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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), 2020

1 February 2021

Marine Mammal Monitoring on Navy Ranges (M3R) Program
Ranges, Engineering and Analysis Department
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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 training ranges, the Southern California Anti-submarine Warfare Range (SOAR) in Southern California and the 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 FY20 the M3R program had six areas of focus for SOAR and PMRF: 1) long-term data collection and the evaluation of abundance and distribution of Cuvier's beaked whales at SOAR and Blainville's beaked whales at PMRF; 2) the effect of two types of mid-frequency active sonar (MFAS), hull-mounted and dipping sonar, on Cuvier's beaked whales at SOAR and Blainville's beaked whales at PMRF; 3) evaluation of the M3R low-frequency detector algorithm at SOAR; 4) determination of Autogrouper detection statistics for Blainville's beaked whales at PMRF; 5) the development of tools to automatically characterize the ambient noise at SOAR using archive files; and 6) the support of on-site field exercises at SOAR and PMRF with real-time monitoring using the M3R system. The methods and results for each of these projects are presented and discussed.

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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 training ranges, the Southern California Anti-submarine Warfare Range (SOAR) in Southern California and the 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 FY20 the M3R program had six areas of focus for SOAR and PMRF: 1) long-term data collection and the evaluation of abundance and distribution of Cuvier’s beaked whales at SOAR and Blainville’s beaked whales at PMRF; 2) the effect of two types of mid-frequency active sonar (MFAS), hull-mounted and dipping sonar, on Cuvier’s beaked whales at SOAR and Blainville’s beaked whales at PMRF; 3) evaluation of the M3R low-frequency detector algorithm at SOAR; 4) determination of Autogrouper detection statistics for Blainville’s beaked whales at PMRF; 5) the development of tools to automatically characterize the ambient noise at SOAR using archive files; and 6) the support of on-site field exercises at SOAR and PMRF with real-

time monitoring using the M3R system. The methods and results for each of these projects are presented and discussed.

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Abbreviations and Acronyms

Acronym	Definition
AG	Autogrouper
AIC	Akaike Information Criterion
AIST	Advanced Instrumentation Systems Technology
ASW	Anti-Submarine Warfare
AUTEC	Atlantic Undersea Test and Evaluation Center
AUV	Autonomous Underwater Vehicle
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
FN	False Negative
FP	False Positive
GAM	Generalized Additive Model
GDOP	Geomteric Dilution of Precision
GLM	Generalized Linear Model
GVP	Group Vocal Period
FP	False Positive
HARP	High Frequency Recording Package
Hrs	Hours
HT	Height of posit (-1*depth)
HYD	Hydrophone
ICI	Inter-Click Interval
kHz	kilohertz
LF	Low-frequency
LIMPET	Low Impact Minimally Percutaneous Electronic Transmitter
M3R	Marine Mammal Monitoring on Navy Ranges

Acronym	Definition
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
NUWC	Naval Undersea Warfare Center
PD	Probability of Detection
PMRF	Pacific Missile Range Facility
RL$_{rms}$	Received Level root mean squared
RMS	Root mean squared
ROC	Range Operations Center
SCI	San Clemente Island
SMRT	Sound and Motion Recording Tag
SOAR	Southern California Anti-Submarine Warfare Range
SOCAL	Southern California
SWTR	Shallow Water Training Range
T	Time
TDOA	Time difference of arrival
Tukey's HSD	Tukey's Honest Significant Difference test
UWTR	Undersea Warfare Training Range
Whdetect	Whale Detection algorithm
WT	Whale Type

1 Introduction

1.1 Background

The Marine Mammal Monitoring on Navy Ranges (M3R) program utilizes the U.S. Navy's (Navy) 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, Pacific Fleet; the Southern California Anti-Submarine Warfare Range (SOAR) located off San Clemente Island (SCI), California, and the Pacific Missile Range Facility (PMRF), located off Kauai, Hawaii.

