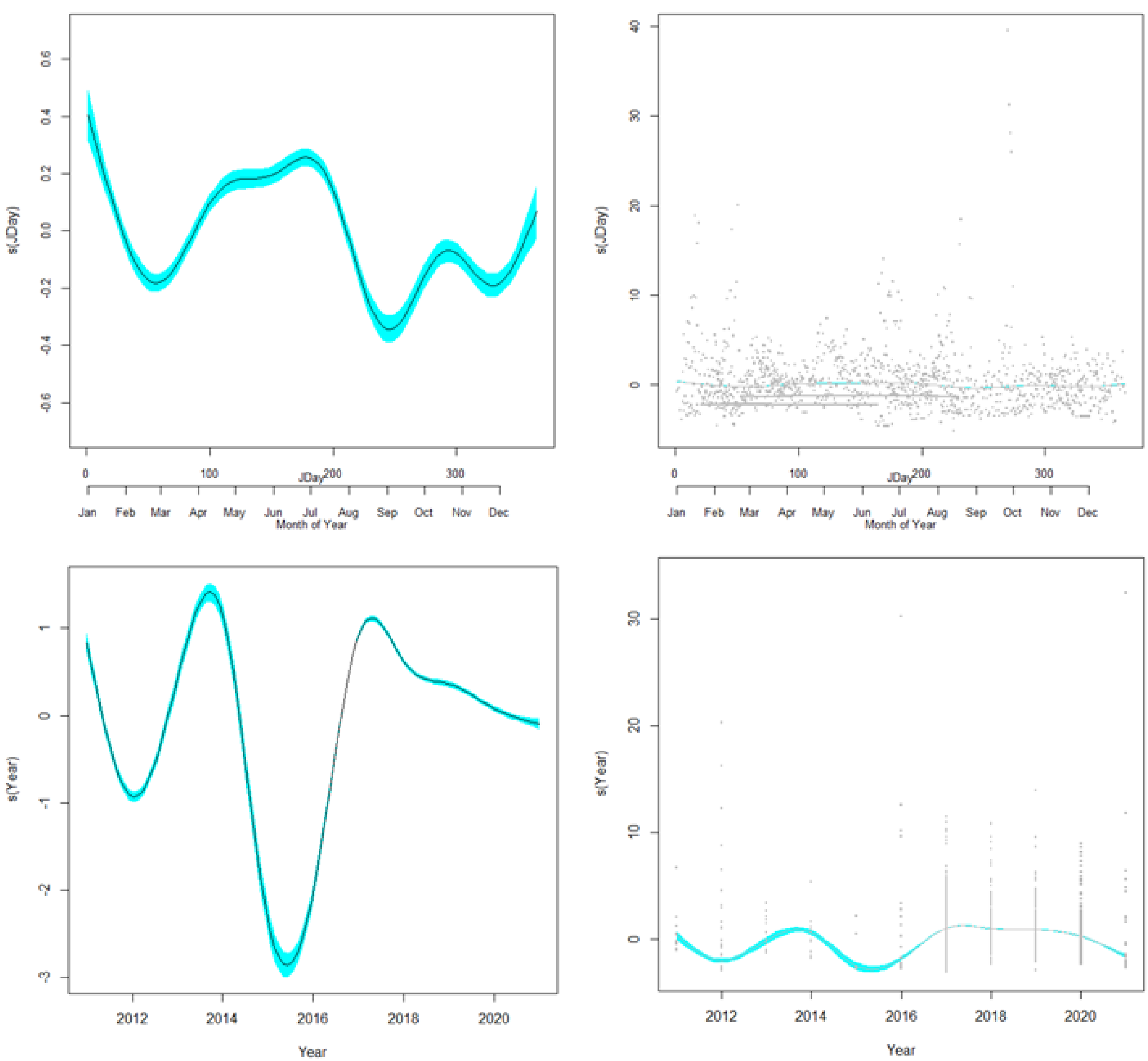

Figure 12. Smooths of the predictors for the number of *Md* GVPs per day at PMRF.

***Top:* Seasonal distribution – smooth of JDay on left, smooth of JDay with residuals on right; *Bottom:* Long-term trend – smooth of Year on left, smooth of Year with residuals on right**

Figure 13 shows the contributions of predictors JDay and Year to the response on the scale of the response variable, the number of GVPs per day on range, if the other predictors are held constant at their median values.

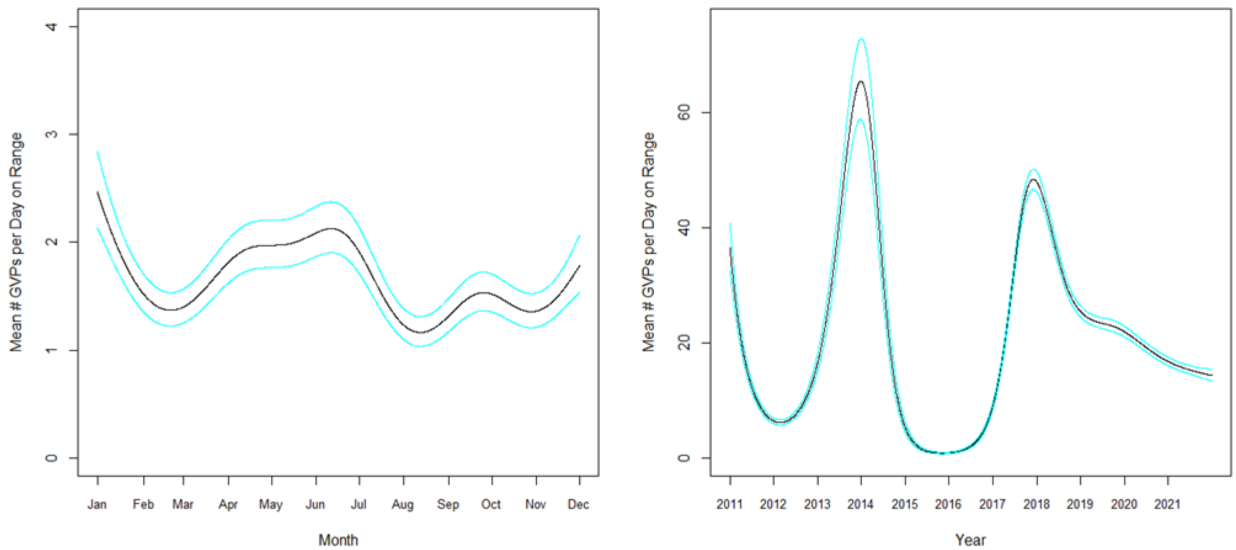

Figure 13. PMRF: Contributions of the predictors (Month and Year) to the *Md* response (# GVPs per day on range) on the scale of the response when other predictors are held constant at their median values. *Left:* Month; *Right:* Year.

The seasonal distribution of Blainville's beaked whales peaks in January and May through July, while it is lowest in September, with another dip in March (Figure 12, top; Figure 13, left).

The long-term trend appears to have fluctuated, with highs around 2014 and 2017, and a low point in 2015-2016, and a less pronounced drop around 2012 (Figure 12, bottom; Figure 13, right). A trend analysis on the number of *Md* GVPs per hour effort was conducted earlier, in section 2.3.2.2.1.1.

2.3.2.2.2 PMRF: Cuvier's beaked whale temporal distribution

2.3.2.2.2.1 GVP Data

GVPs were calculated on the same hourly basis as was used for Cuvier's beaked whales at SOAR. After accounting for effort, the average number of GVPs on any hydrophone in any hour varies from 0.0003 to 0.005 with a maximum of 3 in several years (Table 17).

Table 17. PMRF: Statistics on the number of *Zc* GVPs per hydrophone-hour effort from 2011-2021.

Year	Hours of Effort	*Zc* GVP per hydrophone per hour effort				
		min	max	mean	median	stdev
2011	267	0	1	0.001	0	0.03
2012	4000	0	2	0.000	0	0.02
2013	615	0	2	0.001	0	0.03
2014	187	0	2	0.005	0	0.07
2015	106	0	1	0.000	0	0.02
2016	4593	0	2	0.000	0	0.02
2017	7829	0	3	0.004	0	0.06
2018	5650	0	3	0.004	0	0.07
2019	4941	0	3	0.004	0	0.06
2020	6753	0	3	0.002	0	0.04
2021	2386	0	3	0.000	0	0.02

The average number of GVPs in any hour across the whole range varies from 0.02 to 0.43, with a maximum of 9 GVPs per hour in 2018 (Table 18; Figure 14, left). Note that these values are not yet corrected with the detection statistics.

Table 18. PMRF: Statistics on the number of Zc GVPs per hour of effort from 2011-2021.

Year	Hours of Effort	*Zc* GVP per hour effort				
		min	max	mean	median	stdev
2011	267	0	3.15	0.09	0	0.34
2012	4000	0	3.15	0.02	0	0.18
2013	615	0	2.13	0.06	0	0.27
2014	187	0	4.37	0.43	0	0.83
2015	106	0	1.02	0.03	0	0.17
2016	4593	0	4.15	0.02	0	0.21
2017	7829	0	7.00	0.30	0	0.70
2018	5650	0	9.00	0.35	0	0.75
2019	4941	0	7.00	0.32	0	0.67
2020	6753	0	5.12	0.14	0	0.45
2021	2386	0	3.19	0.04	0	0.24

A trend analysis was conducted for the number of Cuvier's beaked whale GVPs detected per hour at PMRF in the same manner as it was conducted for Blainville's beaked whales, comparing the bootstrap means from 2012-2014 with those from 2018-2020 (Table 19; Figure 14, right).

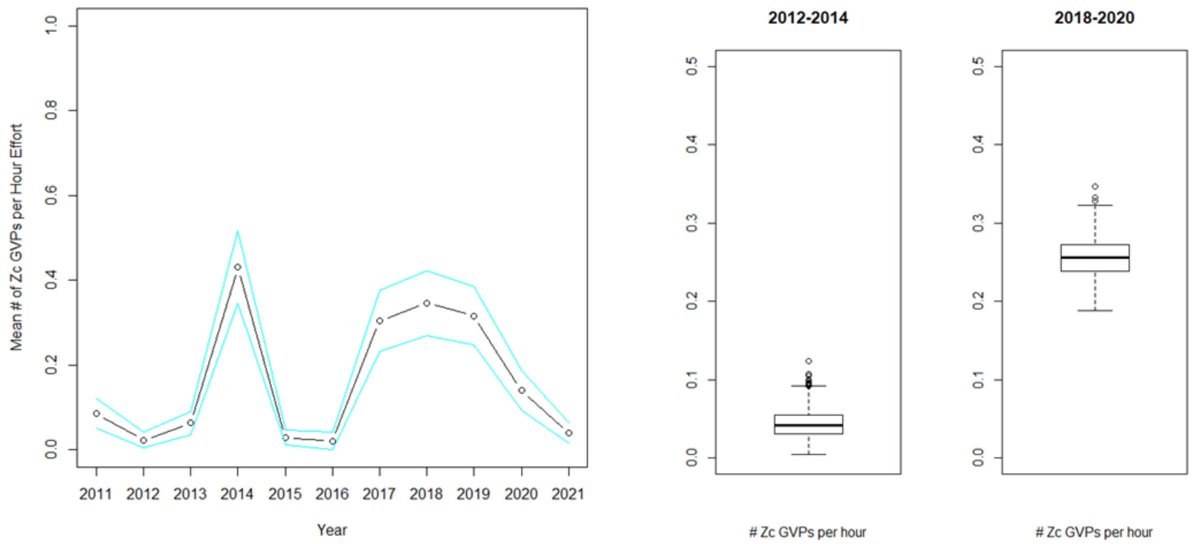

Figure 14. Mean number of *Zc* GVPs per hour of effort at PMRF.
Left: **For each year from 2011-2021; cyan lines indicate 95% confidence intervals. *Right:* Sample means from 1000 bootstrap samples for the periods 2012-2014 and 2018-2020.**

Table 19. PMRF: Statistics for *Zc* bootstrap sample mean GVPs per hour.

Series	Min	Max	Mean	Median	StdDev
2012-2014	0.01	0.12	0.04	0.04	0.02
2018-2020	0.19	0.35	0.26	0.26	0.24

The Welch two sample t-test found a significant difference (p < 2.2e-16) in the bootstrap sample means generated from the years 2012-2014 (μ= 0.04382924) and the years 2018-2020 (μ= 0.25543712), a six-fold increase in the number of *Zc* GVPs detected per hour detected on range. Note, however, that Cuvier's beaked whale detection statistics have not yet been calculated or applied, and are likely to impact these results.

2.3.2.2.2.1 Statistical Model

For the statistical modelling the mean number of GVPs per day after accounting for effort (per effort-day) were used. The number of *Zc* GVPs per effort-day across the PMRF range between 2011 and 2021 varies from 0 to 56 (μ=4.63, median=2) (Figure 15, left). Figure 16, right shows the variation from year to year in the number of *Zc* GVPs detected per effort-day across the PMRF range.

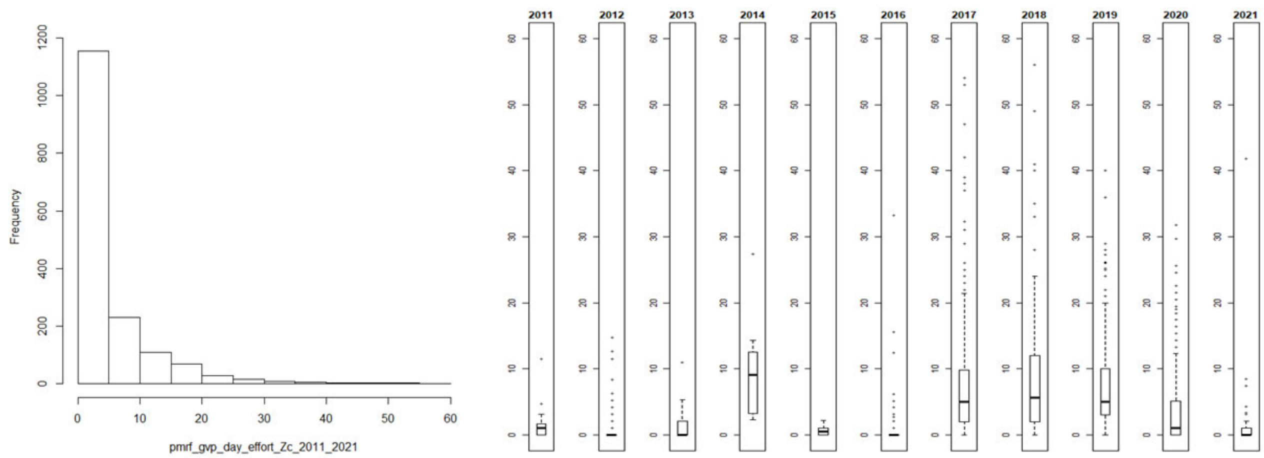

Figure 15. Number of *Zc* GVPs per day of effort on the PMRF range.
***Left:* Histogram of *Zc* GVPs for 2011 to 2021; *Right:* Boxplots for each year 2011 to 2021**

Both the Julian day (JDay) and Year were very significant ($p<2e^{-16}$) for predicting the number of Cuvier's beaked whale GVPs per day on the PMRF range from 2011 to 2021 (Table 20). The model had an R-squared value of 0.424 and explained 50.8% of the deviance, indicating that other factors besides time are important in determining the number of Cuvier's beaked whale GVPs detected on range. Figure 16 shows the smooths for cyclic JDay and Year.

Table 20. Results of the PMRF *Zc* gam in equation 3.