1.2 Study Goals

The goals of the FY20 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*) and Blainville's beaked whales (*Mesoplodon densirostris*)
2. Document the behavioral response of Cuvier's beaked whales and Blainville's beaked whales to Navy mid-frequency sonar training and testing events at SOAR and PMRF
3. Ground-truth results of the installed low-frequency detector algorithm at SOAR
4. Provide Autogrouper detection statistics for Blainville's beaked whale using the Class-Specific Support Vector Machine (CS-SVM) classifier at PMRF
5. Develop methods for ambient noise calculation using the hard-limited fast Fourier Transform (FFT) archives
6. 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 (MFAS), 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, Curtis 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 1.6-1.8 km. 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 (Jarvis et al. 2014). The M3R system was first installed at SOAR in July of 2006.

PMRF is located off the northwest coast of Kaua'i, 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 Tracking 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.

For this analysis, hydrophones in BARSTUR and BSURE were used. The depths of the BARSTUR hydrophones are about 1-2 km, while those of the BSURE hydrophones are about 2-4 km. As beaked whales are not typically found in the shallow waters of SWTR, this area was not included in the analysis. Only the newer BSURE refurb hydrophones were used in the analysis, as beaked whale vocalizations are primarily above 18 kHz. The M3R system was first installed at PMRF in January of 2011.

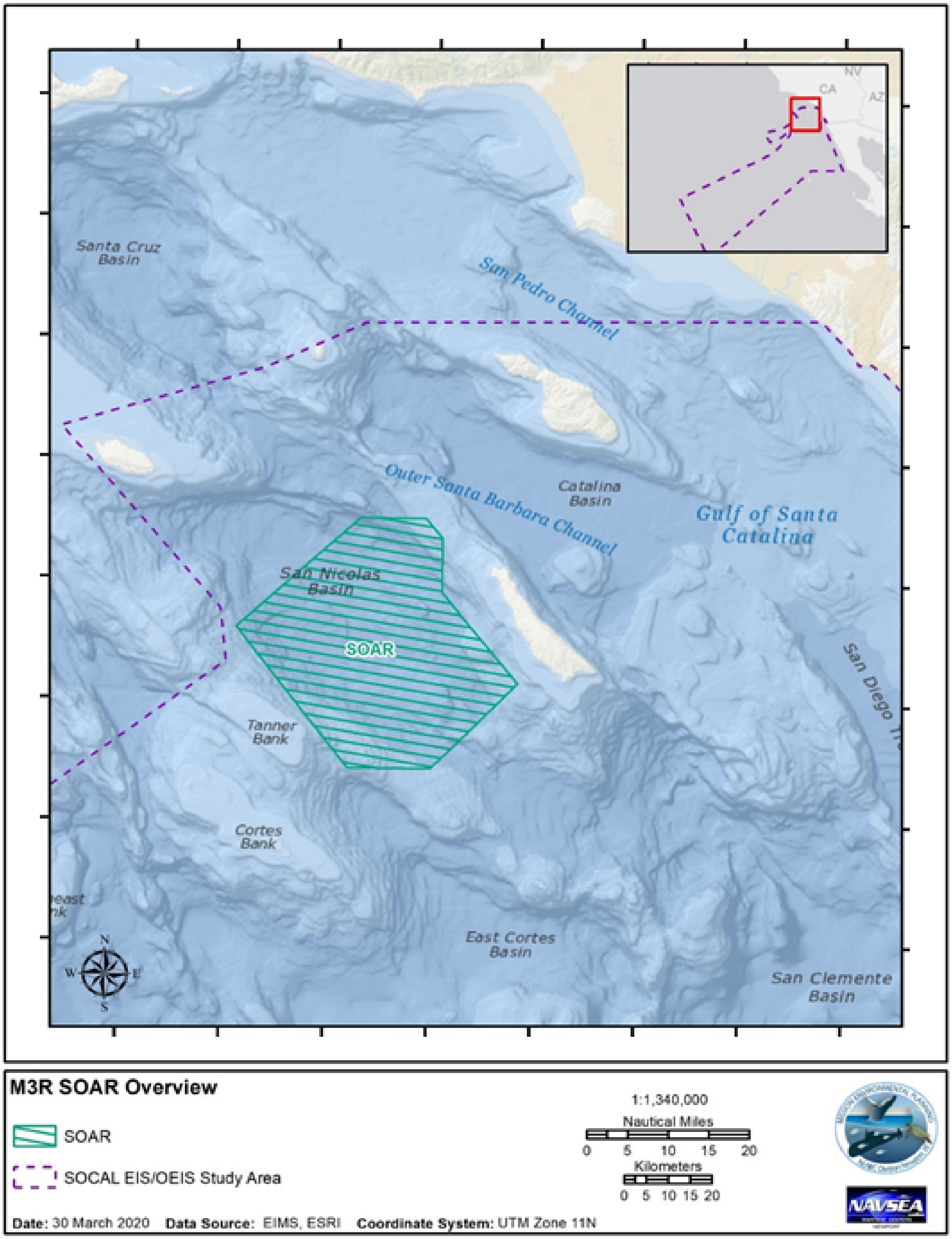


Figure 1. Location of SOAR hydrophone range, west of San Clemente Island off southern California.