Parametric coefficients:				
	Estimate	Std Error	z value	Pr(>|z|)
(Intercept)	-5.5733	0.02153	-309.9	<2e-16 ***
Approximate significance of smooth terms:				
	edf	Ref df	Chi sq	p-value
s(JDay)	8.576	8.944	2222	<2e-16 ***
s(Year)	8.969	8.999	2455	<2e-16 ***
Signif codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
R-sq (adj) = 0.424 Deviance explained = 50.8%				
UBRE = 2.9235 Scale est = 1 n = 1629				

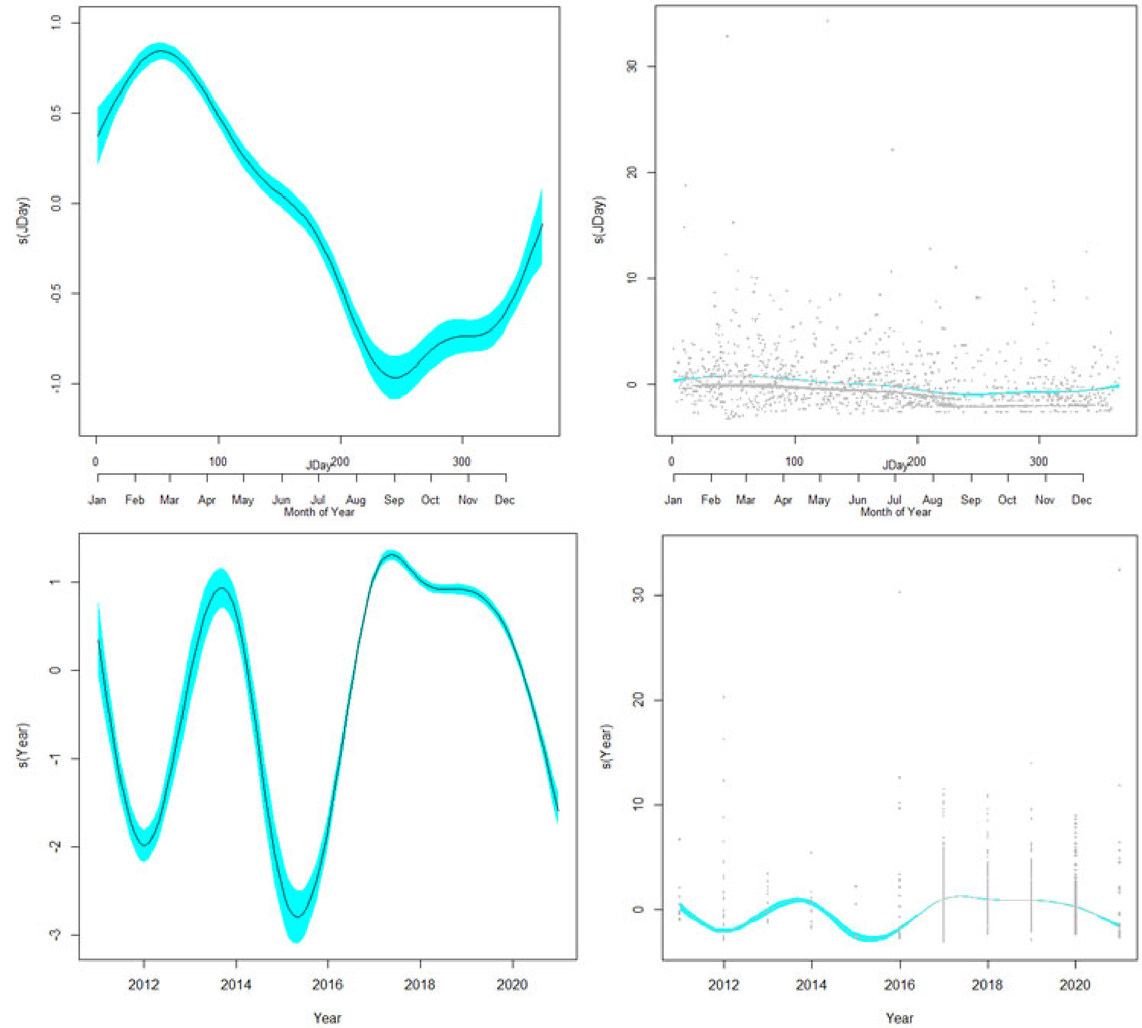

Figure 16. Smooths of the predictors for the number of *Zc* GVPs per day at PMRF.
***Top:* Seasonal distribution – smooth of JDay on left, smooth of JDay with residuals on right; *Bottom:* Long-term trend – smooth of Year on left, smooth of Year with residuals on right.**

Figure 17 shows the contributions of predictors JDay and Year on the scale of the response variable, the number of GVPs per day on range, if the other predictors are held constant at their median values.

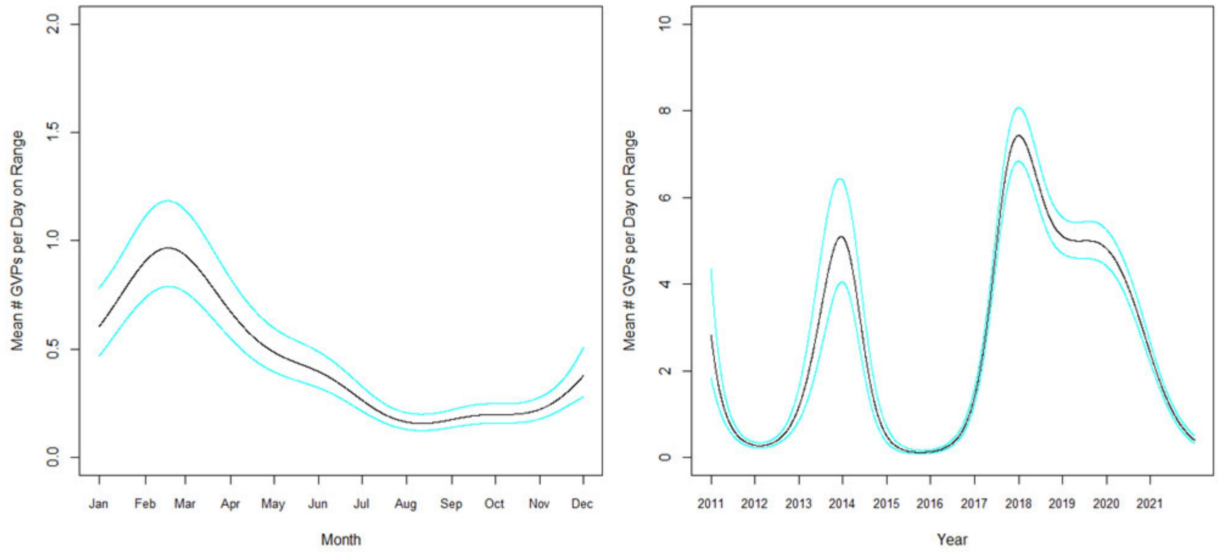

Figure 17. PMRF: Contributions of the predictors (Month and Year) to the *Zc* response (# GVPs per day on range) on the scale of the response when other predictors are held constant at their median values. *Left:* Month; *Right:* Year.

The number of Cuvier's beaked whale GVPs peak in March, during one of the low points for Blainville's beaked whales, and then the numbers of Cuvier's GVPs drop through to September, when they are lowest. They then start to increase until reaching the March peak. Though both species reach peaks at different times, their numbers are both lowest in September (Figure 16, top; Figure 17, left).

The number of Cuvier's beaked whale GVPs detected on PMRF has fluctuated from 2011 to 2021, with the numbers highest about 2014 and 2017-2018, and lowest in 2015, followed by 2012 (Figure 16, bottom; Figure 17, right). A trend analysis on the number of *Zc* GVPs per hour effort was conducted earlier, in section 2.3.2.2.2.1.

2.3.2.3 PMRF: Abundance

2.3.2.3.1 PMRF: Blainville's beaked whale abundance

The monthly Blainville's beaked whale abundance was calculated using equation 9 in section 2.2.1.2. The mean hourly abundance for any month, averaged from 2011 to 2021, peaks at 38 animals in May and is lowest in November at 23 animals (Table 21; Figure 18, left).

Table 21. Mean monthly Blainville's beaked whale abundances at PMRF averaged from 2011-2021.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
upper CI	36.41	33.55	31.63	35.05	44.80	48.99	37.57	34.31	34.33	37.67	31.84	38.78
mean abundance	25.99	24.78	24.11	25.56	37.73	35.25	25.19	24.31	24.33	29.36	23.29	29.65
lower CI	15.57	16.01	16.59	16.08	30.67	21.52	12.82	14.32	14.34	21.04	14.74	20.51

Over the eleven-year time period the mean hourly abundance in any month was highest at 57 animals in June of 2017, and lowest at 1.5 in August, 2011 (Table 22; Figure 18, right).

Table 22. Monthly PMRF Blainville's beaked whale abundances 2011 - 2021.
NAs indicate periods without data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	NA	NA	NA	NA	NA	2.46	2.79	1.54	NA	NA	NA	NA
2012	53.73	NA	NA	NA	NA	56.69	53.50	NA	NA	NA	NA	NA
2013	NA	50.45	NA	NA	NA	NA	50.61	33.44	NA	NA	NA	NA
2014	0.00	41.45	18.89	NA	40.25	39.05	34.45	38.03	NA	43.21	NA	NA
2015	NA	17.02	17.49	14.62	NA	NA	NA	NA	22.59	0.00	NA	NA
2016	NA	21.38	NA	NA	NA	NA	NA	10.51	NA	NA	NA	NA
2017	NA	28.24	37.69	41.65	43.79	56.88	48.44	31.96	34.76	39.66	34.91	43.67
2018	26.78	23.74	32.00	27.53	46.70	26.46	23.42	29.18	38.74	29.41	32.82	NA
2019	13.35	22.98	21.52	31.97	33.09	9.18	4.40	NA	NA	NA	11.11	21.72
2020	24.86	14.52	15.20	13.25	36.80	29.03	7.32	11.37	10.14	15.36	15.50	14.35
2021	13.40	16.26	23.26	20.64	24.86	NA	1.71	3.00	NA	NA	NA	NA

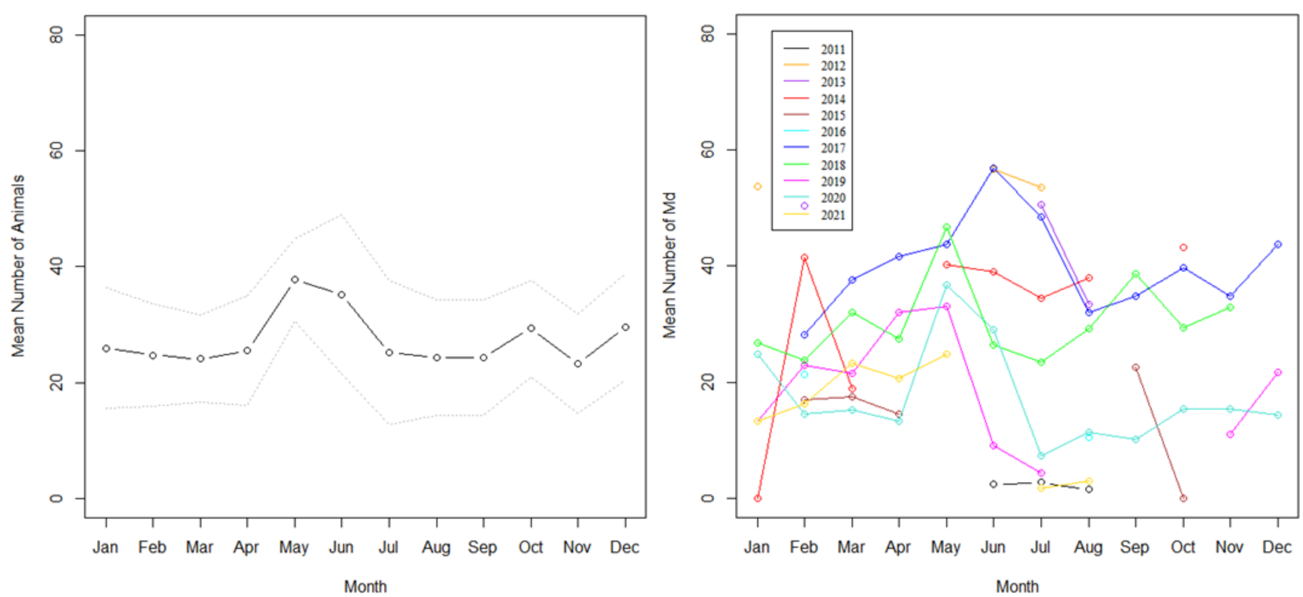

Figure 18. Mean monthly Blainville's beaked whale abundance at PMRF.
Left: **mean of all years; dashed lines indicate 95% confidence intervals,** ***Right:*** **yearly means 2011 through 2021.**

The trend in the Blainville's 's beaked whale abundance per hour at PMRF was calculated in the same manner as described for Blainville's beaked whales GVPs in section 2.3.2.2.2.1 (Table 23; Figure 19, right). Since abundance is proportional to the number of GVPs, similar trends are expected.

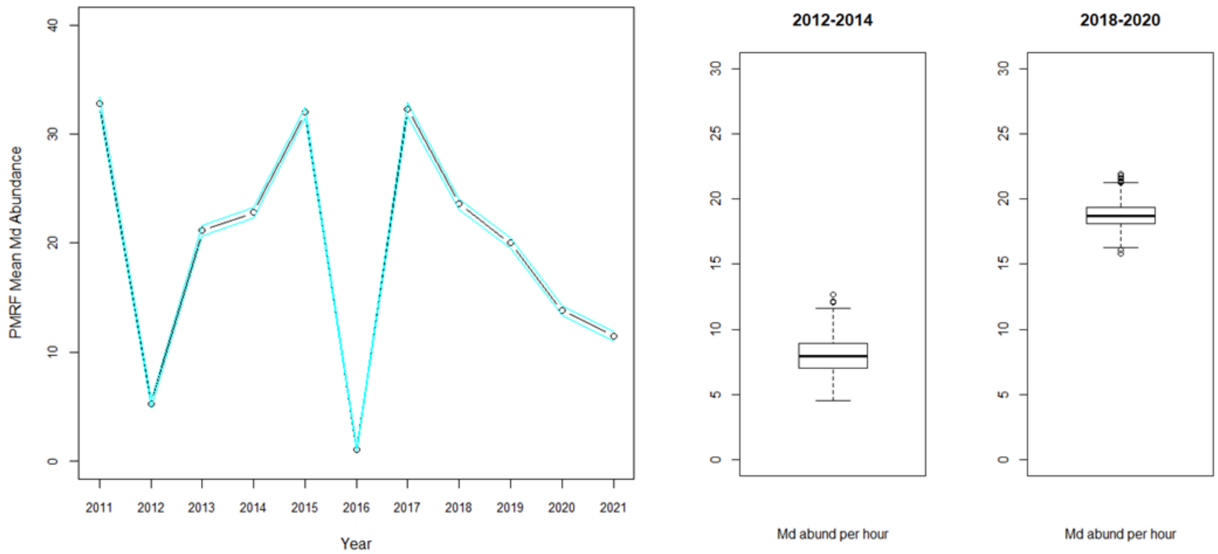

Figure 19. Mean abundance of *Md* per hour of effort at PMRF.
Left: **For each year from 2011-2021; cyan lines indicate 95% confidence intervals.** ***Right:*** **Sample means from 1000 bootstrap samples for the periods 2012-2014 and 2018-2020.**

Table 23. PMRF: Statistics for *Md* bootstrap sample mean abundance per hour.

Series	Min	Max	Mean	Median	StdDev
2012-2014	4.54	12.69	8.01	7.98	1.38
2018-2020	15.79	21.92	18.75	18.72	0.91

The Welch two sample t-test found a significant difference (p < 2.2e-16) in the bootstrap sample means generated from the years 2012-2014 (μ= 8.013756) and the years 2018-2020 (μ= 18.745090), an increase in abundance by a factor of about two.

2.3.2.3.2 PMRF: Cuvier's beaked whale abundance

The monthly Cuvier's beaked whale abundance was calculated using equation 9 in section 2.2.1.2. The mean hourly abundance for any month, averaged from 2011 to 2021, peaks in February at 16 animals and is lowest in September at 4 animals (Table 24; Figure 20, left).

Table 24. Mean monthly Cuvier's beaked whale abundances at PMRF averaged from 2011 to 2021.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
upper CI	19.02	23.93	17.48	17.05	15.74	19.37	14.40	11.59	6.62	10.37	6.42	8.45
mean abundance	10.62	15.50	11.34	10.69	11.12	12.56	9.11	6.75	3.86	5.94	4.14	5.48
lower CI	2.22	7.07	5.20	4.33	6.50	5.74	3.82	1.90	1.10	1.52	1.87	2.52

Over the eleven-year time period the mean hourly abundance in any month was highest at 37 in February, 2014 (Table 25; Figure 20, right) and lowest at 0 in January, 2014.