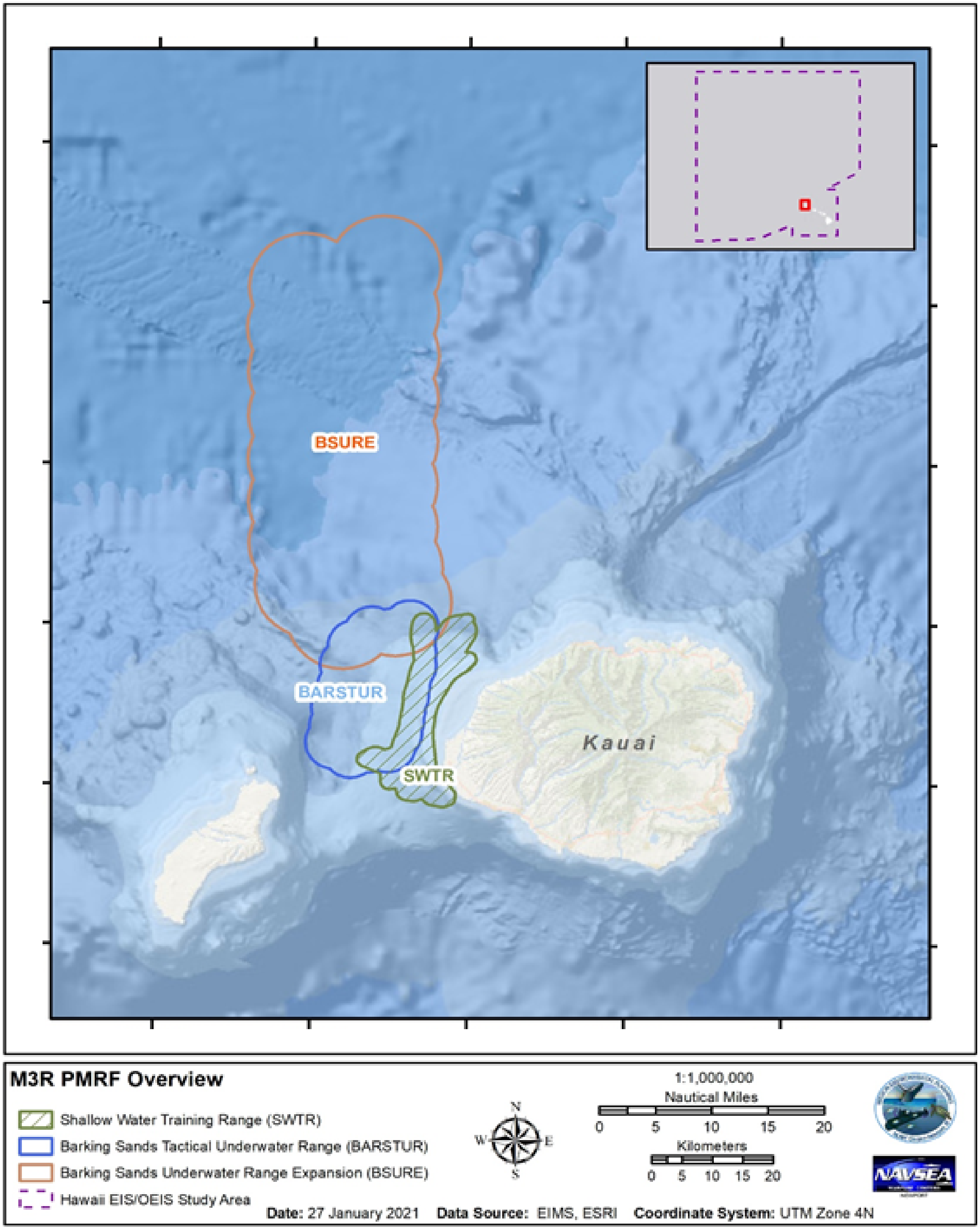


Figure 2. Location of PMRF hydrophone range, west of Kauai, Hawaii

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: an FFT-based detector, a 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.

At SOAR the CS-SVM detections of Cuvier's beaked whale foraging clicks from 2010 to 2020 (Table 1) were used to calculate abundance, and distribution was evaluated for data between August 2010 and October 2019. All hydrophones were included for abundance calculations, and distribution was analyzed using Group Vocal Periods (GVPs) from the newer 89 hydrophones. The GVP is the period of time during which beaked whale echolocation clicks are detected from a group of beaked whales on a deep foraging dive.

Table 1. Number of days per month for which M3R detection archives have been collected at SOAR.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2010					**7**			9	30	29	22	23
2011	22	27	8	3	13		6	28	30	31	22	31
2012	27	23	18	30	15	6	1	4		17	13	10
2013					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		26	22
2017	15		13	17	2		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	20	10+										

PMRF archives from September 2015 through 2020 for the BARSTUR and BSURE refurb hydrophones were analyzed for the Blainville's beaked whale distribution and abundance (Table 2). The CS-SVM detections were used to determine the Blainville's beaked whale groups present on the range.

Table 2. Number of days per month for which M3R detection archives have been collected at PMRF.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2015									5	1		
2016		11						11				
2017	0	27	31	30	31	30	18	29	30	30	30	31
2018	31	28	31	12	7	13	31	22	11	31	25	0
2019	3	17	31	30	31	30	22	0	0	0	30	31
2020	31	14+										

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

The distribution and abundance of Cuvier's beaked whales at SOAR and for Blainville's beaked whales at PMRF are assessed. In order to examine the spatial and temporal distribution of beaked whale foraging groups, their Group Vocal Periods (GVPs) are evaluated, which is the duration between the first and last echolocation clicks received on a hydrophone by a member of a beaked whale foraging group. 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 is 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.

The distribution of GVPs for both SOAR and PMRF is very right-skewed, with a large number of zeros and NAs (periods without effort), and is still very right-skewed with zeros removed. For example, at SOAR, the number of GVPs per hour-hydrophone ranges from 0 to 4 with a median of 0 ($\mu = 0.027$, $\sigma = 0.166$), and with zeros removed they range from 1 to 4 with a median of 1 ($\mu = 0.020$, $\sigma = 0.142$). At PMRF number of GVPs per hour-hydrophone ranges from 0 to 3 with a median of 0 (μ= 0.014, σ=0.120), and with zeros removed they range from 1 to 3 with a median of 1 (μ=1.007, σ=0.087). Log-transforming the data did not improve the normality (Figure 3, Figure 4).