Table 25. Monthly PMRF Cuvier's beaked whale abundances 2011 - 2021.
NAs indicate periods without data.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	NA	NA	NA	NA	NA	25.23	12.45	16.35	NA	NA	NA	NA
2012	35.91	NA	NA	NA	NA	28.07	26.95	NA	NA	NA	NA	NA
2013	NA	32.12	NA	NA	NA	NA	25.92	19.92	NA	NA	NA	NA
2014	0.00	36.83	21.44	NA	23.83	20.92	17.58	11.95	NA	19.79	NA	NA
2015	NA	12.16	6.61	6.82	NA	NA	NA	NA	4.47	1.70	NA	NA
2016	NA	9.06	NA	NA	NA	NA	NA	2.71	NA	NA	NA	NA
2017	NA	12.56	17.58	13.37	9.09	9.42	7.37	4.95	6.35	4.84	5.62	7.80
2018	11.68	19.78	14.37	10.21	13.77	5.75	4.47	4.25	3.40	6.18	4.65	NA
2019	5.45	15.25	14.37	10.80	9.37	6.65	6.23	NA	NA	NA	5.36	5.22
2020	5.82	5.48	6.61	4.98	8.49	6.05	1.05	0.35	1.01	2.00	1.06	1.38
2021	1.81	2.67	3.65	16.19	27.75	NA	4.93	4.47	NA	NA	NA	NA

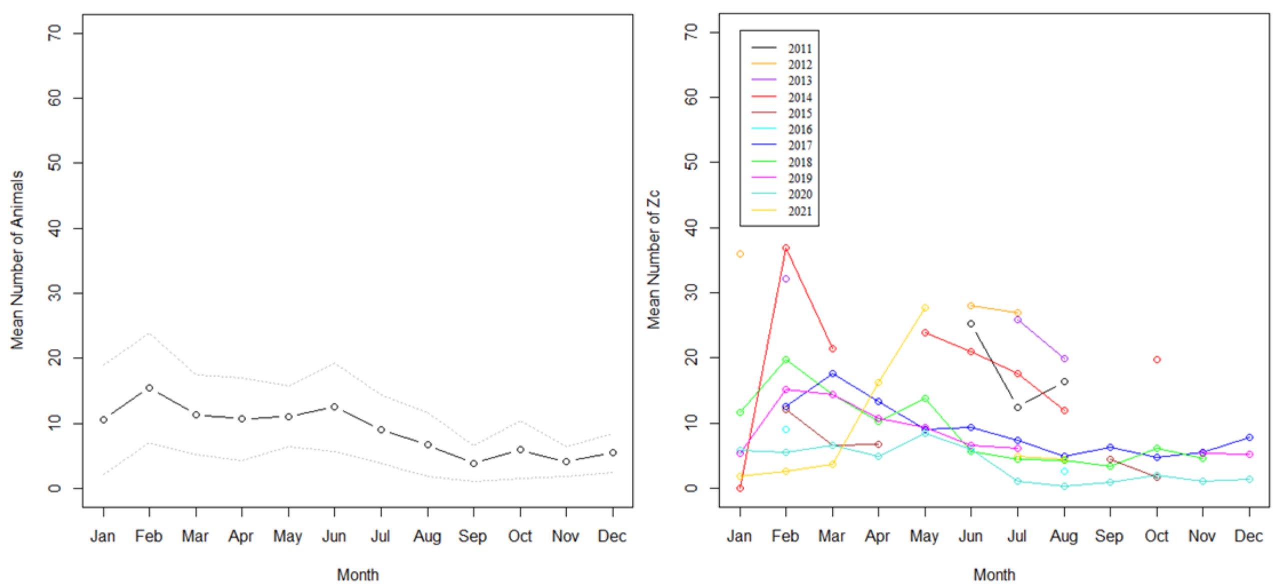

Figure 20. Mean monthly Cuvier's beaked whale abundance at PMRF.
***Left:* averaged between 2011 and 2021, *Right:* for the years 2011 through 2021. Dashed lines indicate 95% confidence intervals.**

The trend in the Cuvier's 's beaked whale abundance per hour at PMRF was calculated in the same manner as described for Cuvier's beaked whales GVPs in section 2.3.2.2.2.1 (Table 26; Figure 21, right). Since abundance is proportional to the number of GVPs, similar trends are expected.

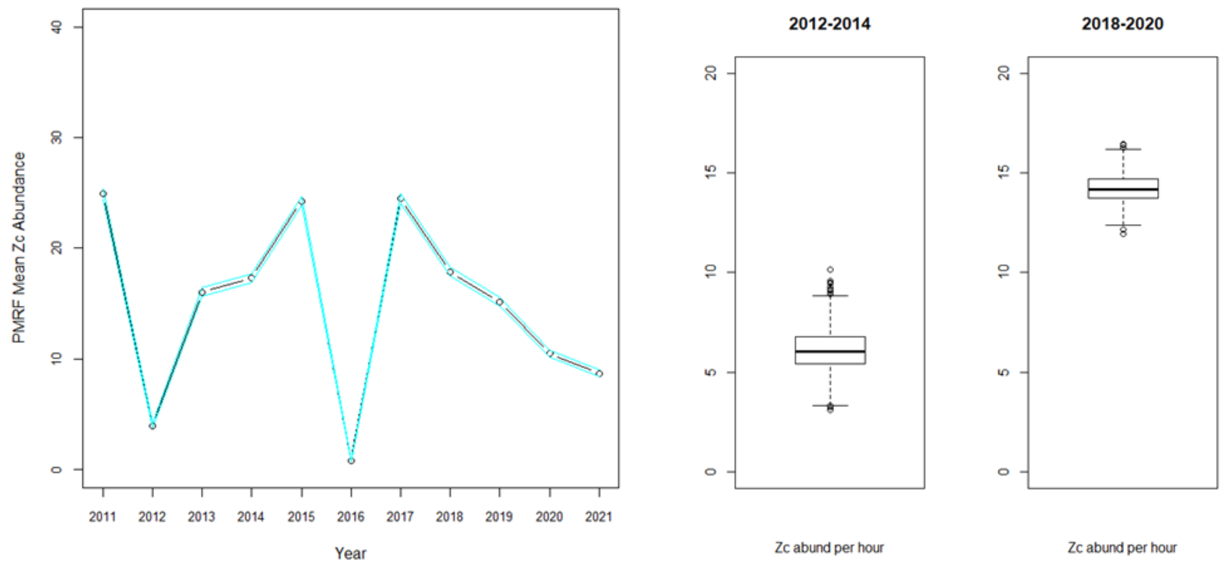

Figure 21. Mean abundance of *Zc* per hour of effort at PMRF.
Left: **For each year from 2011-2021; cyan lines indicate 95% confidence intervals.** ***Right:*** **Sample means from 1000 bootstrap samples for the periods 2012-2014 and 2018-2020.**

Table 26. PMRF: Statistics for *Zc* sample mean abundance per hour.

Series	Min	Max	Mean	Median	StdDev
2012-2014	3.10	10.14	6.10	6.10	1.05
2018-2020	11.93	16.43	14.22	14.19	0.70

The Welch two sample t-test found a significant difference ($p < 2.2e-16$) in the bootstrap sample means generated from the years 2012-2014 (μ= 6.099042) and the years 2018-2020 (μ= 14.216011), a two-fold increase in the Cuvier's beaked whale abundance detected per hour detected on range. Note, however, that Cuvier's beaked whale detection statistics have not yet been calculated or applied, and are likely to impact these results. These results are from applying the detection statistics for Blainville's beaked whales at PMRF, which potentially result in overestimates of the number of Cuvier's beaked whales present.

2.4 Discussion

2.4.1 SOAR

Cuvier's beaked whales exhibit a seasonal pattern on the SOAR range, with the numbers of GVPs detected and abundance peaking in May, and in the December/January timeframe. The numbers are lowest in September, with a second, less pronounced dip in March. The peak in the beginning of the year coincides with a period in which there are typically no sonar exercises on range; thus, it would provide an opportunity for undisturbed foraging. Acoustic detections of Cuvier's beaked whale clicks on High Frequency Recording Packages (HARPs) located in Southern California (SOCAL) have shown a similar low point in September (Baumann-Pickering et al. 2014). From November 2018 to May 2020 data on four HARPS near SOAR, two west of SOAR (E and H) and two south of SOAR (N and U) show many more Cuvier's beaked whale detection on the western HARPS E and H than on sites N and U. Site H, located just to the west of SOAR, has Cuvier's beaked whale peaks in August 2019 and February to May 2020, while site E peaks in December 2019 (Rice, et al., 2021). These peaks overlap to some extent with the peaks on SOAR. For the time period July 2018 to May 2019 peaks on the HARP at site H was highest in spring, 2019 and at site E highest in late fall, 2018, while both were lowest in late summer/early fall (Rice, et al., 2020). The high point at site H in spring and low points in late summer/early fall coincide with our results on SOAR. Note, however, that the results presented for SOAR are averaged over the years 2010 to 2021, while the HARP data results are presented for the given years.

The mean number of Cuvier's beaked whale GVPs per hour has varied from 1.72 to 4.98 between 2010 and 2021, while the mean abundance per hour on range in any month, averaged from 2010 to 2011, is between 22 and 41 animals. The Autogrouper detection statistics have not yet been applied to the GVPs, though the correction factor is 1.074, and so will increase the number of GVPs somewhat. The detection statistics are incorporated into the abundance formula, however, and the abundance is proportional to the number of GVPs. As the SOAR range is about 1700 km^2, the average number of animals per 1000 km^2 varies from about 12 to 24, which is higher than the mean density of 5.12 animals/1000 km^2 found with drifting buoys by Barlow, et al. 2021, supporting the notion that SOAR is an important foraging area for Cuvier's beaked whales (Falcone, et al., 2009). The Barlow results were over a much larger area off the U.S. West Coast, with all the drifting buoy deployments to the north and west of SOAR (Barlow, et al. 2021).

A trend analysis shows that the mean number of Cuvier's beaked whale GVPs detected on range per hour has dropped between the years of 2011-2013 and 2018-2020 from 4 to 3 GVPs, and the mean abundance per hour on range has dropped from 46 to 35 animals. However, in 2015, between these two periods, the mean number of GVPs on range was 1.7 while the mean number of animals was 20, both of which are lower than the estimates during these time periods. This would indicate either that 2015 had an unusually low number of animals, or possibly that the trend seen here could be within normal fluctuations if viewed over a longer time period. Curtis, et al., found an annual rate of change of -0.8% for Cuvier's beaked whales on SOAR, but also conducted simulations that indicated that additional years of data would be needed to reliably detect a trend. So, whereas their results indicated that abundance is either stable or slowly decreasing, they also point out that those results are not conclusive (Curtis, et al, 2020). There are several things to consider with our results, as well. The CS-SVM classes were updated in 2014, and the effects of those updates have not yet been quantified or accounted for. Prior to the updates the classifier included Blainville's and Cuvier's beaked whale foraging click classes, sperm whale clicks, and several dolphin species. After updating in 2014, classes were added for Blainville's and Cuvier's beaked whale buzzes, the Blainville's class was removed from SOAR, the classifier better differentiated Cuvier's and Blainville's, and the dolphin classes were collapsed into a 'generalized dolphin' class. Since clicks could be misclassified (for instance, Cuvier's clicks misclassified as Blainville's, or dolphin detections impacting groupings), quantifying the effects of these changes is important for an accurate trend analysis. For the abundance calculations, an average group size is used, and the Autogrouper detection statistics were drawn from data from 2010 to 2015, so updating these statistics and including actual groups sizes could improve the estimates.

2.4.2 PMRF

2.4.2.1 Blainville's beaked whales

The seasonal distribution of Blainville's beaked whales at PMRF appears to peak in May through July, and in the December/January timeframe, while it is lowest in September, with another dip in March. Henderson, et al. (2016) and Martin, et al. (2020, 2021) also examined the number of Blainville's beaked whale dives per hour on the PMRF range. Since Henderson, Martin, and our analysis all consider the number of beaked whale dives that start within an hour, the number of dives per hour reported by Henderson and Martin is equivalent to the number of GVPs per hour that we report. Henderson examined three years (2011 to 2013) of data from 31 hydrophones and found seasonal variation that did not have a clear pattern, but may indicate increased activity in spring and late summer. Part of this pattern coincides with the higher numbers we see in May through July. Martin, et al. (2020, 2021) however, found no clear seasonal pattern.

Our results show a mean number of Blainville's GVPs per hour from 2011-2021 varying between 0.04 in 2016 to 1.33 in 2011, with a maximum of 10 in 2012. In the years 2011, 2012 and 2013 we calculate mean GVPs per hour of 1.33, 0.21, and 0.86, respectively, which average to a mean of 0.74 GVPs per hour. This is somewhat lower than what Henderson reported for these years, an average of 1.3 GVPs per hour of effort (1.3 to 3.3 GVPs per hour) across the 31 hydrophones. However, our GVP results have not yet been corrected by the Autogrouper detection statistics for Blainville's beaked whales at PMRF, a correction factor of 2.34. After correcting, our mean GVP/hour for 2011-2013 is 1.7, closer to the 1.3 GVPs per hour reported by Henderson. Note also that Henderson's results were on 31 hydrophones, whereas ours were on 83, which included those 31. In more recent work on PMRF, Martin, et al. (2020, 2021) recorded 62 hydrophones at PMRF, and used a random subset of four recordings in each year to manually validate the detections. These 62 hydrophones are a subset of the 83 hydrophones used in this analysis. Martin found the overall rate of Blainville's beaked whale GVPs per hour from August 2018 to August 2019 was 2.33, with a range from 1.38 to 2.62; while the overall rate for September 2019 to September 2020 was 1.79, with a range from 0.52 to 4.44. Our mean rates were 0.81 in 2019 and 0.56 in 2020, which, after correcting are 1.9 in 2019 and 1.31 in 2020, which are in line with those found by Martin. Martin et al. (2020) also reported an overall maximum of 10.53 GVPs/hour in August of 2019. Our maximum in 2019 is 7 GVPs/hour, which is 16.38 after correcting with the detection statistics. The number is higher, but in the same vicinity, and our data incorporated more hydrophones. The Blainville's beaked whale mean abundance per hour, averaged across 2011 to 2021, varies from 23 animals in November to 38 in May and from about 1 animal in 2016 to 33 in 2011.

The long-term trend appears to have fluctuated, with highs around 2014 and 2017, and a low point in 2015-2016, and a less pronounced drop around 2012. A trend analysis on both the number of Blainville's beaked whale GVPs per hour and abundance per hour shows an increase between the time periods of 2012-2014 and 2018-2020 from 0.09 to 0.61 GVPs per hour (corrected) and 8.01 to 18.75 animals per hour. The same caveat applies here as for SOAR, in that the CS-SVM classes were updated in 2014, and any effects of the changes have not yet been quantified; therefore, they could impact the trend. In addition, the Autogrouper detection statistics for Blainville's beaked whales are based on 17 samples, and the sample size should be increased for more accurate results.

2.4.2.2 Cuvier's beaked whales

The seasonal distribution of Cuvier's beaked whales peaks in March, during one of the low points for Blainville's beaked whales, and then drops through to September, when they are lowest. They then start to increase until reaching the March peak. Though both species reach peaks at different times, their numbers are both lowest in September.

The mean number of Cuvier's beaked whale GVPs per hour detected on PMRF varies from 0.02 in 2016 to 0.43 in 2014, with a maximum of 9 in 2018. Note that these numbers are not corrected with Autogrouper detection statistics, as the statistics have not yet been calculated for this species at PMRF. In 2019 there was a mean GVP/hour rate of 0.32 and a maximum of 7, while the mean and maximum in 2020 were 0.14 and 5.12, respectively. Martin, et al. (2020, 2021) found an overall rate of Cuvier's beaked whale GVPs per hour from August 2018 to August 2019 was 0.09, with a range from 1.38 to 2.62; while the overall rate for September 2019 to September 2020 was 0.08, with a range from 0.0 to 0.19. In both reports the maximum number of GVPs per hour that Martin found was two. The numbers we found are higher, but I would caution that they have not yet been corrected with detection statistics. A priority for future work would be deriving these detection statistics to get more accurate results.

The number of Cuvier's beaked whale GVPs detected on PMRF has fluctuated from 2011 to 2021, with the numbers highest about 2014 and 2017-2018, and lowest in 2015, followed by 2012. Similar fluctuations occur in the Cuvier's beaked whale abundance. A trend analysis on the Cuvier's beaked whale mean GVPs/hour and mean abundance between the years of 2012-2014 and 2018-2020 shows both increasing: from 0.04 to 0.26 GVPs per hour, and from 6 to 14 animals on range per hour. However, similar caveats apply to the evaluation of the trend, in that the effects of the change in CS-SVM classes should be quantified, and Autogrouper detection statistics need to be derived and applied to the GVPs. The detection statistics for Blainville's beaked whales at PMRF were used in the abundance equation for Cuvier's beaked whales, and may have overestimated their numbers based on a cursory review of the data. Both studies found Blainville's and Cuvier's beaked whale present on the range year-round, with higher numbers of Blainville's beaked whale GVPs detected than Cuvier's beaked whale GVPs.

2.4.3 Summary

The distribution and abundance of Cuvier's beaked whales have been evaluated on SOAR from 2010-2021, and for Blainville's and Cuvier's beaked whales at PMRF from 2011-2021. The main recommendations for improvements are as follows:

1. Generate and apply Autogrouper detection statistics for Cuvier's beaked whales at PMRF, and increase the sample size for Blainville's beaked whale Autogrouper detection statistics at PMRF.
2. Include samples from more recent years in the Autogrouper detection statistics at SOAR.
3. Quantify the impact of the changes in CS-SVM classes circa 2014 on the beaked whale detections.