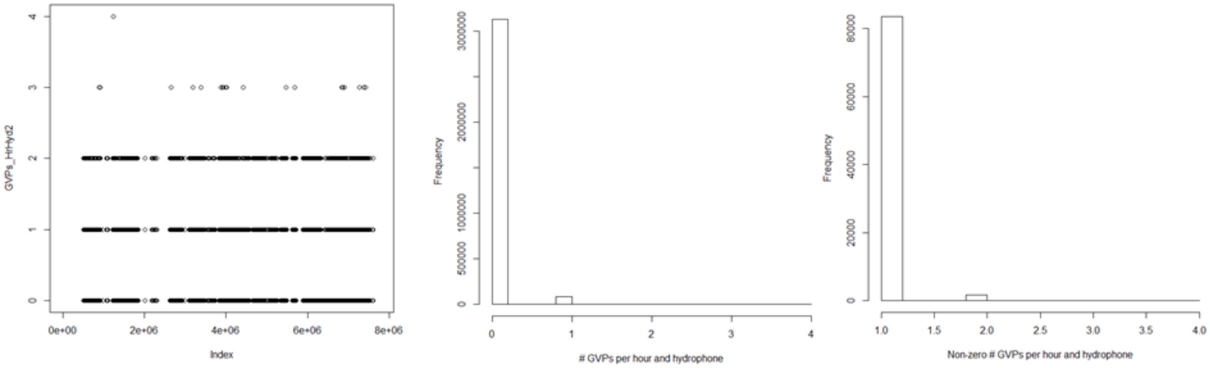


Figure 3. Number of GVPs per hour-hydrophone at SOAR.
Left: scatterplot, Center: histogram of all data, Right: histogram of data with zeroes removed

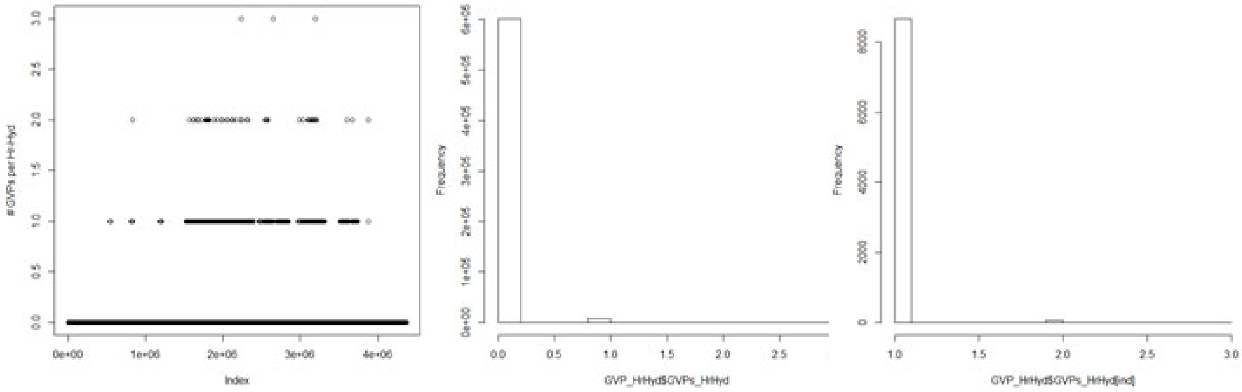


Figure 4. Number of GVPs per hour-hydrophone at PMRF.
Left: scatterplot, Center: histogram of all data, Right: histogram of data with zeroes removed

2.2.1.1 Beaked Whale Distribution - Statistical Modeling

A Generalized Additive Model (GAM) with a Poisson distribution and log link function was used to model the number of GVPs per hour-hydrophone on range (GVPs_HrHyd) (gam function, R version 3.5.1). This approach was chosen as the response GVPs_HrHyd is not normally distributed, and the Poisson distribution with the canonical link function was used as the data contain counts between 0 and 4 (SOAR) or 0 and 3 (PMRF).

The hydrophone latitude, longitude and depth are three of the predictors. The group location is considered the location of the 'center' hydrophone, or the hydrophone within the group with the most detected clicks. The water depth is approximated by the hydrophone depth, as the hydrophones are mounted from the seafloor.

To examine the long-term trend the sequential days over the analysis time period (Dy10Yr for SOAR, Dy6Yr for PMRF) was used as a predictor. Months (Mnths) was used as a predictor for seasonal variation, while the explanatory variable for diel patterns was the hours in a 24-hour cycle (Hrs). The latitude (Ylat) and longitude (Xlon) of the group's center hydrophone were used to estimate group locations, and the hydrophone depth (Dpth) was used as a proxy for water depth as a predictor. Smooths of all predictors were included in the final models (1) and (2), which were selected as the respective models with the lowest Akaike Information Criterion (AIC) value.

(1) *SOAR:* GVP_HrHyd.gam = gam(GVPs_HrHyd ~ s(Dy10Yr) + s(Xlon) + s(Ylat) + s(Dpth) + s(Hrs) + s(Mnths), family=Poisson(link="log"), data=GVP_HrHyd3)

(2) *PMRF:* GVP_HrHyd.gam = gam(GVPs_HrHyd ~ s(Dy6Yr) + s(Xlon) + s(Ylat) + s(Dpth) + s(Hrs) + s(Mnths), family=Poisson(link="log"), data=GVP_HrHyd)

An ANOVA was used with Year as a factor (3), (4), and with Month as a factor (5), (6), to evaluate if there was a statistically significant difference among years or months. These were followed with a Tukey's HSD test to see which pairs of years or months were statistically different.

(3) *SOAR:* GVPs_HrHyd_Year.aov2 = aov(GVPs_per_HrHyd~ as.factor(Year), data=GVPs_per_HrHyd_Year)

(4) *PMRF:* GVPs_HrHyd_Yr.aov = aov(GVPs_HrHyd~ as.factor(Yrs), data=GVP_HrHyd)

(5) *SOAR:* GVPs_HrHyd_Month.aov2 = aov(GVPs_per_HrHyd~ as.factor(Month), data=GVPs_per_HrHyd_Year)

(6) *PMRF:* GVPs_HrHyd_Mnth.aov1 = aov(GVPs_HrHyd ~ as.factor(Mnths),data=GVP_HrHyd)

The long-term trend in the data at SOAR was also evaluated using the scaled GVPs per hour-hydrophone data. As the values of these data ranged from 0.00658 to 0.16667, with a large number of zeros, a gamma distribution was used for the GAM model. Since the gamma distribution did not allow zeros, a small constant was added to the dataset. The number added was half the smallest non-zero value, or 0.00329. The identity link function was found to produce the best model, according to the AIC (7).

(7) *SOAR*: GVPs_HrHyd_Day10yr_gamma2.gam8 = gam((GVPs_per_HrHyd+0.003289474) ~ s(Day_10yr) + as.factor(Month), family=Gamma(link = "identity"), data= GVPs_per_HrHyd_Day10yr_Day_Month_Year)

2.2.1.2 Beaked Whale Abundance

Moretti (et al. 2010) described a passive acoustic method for determining Blainville's beaked whale density and abundance at the 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) $N = \frac{nd\, s}{rd\, T}$

where n_d is the total number of dive starts, 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, based on years of field work at the sites, there appears to be a much higher density of marine mammals, and in particular delphinids, at SOAR and PMRF than at 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:

$$(9)\ N = \frac{nd\ s\ (1-c)}{rd\ T\ PD}$$

where n_d is the total number of dive starts, 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).

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	Baird et al. 2006
rd	0.3 (0.17)	Schorr et al. 2014	0.42	Baird et al. 2008
C	0.185 (0.32)	Calculated	0.19	Calculated
PD	0.76 (0.05)	Calculated	0.28	Calculated

2.3 Results

2.3.1 SOAR

2.3.1.1 SOAR: Cuvier's beaked whale distribution

2.3.1.1.1 SOAR: Overview

Cuvier's beaked whale distribution was analyzed using SOAR archives from August 2010 through October 2019. A total of 49,923 hours of data were processed, with the number of hours per year varying from a low of 2,404 hours in 2010 to a high of 7,239 hours in 2018 (Table 4).

Table 4. SOAR: Total number of hours of effort per year in which SOAR data were recorded.

2010	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*
2404	5054	3474	3565	5975	6008	6294	4592	7239	5318

2.3.1.1.2 SOAR: ANOVAs for the scaled number of GVPs per hour-hydrophone

An ANOVA of the scaled number of GVPs per hour-hydrophone as a function of Year as a factor variable found that there was a significant difference with year (p <2e-16).

Tukey's HSD test determined that all year pairs were significantly different at least at the p=0.01 level except 2011-2010, 2015-2010, 2017-2010, 2019-2010, 2015-2011, 2019-2011, 2016-2014, and 2019-2015 (Table 5).

Table 5. SOAR 2010-2019: Significance level results from Tukey's HSD test between pairs of years.