A direct comparison of the number of GVPs detected at PMRF by M3R and NIWC on the same subset of hydrophones may also be illustrative.

Despite these limitations, the long-term data collected by M3R on SOAR and PMRF remain an incredibly valuable resource for examining the distribution, abundance and trends of beaked whales and other species on the ranges.

3 Accuracy Analysis of M3R Low-frequency Localizations at SOAR

3.1 Introduction

3.1.1 Summary

The purpose of the project was to conduct a first assessment of the accuracy of localizations of low-frequency (LF) calls automatically generated by the Marine Mammal Monitoring on Navy Ranges (M3R) system installed at the So-Cal ASW Range (SOAR). This was done by comparing LF localizations extracted from M3R archive files to fin whale detections and localizations generated by researchers at NIWC, San Diego through their post-processing of whole range acoustic recordings (M3R packet recorder data) for select days.

3.1.2 Background

M3R's current LF detection and localization capability was developed under the AIST Marine Mammal Effects of Test and Evaluation on Ocean Ranges (METEOR). The low frequency spectrogram detector was incorporated into M3R's real-time processing stream in 2014-2015 and automated LF localization was added near the end of 2016. M3R localizes animals using multilateration, which requires determining the difference in time of arrival (TDOA) of a given signal at widely spaced sensors whose positions are precisely known. For odontocete species like beaked whales, sperm whales, and dolphins, M3R associates click trains, as received on neighboring hydrophones, to determine TDOAs. However, for dolphin whistles, M3R uses spectrogram cross correlation among neighboring hydrophones to determine the TDOA. M3R LF localization borrows from the whistle localization and performs cross correlation of hard-limited spectrograms produced by M3R's LF FFT detector. Specifically, it cross correlates 10 second long spectrograms of frequencies <600 Hz. The time delay associated with the correlation peak is the TDOA between that pair of hydrophones. All posits generated are sent to M3R displays and saved to the central archive file. During tagging exercises on SOAR, M3R's LF localization routine has been successfully used to acoustically localize baleen calls and direct on-water partners Marine Ecology and Telemetry Research (MarEcoTel) to fin whales, gray whales, humpback whales, and blue whales. While we have anecdotal evidence of accuracy of M3R LF position points (posits - usually good enough to get a boat within visual spotting range) systematic review of the quality and quantity LF localization is limited. In FY 2020 we conducted the very first systematic review of M3R LF localizations. In that study, all posits were extracted from M3R archives over eight 24-hour periods spread throughout the year. We sought to verify that the LF posits generated were, in fact, localization of baleen calls vice anthropogenic sources. In the data examined we identified numerous posits resulting from calls from fin whales, gray whales, and humpback whales and few from man-made sources.

3.2 Methods

This study was an initial assessment of the accuracy of M3R automatically generated LF posits through direct comparison with the fin whale detections and localizations generated through post-processing of raw acoustic recordings of the broadband hydrophones that comprise SOAR. NIWC processed M3R packet recorder recordings from 2-6 January 2019. Over these days the only activity on-range was a side scan bathymetric survey and the NIWC analysis generated numerous high-quality fin whale tracks. Figure 22 shows the NIWC fin tracks containing 20 or more posits from 4-5 January 2019.

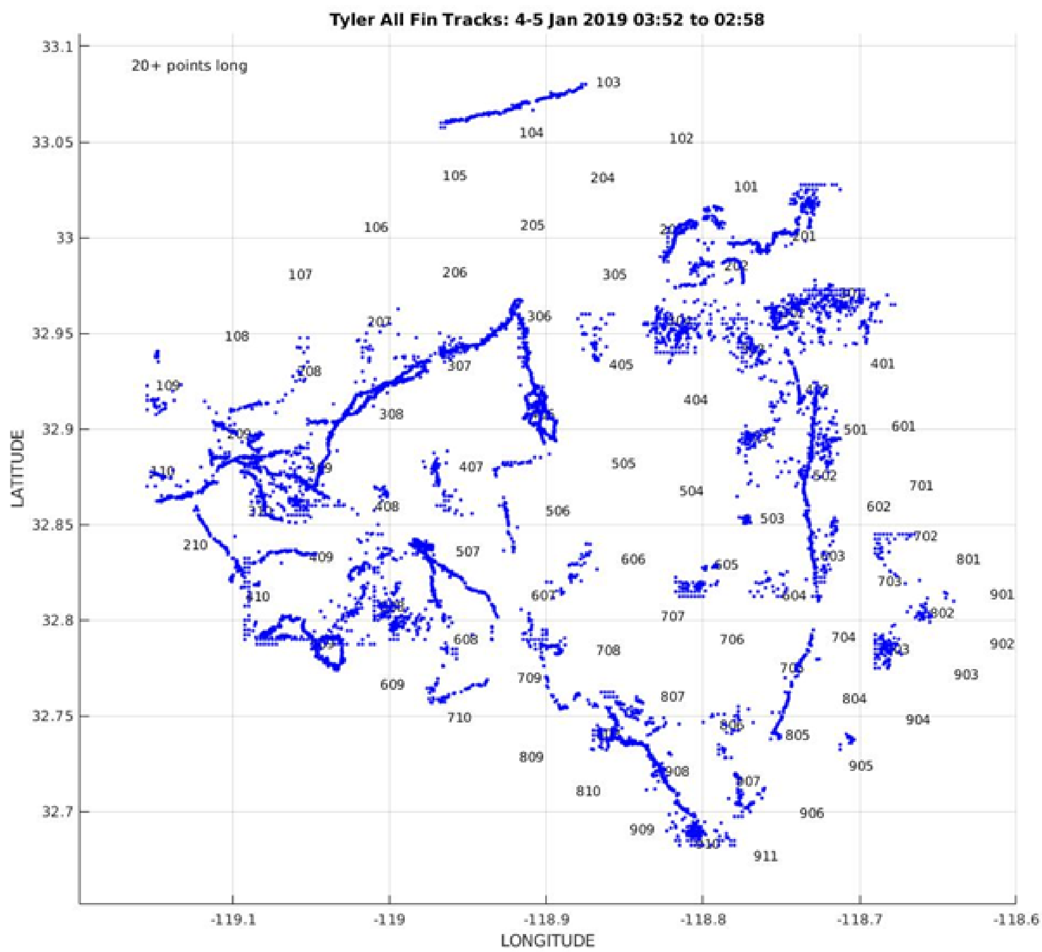

Figure 22. NIWC fin whale tracks containing 20 or more posits from 4-5 Jan 2019.
These tracks were generated by post-processing raw acoustic data recorded from SOAR hydrophones.

3.3 Results

Overlaying M3R LF posits and the NIWC results was initially disappointing (Figure 23). While there were a few spots where M3R and NIWC results agreed well, there seemed to be poor or non-existent agreement elsewhere. NIWC processing had produced orders of magnitude more posits than M3R for the same 24-hr period. Some discrepancy could be attributed to differences in the quality of the signal detectors used. NIWC's shallow neural net likely has better detection performance than M3R's hard-limited energy detector. Other differences might be attributed to a difference in the localization technique, i.e. model-based minimum mean square error fit (NIWC) versus direct path multilateration. However, neither of these would account for the entirety of the problem. M3R was not localizing large numbers of LF calls. Spot checks of M3R LF spectrograms during the times of NIWC track showed that fin whale calls were clearly visible. The calls could even be localized using the manual localization tools in the M3R spectrogram display software, Jacknife, yet there were no corresponding automated posits in the M3R archives. It was as if the LF call association process was not running. This observation led to a working theory.

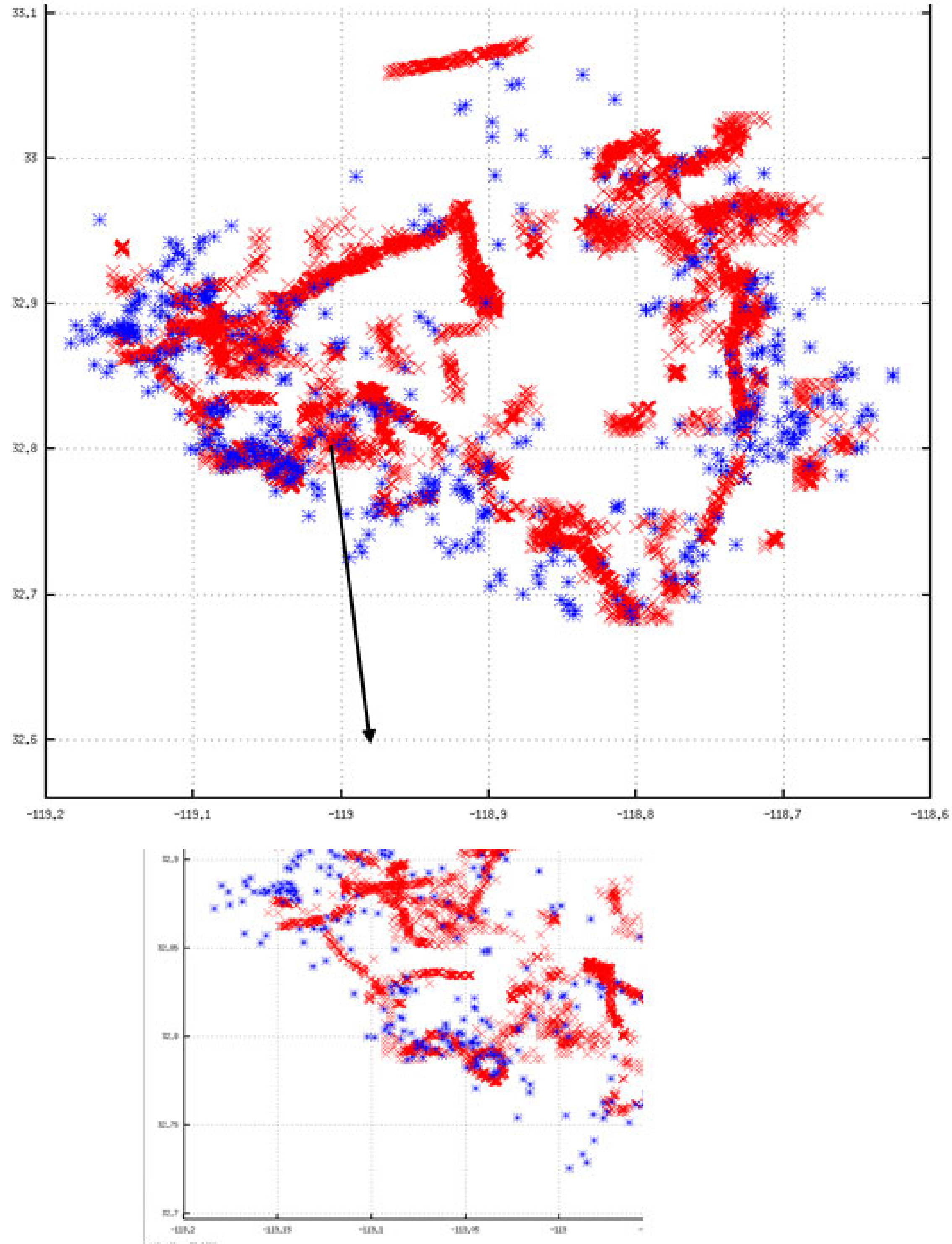

Figure 23. Overlay of posits extracted from M3R archives (blue) and NIWC fin tracks (red) from 4-5 Jan 2019. Agreement between the tracks is disappointing.

During field work at SOAR, M3R operators have regularly observed (on the M3R system health display) a heavy processing load on the computers that perform association of detections among hydrophones to find the TDOA – the Associator nodes. However, M3R generated more than 900,000 raw posits for 5 marine mammal call types during the 24-hrs study period. With that many posits continually being generated and displayed, it is impossible to determine just by looking whether some detections were missing. Furthermore, the amount of dolphin click activity increases dramatically at night (600,000+ posits were from dolphin clicks), leading to the possibility that associator nodes that are heavily loaded during the day are being overwhelmed by dolphin activity at night and are no longer able to keep up in real-time. Figure 24 shows a histogram of the M3R archived LF posits from 4-5 Jan 2019 versus time of day. Note that 2/3 of these posits occurred during local daylight hours.

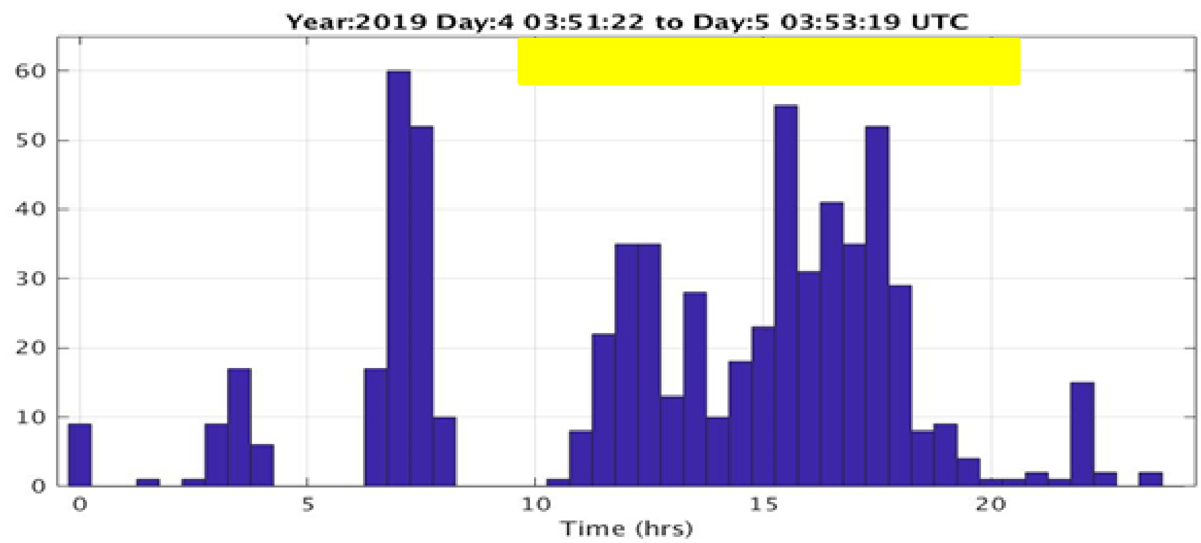

Figure 24. Histogram of LF posits extracted from M3R archives from 4-5 Jan 2019. Most of the posits archived are from local daytime (yellow bar).

The LF spectrogram data from M3R archive files from 4-5 Jan 2019 were reprocessed through the LF call associator and localization code, and the results were stored in a new series of archive files. No association of any other call type was performed, and no loading of computer nodes was observed. The LF posits were then extracted from the new archives (a total of 153 one GB files). The reprocessed data contained over 59000 raw LF localizations, which were filtered to exclude bogus posits (Figure 25). A simple swim-speed rule (assumed 10 kph swim speed) was used to join neighboring posits into tracks. These tracks compare much more favorably with the NIWC fin tracks (Figure 25).

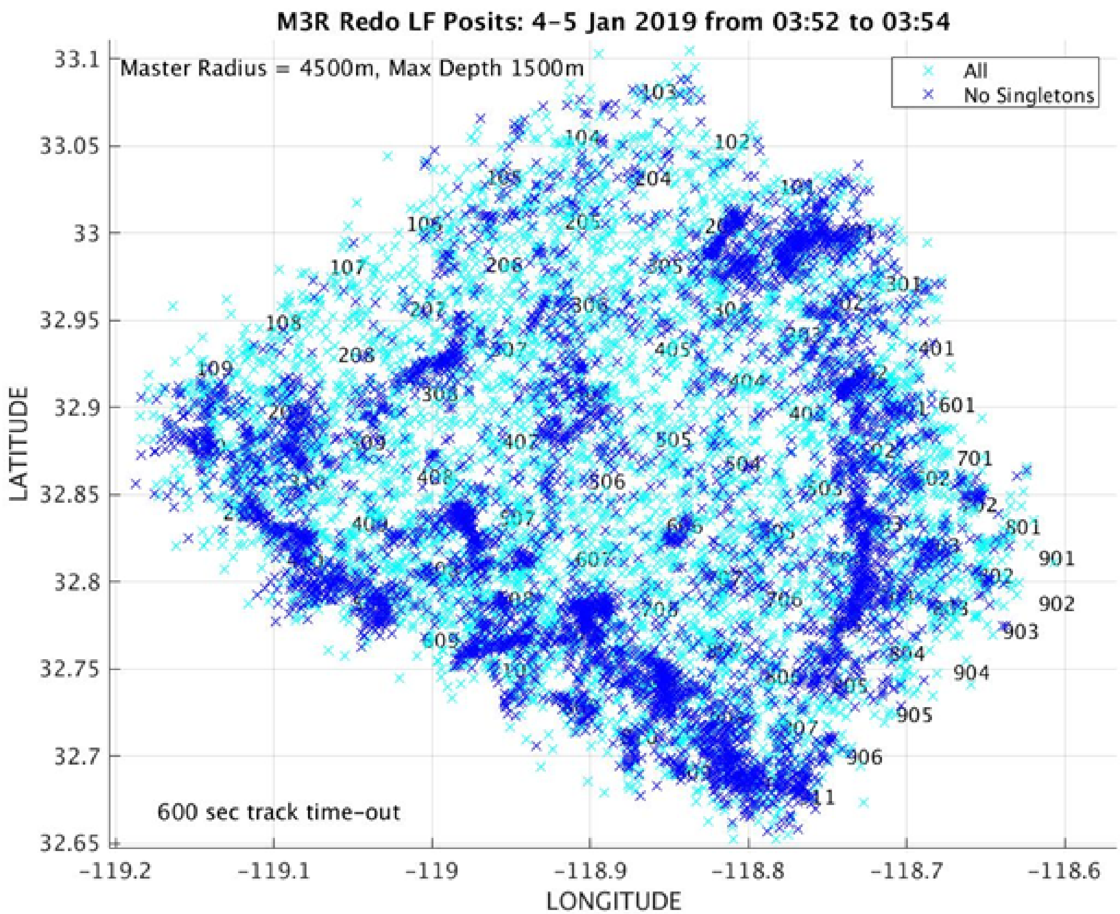

Figure 25. Reprocessed M3R LF posits. All posits (cyan) and posits with at least one neighbor (dark blue).