Tukey's HSD significance levels between year pairs: SOAR 2010-2019								
2011-2010	2012-2011***	2013-2012***	2014-2013***	2015-2014***	2016-2015***	2017-2016***	2018-2017*	2019-2018***
2012-2010***	2013-2011***	2014-2012***	2015-2013***	2016-2014	2017-2015***	2018-2016***	2019-2017***	
2013-2010***	2014-2011***	2015-2012***	2016-2013**	2017-2014***	2018-2015***	2019-2016***		
2014-2010***	2015-2011	2016-2012***	2017-2013***	2018-2014***	2019-2015			
2015-2010	2016-2011***	2017-2012***	2018-2013***	2019-2014***				
2016-2010***	2017-2011***	2018-2012***	2019-2013***					
2017-2010	2018-2011***	2019-2012***						
2018-2010***	2019-2011							
2019-2010								
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1								

Similarly, using Month as a factor variable found a significant difference with month (p <2e-16), with all month pairs being significantly different at least at the p=0.01 level except 5-1, 7-3, 6-4, 12-5, 11-7, and 10-8 per Tukey's HSD test (Table 7).

Table 6. SOAR 2010-2019: Significance level results from Tukey's HSD test between pairs of months.

Tukey's HSD significance levels between year pairs: SOAR 2010-2019										
2-1***	3-2***	4-3***	5-4***	6-5***	7-6***	8-7***	9-8***	10-9***	11-10***	12-11***
3-1***	4-2***	5-3***	6-4	7-5***	8-6***	9-7***	10-8	11-9***	12-10***	
4-1***	5-2***	6-3***	7-4***	8-5***	9-6***	10-7***	11-8***	12-9***		
5-1	6-2***	7-3	8-4***	9-5***	10-6***	11-7	12-8***			

6-1***	7-2***	8-3***	9-4***	10-5***	11-6***	12-7***				
7-1***	8-2***	9-3***	10-4***	11-5***	12-6***					
8-1***	9-2***	10-3***	11-4***	12-5						
9-1***	10-2***	11-3**	12-4***							
10-1***	11-2***	12-3***								
11-1***	12-2***									
12-1*										
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1										

2.3.1.1.3 SOAR: GAM with Gamma distribution for the scaled number of GVPs per hour-hydrophone

The time series of days over ten years was a significant factor in determining the number of scaled GVPs per hour-hydrophone on range ($p<2.2e-16$). The smooth of the daily time series is shown in Figure 5, with plots of the residuals in Figure 6. This model shows fluctuations in the number of GVPs over the ten-year period from 2010 to 2019, though there appears overall to be a downward trend. There are peaks around 2010, 2013, and 2017, and the lowest numbers in 2018. The pattern of peaks and troughs, and the overall downward trend, is similar to the GAM fit with the Poisson distribution on the unscaled count data (Figure 7, a), except that the patterns towards the low and high ends of the Year scale (from 2010 to 2012, and 2019) are nearly mirror images. In both cases, the fits don't appear to be adequate at these extremes.