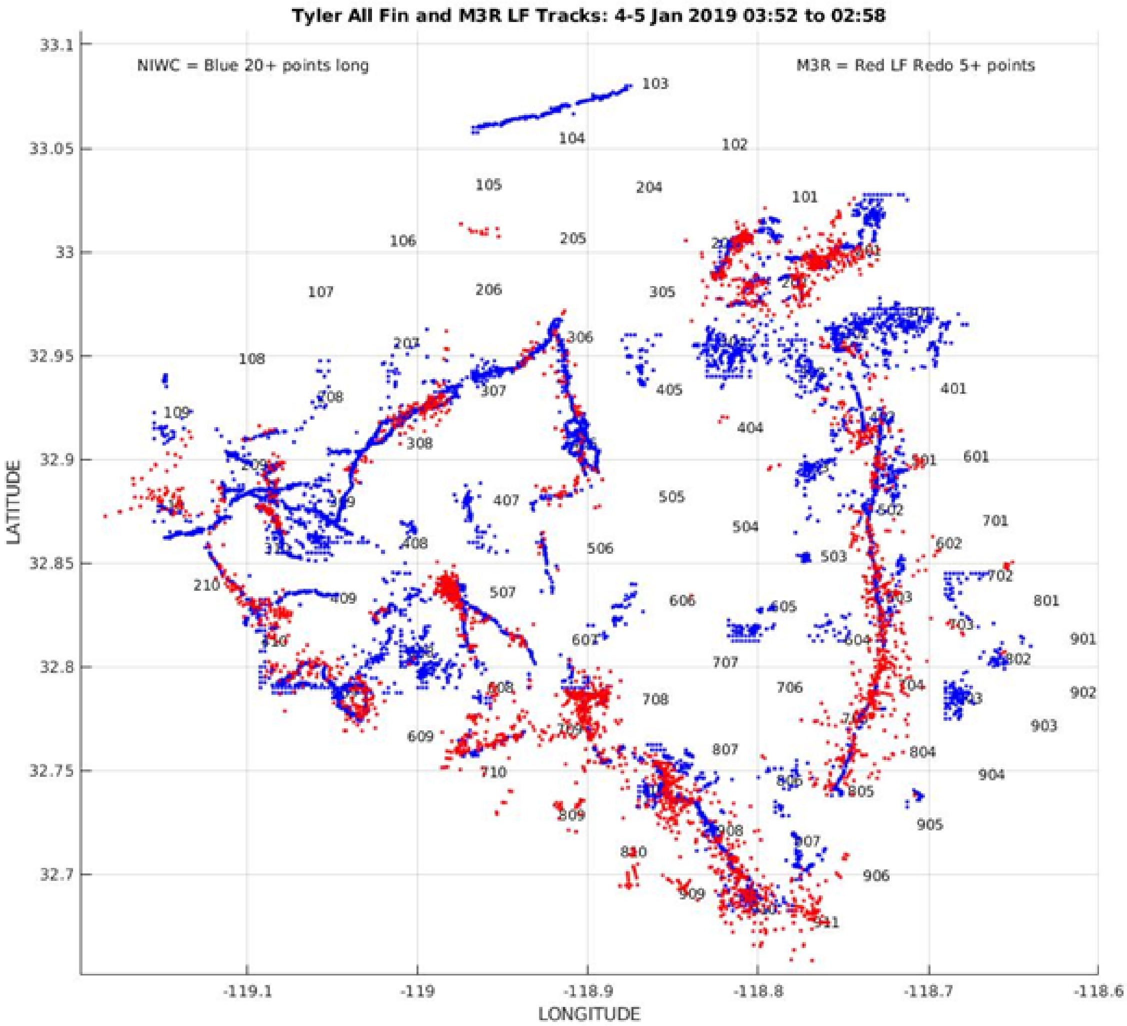

Figure 26. Overlay of reprocessed M3R LF posits (red) and NIWC fin whale tracks (blue) from 4-5 Jan 2019. Reprocessed M3R data exhibits improved agreement with NIWC results.

Closer examination of the overlay of the M3R and NIWC tracks (Figure 26) show that the M3R posits exhibit more scatter than the NIWC localizations. We believe this is largely because the timing resolution of the M3R LF detector (170.67 ms) is much coarser that the timing resolution of the NIWC fin detector. The scatter of one-off (or singleton) posits in Figure 27 is likely a bi-product of trying to use direct path multilateration with calls received on an array of hydrophones far from the animal (i.e. the animal is not within the array, thus the direct path assumption is not met). As also shown in Figure 27, simple filtering rules discount such bogus posits.

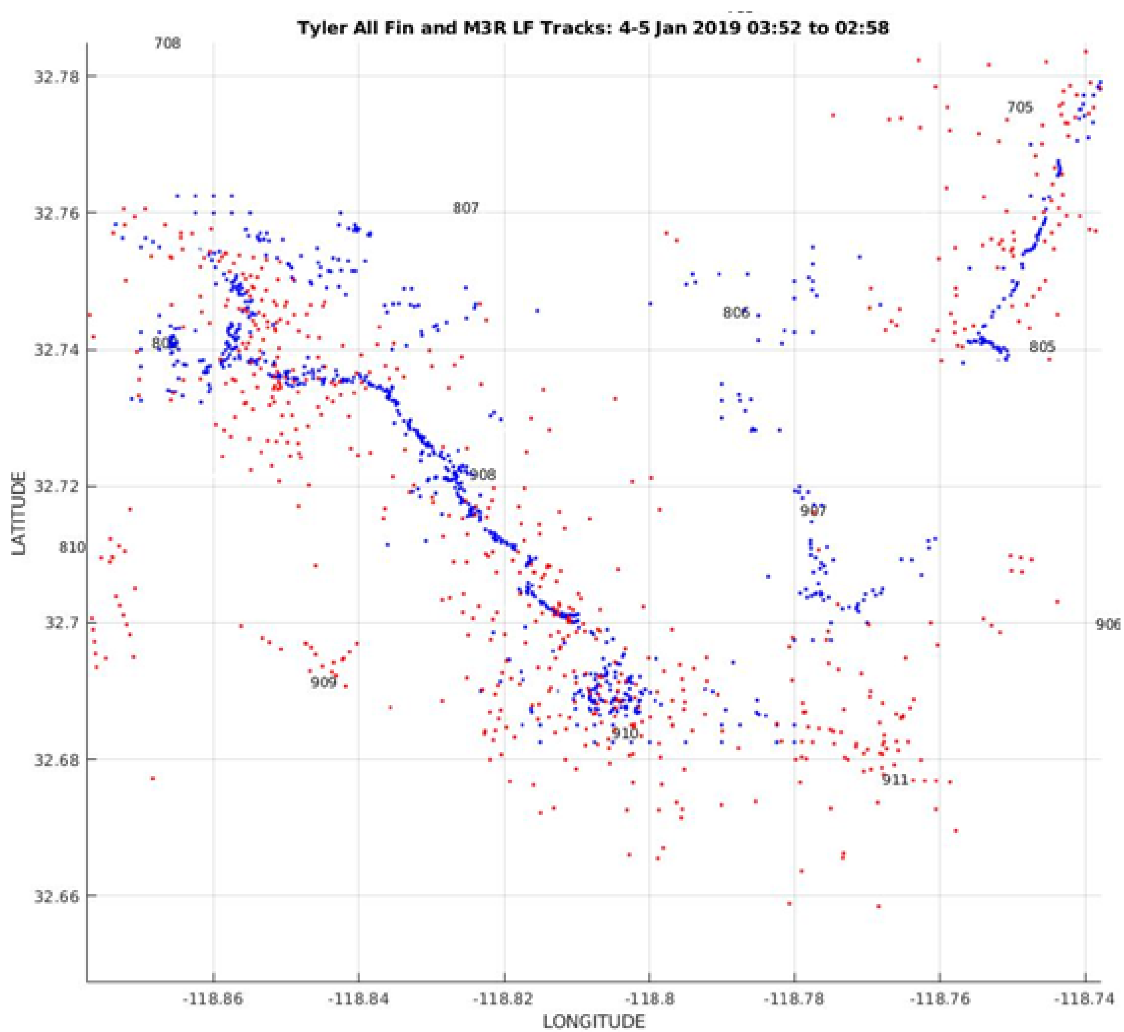

Figure 27. Close-up of overlay of reprocessed M3R LF posits (red) and NIWC fin whale tracks (blue) from 4-5 Jan 2019. M3R posits exhibit greater scatter because of coarser detector timing.

Discussion

In this project we conducted a preliminary review of the accuracy of automatically generated M3R LF localizations extracted from archive data collected at SOAR. The M3R-generated LF posits were compared to fin whale detections and localizations generated by researchers at NIWC, San Diego through their post-processing of raw acoustic recordings for select days. The overlay of the M3R LF posits and the NIWC results was initially disappointing but helped identify a processor loading problem within the M3R cluster at SOAR. The associator nodes were apparently being overwhelmed by dolphin activity, especially at night. Reprocessing just the M3R LF spectrogram data (alone) through the LF association/localization code produced tens of thousands of LF posits resulting in closer parity between NIWC fin tracks and M3R LF tracks. Beyond identifying the need to change the dolphin click processing stream at SOAR, this study has also identified other steps that can be taken to improve M3R's real-time LF tracks, such as changing the parameters of M3R's LF FFT detector to improve time resolution, interpolating correlation peak positions to improve time resolution in spectrogram cross correlation and adding posit filtering techniques to better reject bogus posits generated by distant arrays (non-direct path solutions). These near-term improvements could be made relatively quickly. The results of this project demonstrate that M3R's LF localization routine can effectively localize calls from several baleen species. However, because the localization is based upon simple energy detection in the band <600Hz, it is not well suited to differentiating between calls from different species. A better solution, that would likely offer much improved detection timing resolution also, would be to add a dedicated detector-classifier capability for low-frequency calls. The times of detection from the classifier could then be passed to the existing multilateration localization algorithm or, alternatively, to a model-based localization algorithm.

4 Ambient noise calculation using the FFT archives

4.1 Introduction

4.1.1 Objectives

Ambient noise has been increasing in the Northeast Pacific and Indian Ocean basins, particularly in the lower frequencies typically associated with shipping traffic (Hildebrand 2009, McDonald et al. 2006, Chapman and Price 2011, Miksis-Olds et al. 2013). The M3R program has collected a long-term dataset of archived acoustic detections at the U. S. Navy's Southern California Antisubmarine Warfare Range (SOAR). This dataset can be used to evaluate the seasonal variation and long-term trend of ambient noise on the range.

Changes in ocean acoustic ambient noise directly impact the efficacy of a wide variety of Navy systems, from sonar systems to environmental models. Information on ambient levels and how they vary both geographically and temporally is critical to Navy operations, especially in areas where the Navy frequently trains and tests. Increasing ambient noise can impact the probability of detection of signals of interest. The M3R program has been archiving data at the deep-water ranges for multiple years. In FY20 tools were developed to extract ambient noise data from M3R data archives. These will provide the Navy with data that can be used both immediately and in the future for ambient noise analysis. Refining data processing and analysis techniques will enable data sets to be continually processed as new data are collected.

In FY21 personnel at the Naval Undersea Warfare Center (NUWC) and the Naval Information Warfare Center (NIWC) compared ambient noise datasets collected on the SOAR range to validate the proposed ambient noise extraction method and to determine conversion factors to align the ambient from broadband recordings to ambient extracted from M3R archives. Periods of time with both broadband ambient recordings and M3R archive files available at SOAR were identified for analysis. NIWC conducted an analysis of the ambient noise from the broadband recordings and NUWC extracted ambient from the associated archive files. Ambient noise curves from both methods were compared to validate the efficacy of the ambient curves extracted from M3R archives, and conversion factors were identified to align the two datasets.

The goals of this project were as follows:

1. *FY20:* Develop tools to extract ambient noise data from M3R data archives.
2. *FY21:* Compare ambient noise extracted from M3R archives (NUWC) to analysis of ambient from broadband recordings (NIWC) to validate the method, and determine conversion factors to align the ambient noise curves.

4.1.2 Technical Background

Undersea Warfare Training Ranges (USWTRs) provide the fleet with instrumented open ocean areas in which to conduct both systems testing and crew training. The M3R system at SOAR was installed in 2006. The system has been in constant operation, and consequently a nearly continuous multi-year dataset is now available. This dataset has value for multiple analyses, including animal abundance, SONAR impact, and ambient noise analysis.

4.2 Methods

4.2.1 Overview

4.2.2 Dataset Identification

All periods of time at SOAR with both M3R archives and M3R broadband recordings were identified for potential analysis. Furthermore, since NIWC has a broadband recorder at PMRF in addition to NUWC's broadband recorder and binary archives, periods of time in which the three datasets (NIWC recordings, NUWC recordings, and NUWC binary archives) were available were also identified for potential analysis and comparison. Overlapping periods of at least 24 or 48 continuous hours at SOAR between 2013 and 2019, and similar periods at PMRF from 2019 to 2020, were copied to disks and sent to NIWC for analysis.

NUWC and NIWC first independently processed ambient noise data at SOAR and PMRF, and then shorter periods of time were compared using both methods. NUWC analyzed data using the ambient noise extraction method, and NIWC conducted ambient noise analyses using both the NUWC and NIWC broadband recordings.

NUWC initially reviewed sampled hydrophones across the SOAR range in 2018 and 2019, and in 2019 and 2020 at the PMRF range. NIWC examined hydrophones in May 2015, January 2018 and January 2019 at SOAR, and in March and June 2019 and January 2020 at PMRF.

To compare the ambient curves generated with the two methods, shorter datasets were identified. At SOAR, four hours of data starting at 21:58 on January 2, 2019 were compared. At PMRF, five time periods were compared: March and June of 2019, and three periods from January 2020.

4.2.3 Ambient Noise Extraction Method ("Sprinkle Analysis")

4.2.3.1 Data Description

4. Overview

Each undersea range is instrumented with multiple hydrophones cabled back to shore. The hydrophone spacing varies primarily with water depth. The hydrophones at SOAR are spaced approximately 4 km apart with sensor depths of approximately 1600–1800 meters. The hydrophone spacing at PMRF varies from 1 to 7 km, depending on the water depth, which varies from less than 80 meters to more than 4700 meters. The beam patterns of the hydrophones are nearly hemispherical toward the surface, and the acoustic output from each hydrophone is available individually on shore.

5. FFT-Based Detector

The M3R system employs a variety of detectors, including both species-specific and generic-event detectors. In particular, a fast Fourier transform (FFT)-based detector is utilized for generic event detection. The FFT detection reports contain sufficient information from which to estimate an average noise spectrum.

6. Data Available in FFT Detection Reports

The hydrophones are sampled at a rate f_s = 96 kHz, allowing for an analysis bandwidth up to 48 kHz. A spectrogram $X_i(f, n)$, where f is the discrete frequency and n is the time slice, is formed from the time-series data for each hydrophone H_i where i ranges from 1 to the total number of hydrophones. A 2048-

point fast Fourier transform (FFT) with a rectangular window and 50% overlap is used to form each spectrogram. At the 96 kHz sample rate, this results in a frequency resolution of 46.875 Hz and a time step of 10.67 ms. Each time-frequency bin of $X_i(f,n)$ is compared to a time-varying threshold $D_i(f,n)$. The threshold is set to be a multiplicative factor k above an exponential average of the power $N_i(f,n)$ within frequency bin f.

$$N_i(f,n) = (1-\alpha)X_i(f,n) + \alpha N_i(f,n-1), \qquad (1)$$

where α is the averaging time constant, $0 < \alpha < 1$, and

$$D_i(f,n) = kN_i(f,n). \qquad (2)$$

The output of the FFT detector for each hydrophone is a binary-valued detection spectrogram $Q_i(f,n)$, which contains a "1" in each time-frequency bin that exceeds $D_i(f,n)$ and a "0" everywhere else (see the decision point "Is the bin count 1?" in the flowchart in Figure 28). The parameter α has been empirically chosen to provide an averaging time constant of 0.2 second. The threshold factor k has also been empirically set. The current setting has a measured false alarm rate of approximately 20 false alarms per second (Ward et al. 2008) and a theoretical probability of false alarm, P_{fa} , of 0.214 (Ward et al. 2011). When viewed on a detection spectrogram (Figure 28), these false alarms from the FFT detector appear as speckle.

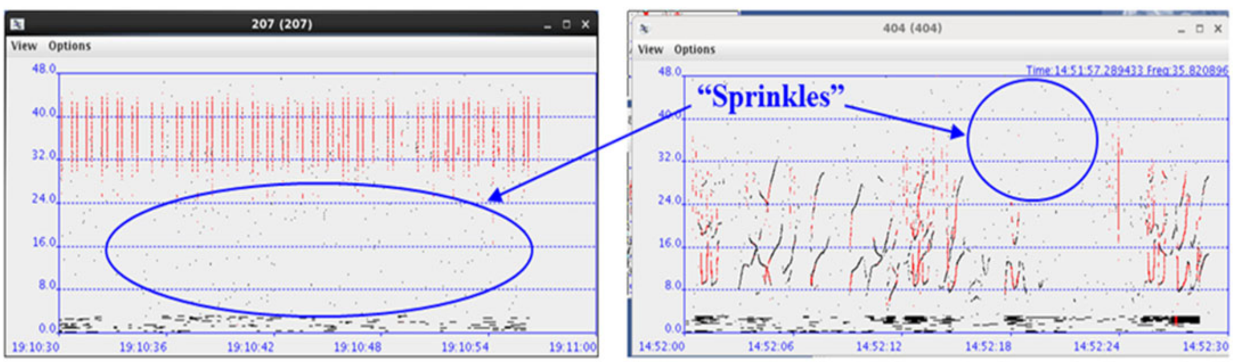

Figure 28. FFT detector speckle, or "sprinkles"

In addition to the binary spectrogram data, the FFT detection report stores the peak amplitude and associated frequency. A summary of the data available in the detection report is shown in Table 27 (Fisher 2018).

Table 27. Information in FFT Detection Reports (Morrissey, 2021)

Length (bytes)	Type	Description	Explanation
2	u16	Sensor Id	Hydrophone reporting detection
4	u32	Seconds	Seconds from 1 January, current year
4	u32	Nanoseconds	Nanoseconds from seconds mark
4	u32	Sample Count High	High 32-bit word of 64-bit sample count (bits [63:32])

4	u32	Sample Count Low	Low 32-bit word of 64-bit sample count (bits [31:0])
2	u16	FFT Size	FFT size in samples (typically 2048)
4	f32	Frequency Resolution	FFT frequency resolution (Hz)
4	f32	Time Resolution	FFT time resolution in (seconds)
4	f32	NVT	Noise variable threshold (dB)
4	f32	FT	Fixed threshold (volts)
4	f32	Threshold	Selected threshold (higher of NVT or FT)
4	f32	Peak Frequency	Peak frequency (Hz)
4	f32	Peak Magnitude	Magnitude of peak frequency (volts)
2	u16	Peak Bin	Bin index of peak frequency
2	u16	Num Detections	Number of bins set in FFT
4∗32	u32[32]	Bin FFT	Bits in order from most significant to least significant (2048 points = 32 words)

[∗ denoting 'multiplied by'; u=unsigned integer, f=float]

4.2.3.2 Processing Algorithm

Data available in the detection reports, specifically binary FFTs with only a single bin above threshold, were aggregated over time to produce an average noise spectrum (Table 27). This was done by setting the noise variable threshold (NVT) as low as possible without overloading the system. Choosing a threshold in this manner resulted in a significant number of detection reports where the system was triggered purely by noise. These detection reports are colloquially known as "sprinkles" and are shown in the binary spectrograms in Figure 29.

Noise spectra were differentiated from spectra containing acoustic events by filtering the results for "single bin" detections. The peak magnitude of each bin was collected until a statistically significant number of samples had been obtained for each bin. These data were then averaged to obtain an estimate for the noise level after backing out the system transfer function.

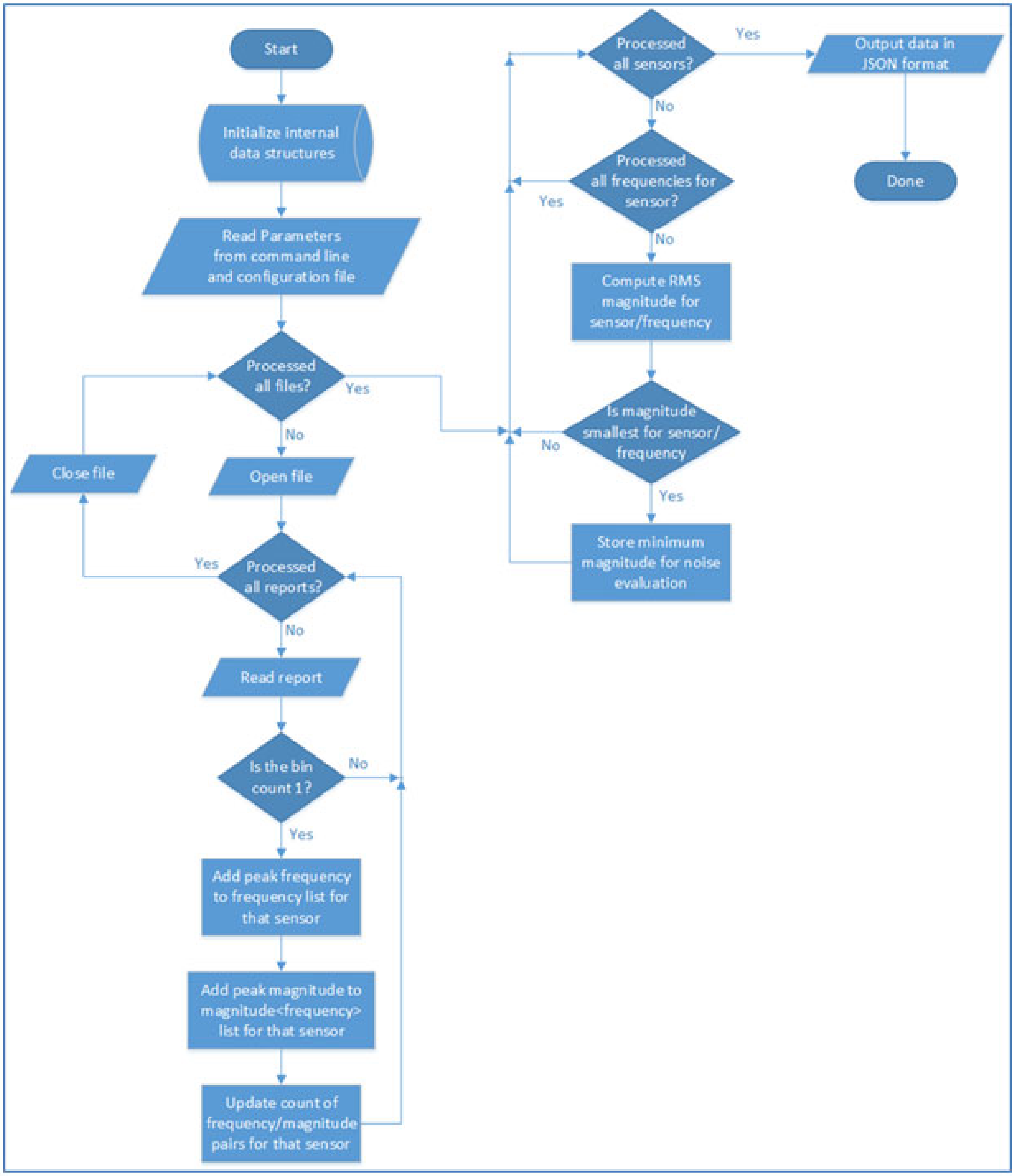

Figure 29. Flowchart for Ambient Noise "Sprinkle" Algorithm (Morrissey, 2021)

For further processing details see Morrissey, 2021.

4.2.3.3 NUWC Comparison of Ambient Noise Code and Broadband Recordings

The output of the ambient noise sprinkle code, which is based off a binary FFT, is in units of V_{rms}^2 measured in a 46.875 Hz band. Sounds received at the face of the hydrophones pass through a Shore Electronics System (SES) before reaching the M3R system, which generates the binary FFTs. Ultimately, the output of the ambient noise sprinkle algorithm should be converted to units of dB re 1 uPa measured in a 1 Hz band. Three steps are required for this conversion: 1) conversion of the measurement units from V_{rms}^2 to dB re 1 V_{rms}, or dBV, 2) a bandwidth correction to convert to dBV in a 1 Hz band, and 3) application of a transfer function to convert from units of dBV to dB re 1 uPa. This transfer function represents the system transfer function of the SES.

As the system transfer function has not yet been derived, the shapes of the ambient noise curves were compared by using the following empirically determined correction factor to convert both to units of dB re 1 V_{rms}:

(1) X dB re V_{rms} = 20 log10 ((V_{rms}^2)/46.875)

The sprinkle analysis data were measured in a 46.875 Hz band while the ambient noise from the broadband recordings were measured in a 5.86 Hz band, so both were band-corrected to a 1 Hz band.

NUWC used two methods to compare the curves:

Method 1: The correction term in equation 1 was first applied to the output of the sprinkle analysis. The high frequency endpoints of the two curves were then aligned by adding 94.5 to the NUWC data, and the frequency axes were aligned by multiplying the NIWC data by 5.86.

Method 2: The second method was a slightly modified version of the method used by NIWC. First, every eight bins of the NIWC data were averaged. Then the average difference between the two curves was found for each hydrophone, followed by the average of all differences for a given hydrophone type. The resulting factor was used as the offset.

4.2.4 Broadband Recording Ambient Noise Analysis

NIWC compared the shapes of ambient noise curves from three data sources at PMRF: NIWC's legacy broadband recorder, NUWC's M3R broadband packet recorder, and the M3R sprinkle analysis output. Offset values were determined between the two recorders and between NUWC's packet recorder and the sprinkle analysis output when comparing the datasets.

To determine the offset values for PMRF the sprinkle analysis output was first interpolated; then the difference across the full bandwidth was found between the two recorders, and between the M3R recorder and sprinkle analysis output; and finally the offsets for all hydrophones were averaged (Martin, et al., 2022).

4.3 Results

4.3.1 SOAR Comparison

At SOAR the hydrophone ambient noise curves were compared for four hours of data starting at 21:58 on January 2, 2019. Overlay plots for the hydrophones circled in red in Figure 30 were generated after correcting with the appropriate conversion factors. Only unidirectional hydrophones were included in the final comparison. The two methods described in Section 4.2.3.3 were used to find the correction terms, with each producing good matches between the ambient noise sprinkle analysis output and the broadband recording ambient analysis (Figure 31 to Figure 33).

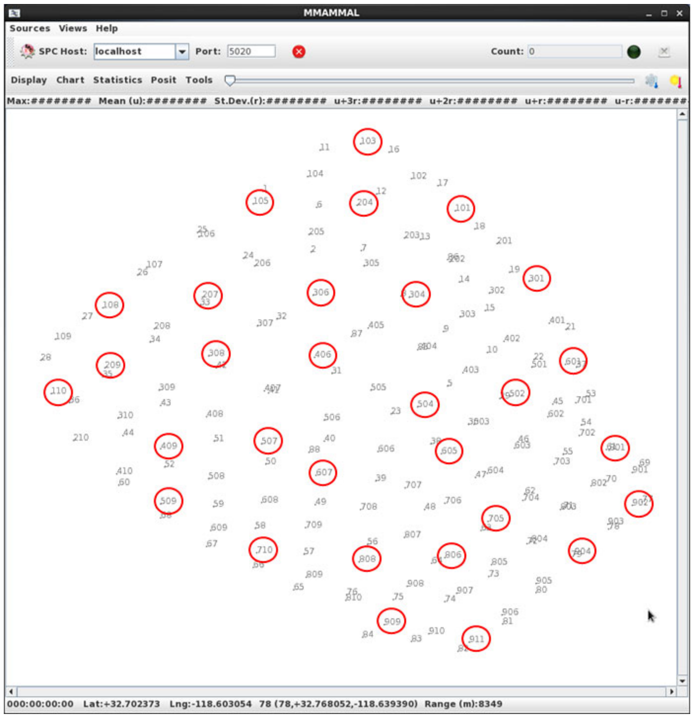

Figure 30. SOAR hydrophones for which overlay plots were generated to compare the ambient noise sprinkle analysis output with ambient noise analysis from broadband recording (red circles).

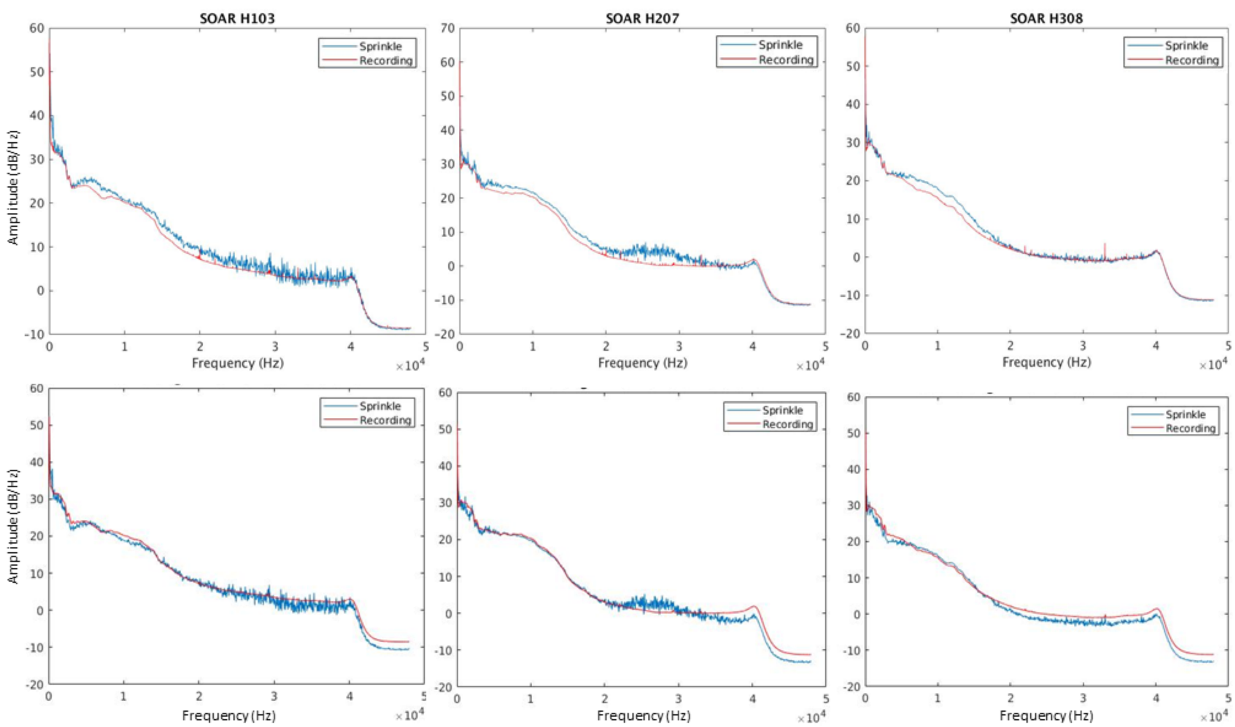

Figure 31. Representative SOAR ambient noise plots comparing the sprinkle method output to broadband recordings for hydrophone strings 100 through 300.
Top Row: **comparison using method 1;** ***Bottom Row:*** **comparison using method 2.**

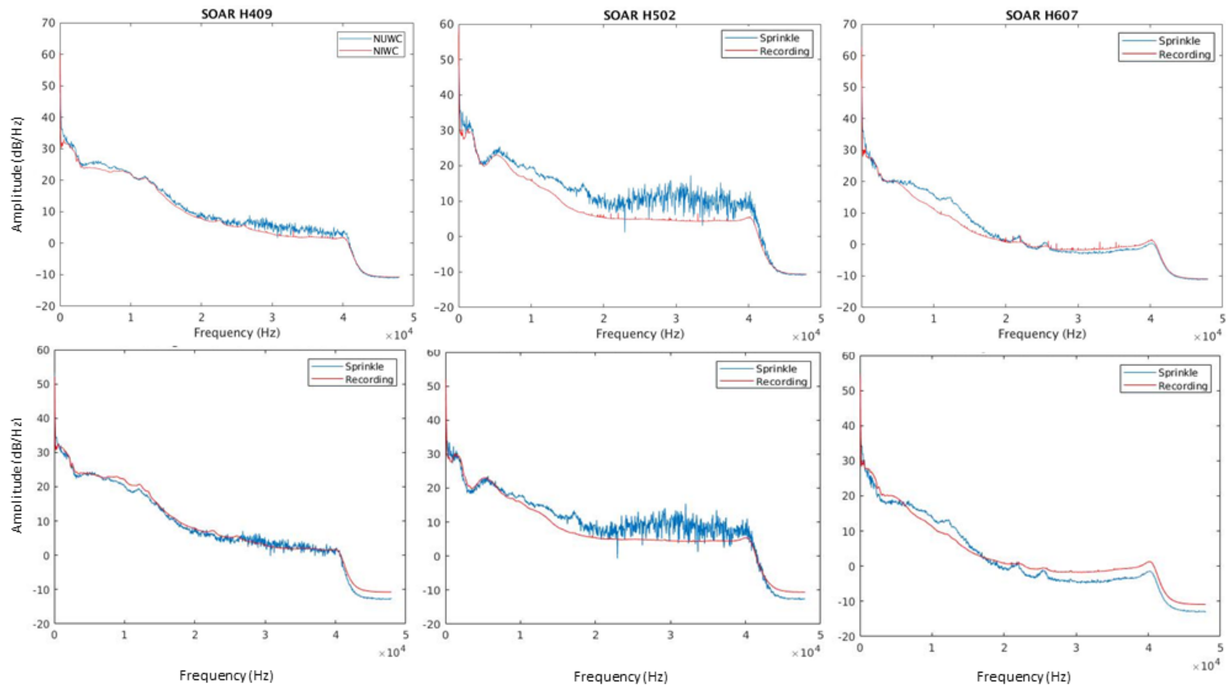

Figure 32. Representative SOAR ambient noise plots comparing the sprinkle method output to broadband recordings for hydrophone strings 400 through 600.
Top Row: **comparison using method 1;** ***Bottom Row:*** **comparison using method 2.**

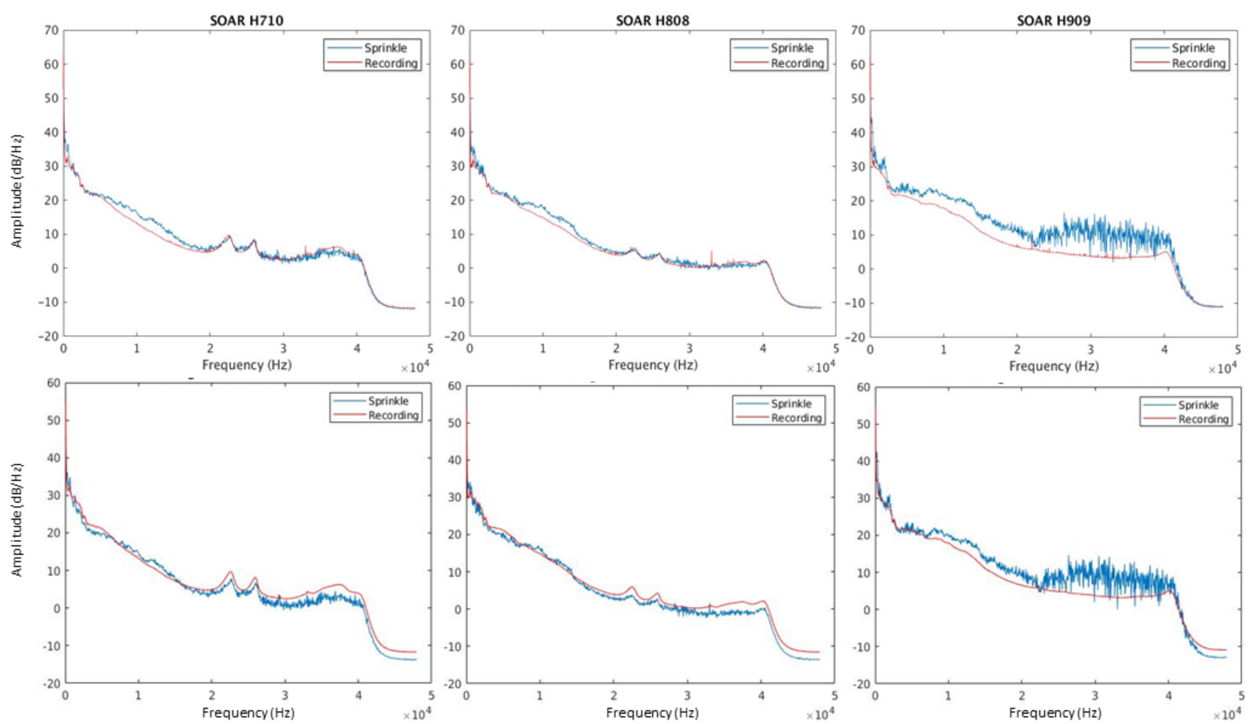

Figure 33. Representative SOAR ambient noise plots comparing the sprinkle method output to broadband recordings for hydrophone strings 700 through 900.
Top Row: **comparison using method 1;** ***Bottom Row:*** **comparison using method 2.**

4.3.2 PMRF Comparison

NIWC conducted a comparison between three data sources at PMRF: the NIWC legacy recorder, the NUWC M3R packet recorder, and binary archived from the M3R system at PMRF. The three datasets were compared for four time periods (March 15, 2019 and January 8, 10, and 17, 2020). In addition, two of the January datasets were recorded at two different gain settings, and both settings were analyzed.

Figure 34 gives an example of the comparison of data recorded from the three systems at PMRF after they were aligned. Details on the analysis and offset values found for the four datasets can be found in Martin, et al., 2022.

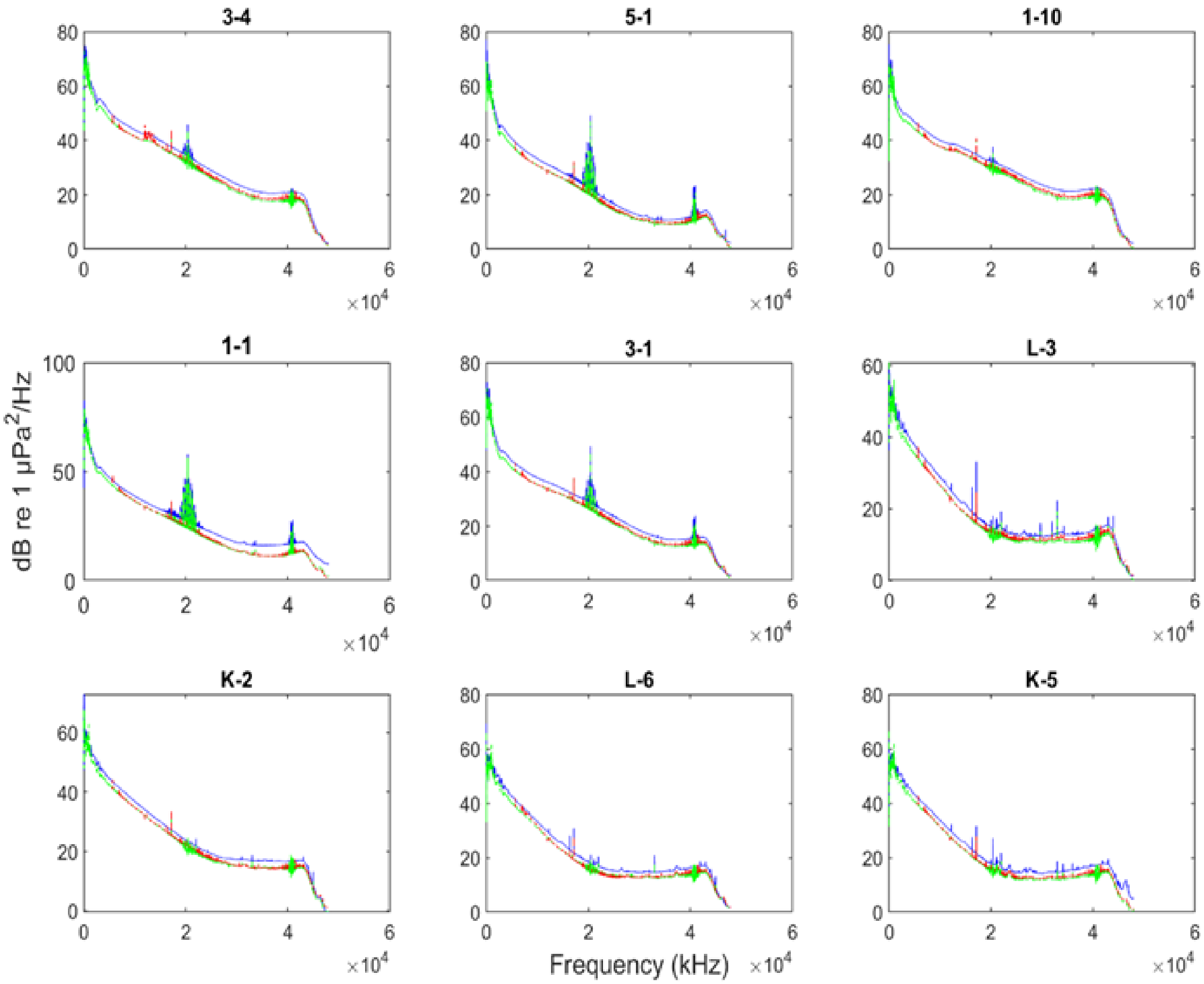

Figure 34. Spectral density values for the three systems recorded at PMRF on nine of the hydrophones (shown for BSURE replacement phones and BARSTUR broadband phones after they were aligned with offset values (in dB re 1 V/Hz) to the spectral density levels of the NIWC Pacific legacy recorder. These data are from 15 March 2019. (Martin, et al., 2022)

4.4 Discussion

The close matches between the shapes of the ambient noise curves from the three systems (the sprinkle analysis ambient noise output, the M3R packet recorder, and the NIWC PMRF legacy recorder) appear to validate the sprinkle analysis method for representing ambient noise on the U.S. Navy's undersea ranges. Additional work is needed to derive the system transfer functions at each range, to investigate the varying offset values for different hydrophone groupings (e.g. unidirectional vs bidirectional, or broadband vs high-pass), and to compare datasets from different time periods; however, this initial work is very promising. M3R binary archives have been collected at the SOAR range since 2006 and at PMRF since 2011, and continue to be collected on a year-round basis. The sprinkle analysis method provides a relatively straightforward way to leverage these data to examine the temporal and spatial variation in ambient noise levels on the ranges over time. Such insight into the changes in ambient noise could provide useful information for environmental analysis, the development of detectors, and acoustic effects models.

5 Real-time monitoring of on-water tagging operations

5.1 SOAR

Two field tests were conducted in FY21 on SOAR in coordination with Marine Ecology and Telemetry Research (MarEcoTel). Others that were tentatively scheduled were cancelled due to issues with COVID and/or poor weather. The field tests were conducted in October, 2020 and September, 2021, and supported the photo-ID, biopsy, and tagging of marine mammals. During these field tests MarEcoTel personnel work from San Clemente Island (SCI), transiting daily at sunrise onto the SOAR range in their Rigid Hull Inflatable Boat (RHIB). M3R personnel use the M3R system to acoustically monitor animals on the range and direct MarEcoTel to their locations. Upon finding animals MarEcoTel collect photo-ID and behavioral data and biopsy samples, and potentially place Sound and Motion Recording Tags (SMRT tags) or Low Impact Minimally Percutaneous Electronic Transmitter (LIMPET) satellite tags on individuals, depending on the focus of the particular effort. This effort has been focused primarily on Cuvier's beaked and fin whales, though data on other species have been collected.

M3R personnel work from a conference room at the Range Operations Center (ROC) at Naval Air Station North Island. The system is set up, and broken down and stored, at the beginning and end of each field test. They monitor the system, keeping track of species acoustically detected throughout the day, including baleen whales, but usually with a focus on tracking Cuvier's beaked whale group locations. These data and additional notes are recorded in a Logger program; raw acoustic data from the whole range or from selected hydrophones may be recorded; and all detections, localizations, and ancillary data are automatically saved to binary archive files ('spc archive' files) on a continuous basis.

M3R personnel use both a real-time review of binary spectrograms and output from the CS-SVM classifier and FFT detector via a click train viewer display in order to identify relevant species. Raven Pro Sound Analysis Software (Cornell University, Ithaca, NY) has been modified to stream M3R data and is available to view individual hydrophones on demand, which assists with species identification. Both the MMAMMAL and WorldWind display show animal localizations ('posits'), with each having a different method of indicating the highest confidence posits. M3R personnel use these posits or dead-reckoning from the binary spectrograms to direct the on-water personnel to the locations of animals of interest. Communications are maintained throughout the day, via satellite texts, radio, and cell phone, to relay information such as animal locations and the start and stop times of vocalizing beaked whale groups.

Table 28 lists the cetacean species acoustically identified using the M3R system during the two field tests in FY21, along with summary information extracted from the associated SOAR field logs. More detailed information from these field logs can be found in Appendix A.

A total of 146 acoustic detections were logged, including 89 of Cuvier's beaked whales, 13 of fin whales, two of blue whales, one of common dolphins, 38 of unidentified dolphins, and three of unidentified baleen whales. Note that the detections do not necessarily indicate unique groups; in fact, Cuvier's beaked whale sightings often recur in the same area periodically throughout the day, which may indicate a unique foraging group in a particular location. In addition, not all species that are present are logged. In particular, dolphins are always present on the range, particularly in the east, and are not always logged. In addition, all fins and other baleen whales were not necessarily logged.

Of these acoustic sightings, there were about 22 cases in which M3R directed MarEcoTel to Cuvier's beaked whales and nine instances of direction to fin whales. Additional posits were logged, and potentially sent to the field team, depending on conditions. Here 'directed' sightings are considered those in which a location was sent and the field team decided to go to the location. MarEcoTel visually verified two groups of Cuvier's beaked whales and three to four groups of fin whales, and collected numerous photos, biopsies and behavioral data from both species.

Table 28. Species acoustically identified with the M3R system or visually sighted on SOAR. Data are extracted from the two field test logs in FY21. Visual sightings without a corresponding acoustic detection are noted below the table.

Species			# Acoustic Detections Logged	# Acoustic Detections Directed	# Acoustic Detections Visually Verified	# of Tags
ID	Common Name	Scientific Name				
Zc	Cuvier's beaked whale	*Ziphius cavirostris*	89	22	2	0
Bp	Fin whale	*Balaenoptera physalus*	13	9	3-4	0
Bm	Blue whale	*Balaenoptera musculus*	2	1	1	0
Dd	Common dolphin	*Delphinus delphinus*	1	0	0	0
UD	unidentified dolphin	Delphinidae sp.	38	0	0	0
UM	unidentified baleen whale	Mysticeti sp.	3	1	0	0

Notes: Baird's beaked whale (*Berardius bairdii*) was reported by an outside source on SCTTR near sensor 505 heading north on 9/7/21 but was never visually or acoustically observed. No time was listed in the report. On the same day, visual observers found two Bryde's whales (*Balaenoptera brydei*) milling NE of sensor 202. M3R took sound cuts on sensor 101 nearby of potential acoustic signals from these animals, but no formal acoustic detection was generated. On 9/8/21 a single blue whale was seen by visual observers between sensors 503 and 603, but no acoustic observation was made.

5.2 PMRF

M3R conducted one field test in 2021 in conjunction with the Cascadia Research Collective (CRC), from July 29th through August 13th. CRC personnel typically transit from Kikiaola Harbor at sunrise to the PMRF range. During these tests NUWC personnel use the M3R system to acoustically monitor animals on the range and direct CRC to their locations. Upon finding animals, CRC personnel will collect photo-ID, behavioral data, biopsy samples, and potentially place tags on the animals, with the tag type varying depending on the focus of the particular effort.

M3R personnel use the M3R system at PMRF as they do at SOAR to direct the on-water personnel to the locations of animals of interest. Communications are maintained via radio and cell phone. The cetacean species acoustically identified by M3R system during the August 2021 field test at PMRF, along with summary information extracted from the associated field logs, are shown in Table 29. The first on-water day for CRC was August 1, 2021; however, some incidental monitoring was conducting in the three days prior, and are included in the results. If the observer believed the acoustic detection was associated with a particular species it was marked as such. However, acoustic detections were not all verified, and at times there was confusion among species; therefore, a range of detection counts is included. More detailed information can be found in Appendix B.

A total number of 197 acoustic detections were logged, including 86 of Blainville's beaked whales, one of Cuvier's beaked whales, four of sperm whales, 11 to 12 of melon-headed whales, 10 to 12 of bottlenose dolphins, 25 of rough-toothed dolphins, one group of Fraser's dolphins, three to four of false killer whales, a possible Risso's dolphin group, three to four of short-finned pilot whales, 47 to 48 of unidentified dolphins, and six of unidentified baleen whales. Each acoustic detection may represent either a single animal or a group of animals; however, note that each detection is not necessarily a new individual or a new group, as the same animal or group could be detected more than once over the course of the day. In addition, individuals could potentially move between groups. Of the acoustic detections, 22 were directed, and 14 were visually verified. Two satellite tags were placed on Blainville's beaked whales, three on melon-headed whales, two on bottlenose dolphins, and one on a rough-toothed dolphin. It was a very successful trip (Table 29).

Table 29. Species acoustically identified with the M3R system on PMRF.
Data are extracted from the logs of the field test completed in August 2021. Visual sightings without a corresponding acoustic detection are noted below the table.

Species			# Acoustic Detections Logged	# Acoustic Detections Directed	# Acoustic Detections Visually Verified	# of Tags
ID	Common Name	Scientific Name				
Md	Blainville's beaked whale	*Mesoplodon densirostris*	86	3	1	2
Zc	Cuvier's beaked whale	*Ziphius cavirostris*	1	0	0	0
Pm	Sperm whale	*Physeter macrocephalus*	4	0	0	0
Pe	Melon-headed whales	*Peponocephala electra*	11-12	5	4	3
Tt	Bottlenose dolphin	*Tursiops truncatus*	10-12	4	3	2
Sb	Rough-toothed dolphins	*Steno bredanensis*	25	7	6	1
Lh	Fraser's dolphins	*Lagenodelphis hossei*	1	0	0	0
Pc	False killer whales	*Pseudorca crassidens*	3-4	0	0	0
Gg	Risso's dolphin	*Grampus griseus*	0-1	0	0	0
Gm	Short-finned pilot whale	*Globicephala macrorhynchus*	3-4	0	0	0
UD	unidentified dolphin	Delphinidae sp.	47-48	3	0	0
UM	unidentified baleen whale	Mysticeti sp.	6	0	0	0

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7 Appendix A: SOAR Field Work Logs

Table 30 and Table 31 show excerpts from the M3R log files from the two field efforts conducted with MarEcoTel in FY21 on SOAR. The excerpts indicate the species acoustically identified and the number of such detections, along with the number of detections to which the RHIB was directed, the number of species detections verified, and the number of tags deployed. Note the detections do not necessarily indicate the number of groups present, as the same group may be re-sighted over the course of the day. In addition, these log excerpts indicate minimum numbers present on the range, as not all activity is logged. There are a variety of reasons for this, such as: particular species or parts of the range may be the focus on a particular day; personnel may have different levels of experience; and certain ever-present groups of animals such as dolphins are not usually logged.

Table 30. Excerpts from M3R log files from a field effort on SOAR from October 5-7, 2020.

Test Dates	# Hours Monitored	Species	# Acoustic Detections Logged	# Acoustic Detections Directed	# Acoustic Detections Visually Verified	Tagged?	Notes
10/5/2020	8.8	Zc	20	9	0	No	
10/6/2020	6.6	Zc	21	4	0	No	5 foot swells;-Beaufort 3.
		UD	1	0	0	No	
10/7/2020	8.95	*Bp*	9	5	2-3	No	Focus on fin whales today; may try beaked whales if they're in the vicinity. Weather is not good. 3 fins by 108, 109, 209; 1 fin E of 307. 1515 local: Got photo IDs & biopsies. Current weather: Beaufort 3-4 ft swell; completely

							overcast. 2 mile visibility.
		Bm	1	0	0	No	Blue whale posit S of 410/60
		Zc	9	1	0	No	

Table 31. Excerpts from M3R log files from a field effort on SOAR from September 7-10, 2021. Acoustic detection marked with an 'X' indicates a species was acoustically observed on the range, but group number was not tracked. An '*' indicates visual sightings occurred without an associated acoustic detection, details for which can be found at the bottom of the table.

Test Dates	# Hours Monitored	Species	# Acoustic Detections Logged	# Acoustic Detections Directed	# Acoustic Detections Visually Verified	Tagged?	Notes
09/07/2021*	8.5	*Zc*	12	2	1	No	Group of 3 E of H35, one male seen yesterday. Light colored individual amongst group. Lots of fishing vessels on southern portion of range, making strange sounds that could be scaring Zc away from the area. Visual observers had them present 9/08/21 as well.
		Dd	1	0	0	No	
		UD	6	0	0	No	
		UM	1	1	0	No	Unknown low frequency sound H407
		UM	X	NA	NA	NA	Possible blue whales heard throughout the day (area not mentioned, no formal detections just a comment).
		UM	2	0	0	No	Possible Fin whale. Heard on Hyds 407, 408, 507.

09/08/2021*	4	*Zc*	8	2	0	No	Multiple animals estimated from acoustics
		UD	4	0	0	No	
09/09/2021	6	Zc	9	3	0	No	No posits until close to end of day, then a few between Hyds 209 & 35. Sounded like multiple animals.
		Bp	2	2	1	No	Tried to tag fin whale NW of 207 but were unsuccessful.
		UD	12	0	0	No	Lots of dolphins and fishing vessels (echosounders)
09/10/2021	9	Zc	10	1	1	No	Saw Zc shaped body breach ENE of Hyd 40 (2mi from posit location), but not a positive ID. Later visually confirmed Zc next to Hyd 505.
		UD	15	0	0	No	Possibly common dolphins. The range was full of dolphins, unable to track all groups.
		Bm	1	1	1	No	Two individuals seen rolling around on the surface between Hyds 403, 405, and 505.
		Bp	2	2	0	No	First individual SW of Hyd 101, second was N of Hyd 203.

Notes: Baird's beaked whale (*Berardius bairdii*) was reported by an outside source on SCTTR near sensor 505 heading north on 9/7/21 but was never visually or acoustically observed. No time was listed in the report. On the same day, visual observers found two Bryde's whales (*Balaenoptera brydei*) milling NE of sensor 202. M3R took sound cuts on sensor 101 nearby of potential acoustic signals from these animals, but no formal acoustic detection was generated. On 9/8/21 a single blue whale was seen by visual observers between sensors 503 and 603, but no acoustic observation was made.

8 Appendix B: PMRF Field Work Logs

Table 32 shows excerpts from the M3R log files from the field effort with Robin Baird from the Cascadia Research Collective in FY21 on PMRF. The excerpts show the species acoustically identified and the number of such detections, along with the number of detections to which the RHIB was directed, the number of species detections verified, and the number of tags deployed. Note the detections do not necessarily indicate the number of groups present, as the same group may be re-sighted over the course of the day. In addition, these log excerpts indicate minimum numbers present on the range, as not all activity is logged. There are a variety of reasons for this, such as: particular species or parts of the range may be the focus on a particular day; personnel may have different levels of experience; and certain ever-present groups of animals such as dolphins are not usually logged.

Table 32. Excerpts of M3R log files from the field effort on the PMRF range in August 2021. Acoustic detections marked with an 'X' indicates a species was acoustically observed on the range, but group number was not tracked. An '*' indicates visual sightings occurred without an associated acoustic detection, details for which can be found at the bottom of the table. '' indicates days the visual observers were unable to work on the range due to naval ops.**

Test Dates	# Hours Monitored	Species	# Acoustic Detections Logged	# Acoustic Detections Directed	# Acoustic Detections Visually Verified	Tagged?	Notes
07/29/2021	0.9	*Md*	1	0	0	0	
		Gm	2	0	0	0	2-3, 2-4: possible pilot whale? B-3, B-2, I-4, I-3: Decided these might be pilot whales. After looking in Raven; most clicks look like dolphin.
		Pc or Gg	1	0	0	0	Possibly false killer whale or Risso's - large group
		UD	7	0	0	0	

07/30/2021	0.02	*Gm or Tt*	1	0	0	0	Possible pilot whales or bottlenose dolphin
07/31/2021	0.6	*Md*	2	0	0	0	
		Pm	1	0	0	0	Sperm whale slow clicks?
		Gm	1	0	0	0	possible pilot whales
		Pe	1-2	0	0	0	3-3, 3-4, 2-6: possible Melon-headed whales; Could be a very large melon-headed whale group stretching from F-16 down to 3-4.
		Tt	0-1	0	0	0	F-16, F-17, F-18, F-12: possible Tursiops or Melon-head
		UD	2	0	0	0	
08/01/2021	5.5	*Pe*	1	1	1	1	FastLoc Tag deployed at 18:00 UTC near H-19. Additional recordings taken from 19:04-21:14 UTC. Estimated group size

							150+. Groups splitting and rejoining constantly.
		Lh	1	0	0	No	Found with melon-headed whales
		Md	7	0	0	No	
		Sb	X	0	0	No	Posits scattered throughout a large area of the southern portion of the range. Number of acoustic groups not tracked.
		UM	1	0	0	No	Possible blue whale near sesnors I-1, I-2, B-1
		UM	1	0	0	No	Possible false killer whale at 20:28 UTC near 3-4.
08/02/2021**	6.5	UD	2	0	0	No	Possible rough-toothed dolphins. Dense clicks and then upsweep whistles at 8 kHz. Similar area as yesterday's rough-tooth

							groups. Other unidentified near F-7.
		UM	1	0	0	No	Low frequency sound between I-1 and B-1
08/03/2021**	6.5	*Sb*	5	0	0	No	Still in same area they were on 8/1 (southern portion of range). Possible bottlenose among the group.
		Tt	2	0	0	No	Among the rough-tooths.
		Md	1	0	0	No	L-9, K-9
		Pm	1	0	0	No	Faint, probably just off range? F-10, F-16, F-20. Slow ICI to start (>2 seconds), then ~1.6 seconds starting 22:05 UTC creating a nice posit track.
		UM	1	0	0	No	Low frequency posits, tones

							around 200 Hz (L-1, 5-1)
		UD	3	0	0	No	
08/04/2021	8	*Md*	2	0	0	No	
		Sb	3	3	3	No	With bottlenose. Extra recordings taken between 16:58-22:00 UTC. Visually identified south of G-18 at 18:57 UTC.
		Tt	1	1	1	No	Visually confirmed at 19:55 UTC
		UD	2	1	0	No	Either melon-head and or pilot whales for one group, the other is unknown.
		UM	1	0	0	No	Low frequency tone at 30 Hz, between K-2 and A-1. Loud call, propagates all the way to 1-10
08/05/2021	5	*Sb*	1	0	0	0	
		Tt	2	1	0	0	Too far north for visuals due

							to weather. Other group attempted but water too rough near F-1.
		Md	7	0	0	No	Between L-1, K-1, & 5-1. Too far north for visuals due to weather.
		UD	2	0	0	No	Possibly false killer whale.
		UD	1	0	0	No	Near 3-3. Not rough-tooth dolphins, odd flat whistles ~8.5 kHz and a few higher harmonics. Radio communications went down so couldn't get information to visuals before animals went quiet.
		UM	1	0	0	No	Near K-2 and/or I-2. Too far north for visuals due to weather.
08/06/2021	6.5	*Sb*	1	1	1	No	Larger down sweeps and large buzzy sounds.

		Md	10	2	0	No	I & K string (1-4 through K-4 region). Rough waters, no visual confirmation.
		UD	2	1	0	No	Possibly false killer whales on 3-4. Again by K-8, visually couldn't make it past 5-3 due to weather.
		UD	6	0	0	No	Spread out whistle posits throughout southern portion of range. Most likely rough-tooths, but unsure.
08/07/2021*	7	*Sb*	4	1	1	No	Directed to last group later in the day after returning from pilot whales south of range around 22:139:39 UTC.
		Tt	3	0	0	No	
		Md	11	0	0	No	
		UD	1	0	0	No	Possible false killer whales

							near B-9 and I-10. Too far north for visuals to get.
		UD	3	0	0	No	Species unknown.
08/08/2021*	6.5	*Sb*	X	NA	NA	NA	Heard throughout the day, groups not followed
		Tt	X	NA	NA	NA	Heard throughout the day, groups not followed.
		Md	12	0	0	0	Too far north for visuals to make with NE winds.
		UD	1	1	0	NA	Possible melon headed whales heading SE. Click posits between 4-7 and 2-9, and whistle posits just SW & SE of 3-6. Weather got too rough before visuals could reach the directed location.
		UD	1	0	0	NA	Possible false killer whales

							near F-6 at 21:28:13 UTC
08/09/2021	6	*Md*	8	0	0	0	
		Sb	1	1	1	1	with a group of RT dolphins NE of F-8 and had tagged one NE of F-8 at about 2036
		Pe	1	1	1	1	Confirmed melonheads travelling NW; with melonheads between 5-3 and 4-5, got a tag on
		Pc	2	0	0	0	False killer whales? Posits between A-4 and L-5
		UD	4	0	0	0	
08/10/2021	1.6	*Md*	1	0	0	0	
		Pe	2	0	0	0	Melon-heads
		Pc	1	0	0	0	False killer??
		UD	5	0	0	0	
08/11/2021	6.3	*Md*	11	1	1	2	Cascadia just reported that they found the Md at 4-6. It was a group of 7 animals. They deployed 2 tags and got

							1 genetic sample. Great day!!
		Pe	3	2	1	1	melonheads moving N towards F18; seem to be moving off range; moving slowly to NE; moved off range. they did find this group of melon head and were able to get a tag out. might be melon headed - maybe are coming back on range? Maybe not coming back on range afterall.
		Sb	3	0	0	0	Steno?
		Pm	1 -> 2	0	0	0	sperm whales might be slowly moving N; seem to have split into 2 groups. 1-2 animals near L-9 and others closer to A-9; K-11; range pretty quiet aside from sperm whales right now.

							only clicking on A-9 now. Some animals might have moved N;- some E.
		UD	4	0	0	0	
08/12/2021*	5.8	*Md*	2	0	0	0	
		Pe	1	1	1	0	they picked up the melon headed whales between 3-4 and 3-3
		Sb	3	0	0	0	looks like Steno - closest to 1-10
		Tt	1	1	1	1	likely Tursiops inshore of F6/F7. bunch of manual posits between C5/C6. That is the area that they went to and found a group of Tursiops and got a tag on one.
		UD	2	0	0	0	
08/13/2021*	3.3	*Md*	3	0	0	0	
		Zc	1	0	0	0	
		Pe	1	0	0	0	could be Peps

		Sb	1	1	0	0	Robin is heading towards 3-7. maybe Steno? they tried to get to 3-6 but it is really choppy
		UD	1	0	0	0	
08/14/2021	3.9	*Md*	8	0	0	0	
		Tt	1	1	1	1	Robin reported a dispersed group of Tursiops moving quickly to the South along the shore. got a tag out on a Tursiops
		Sb	2	0	0	0	
		Pe	1	0	0	0	melon headed? have been moving to the SE
		UD	3-4	0	0	0	One group may have been beaked whale or dolphin; confusing. Group by G-9, G-10, G-11, G-7 ,inshore of H phones: Robin said that they had been with

							a group of Tursiops that came in from the south just now, which may be this group.

Notes: Visual observers were not on range between 8/2-8/3/2021 due to ongoing naval ops, so no acoustic observations could be visually verified. Funding sponsor requested no tagging of rough-tooth and bottlenose dolphins until the last couple of days to conserve tags. On 8/07/2021 the visual observers were directed by a tour operator to a group of 25 pilot whales just south of the range at 17:55:23 UTC. Weather too rough to successfully tag. On 08/08/2021 the visual observers encountered a group of false killer whales 11 minutes after leaving the dock and followed them down to Poipu, successfully deploying 1 tag. On their way to the range afterwards, they ran into a group of short-finned pilot whales and successfully tagged one individual. Weather deteriorated soon after, so they never made it on range. On 08/12/2021 at 21:31 Cascadia was near E-7 with a large mixed group of Steno and Tursiops. On 08/13/2021 Cascadia got info from a crew boat about a sighting of melon-headed whales southeast of the range. They went there and found a large group of melon heads south of the range. It was the same group they were with several days ago, and they got a tag on.