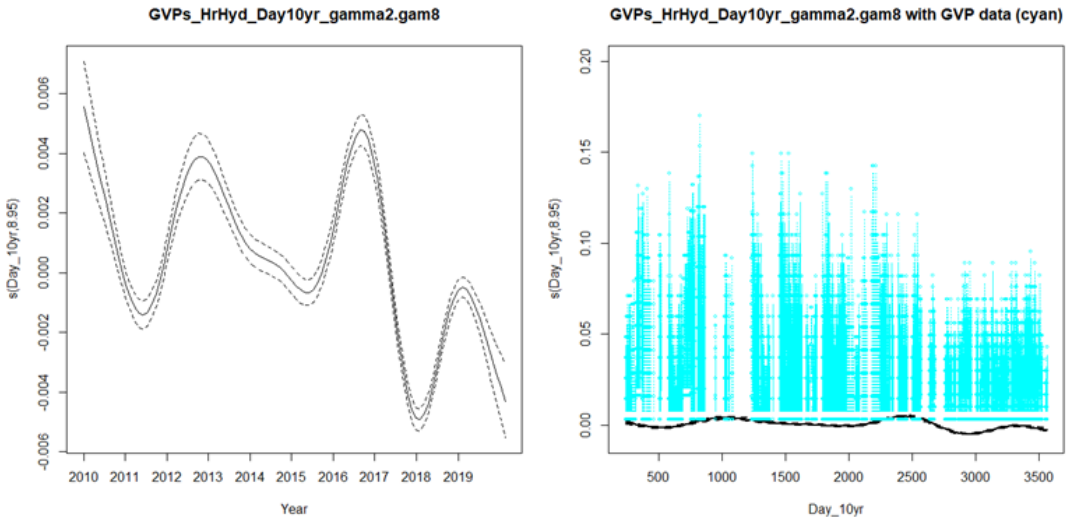


Figure 5. GAM for the scaled number of GVPs per hour-hydrophone
Left: **Smooth for the long-term trend predictor (Dy10Yr),** ***Right:*** **The smooth (black line) overlaid with the GVP data (cyan)**

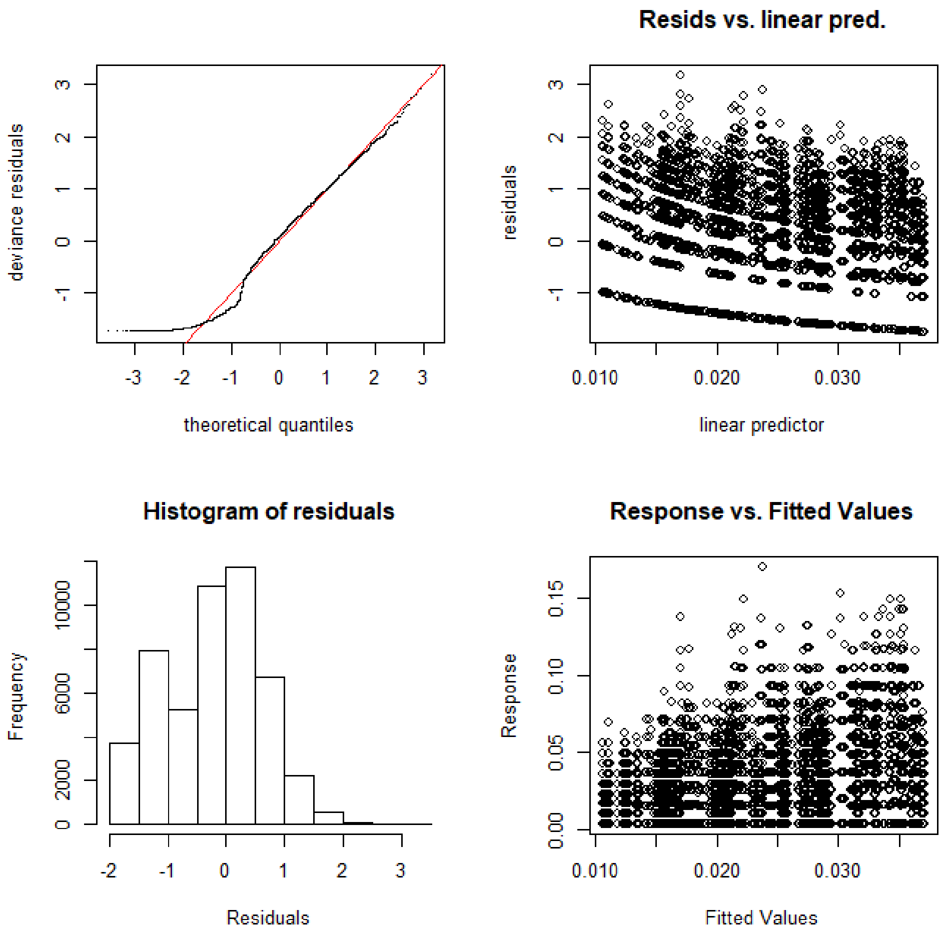


Figure 6. GAM model residuals

2.3.1.1.4 SOAR: GAM with Poisson distribution for the number of GVPs per hour-hydrophone

All predictors were significant for determining the number of GVPs per hour-hydrophone on the range (p<2.2e-16 for all predictors, for both parametric and nonparametric effects). The smooths for each predictor are shown in Figure 7.

Temporal Distribution: Over the past 10 years the number of GVPs per hour-hydrophone has fluctuated, but overall there appears to be a decreasing trend. The numbers peaked in about 2013 and again in 2016 to 2017, and reached a low point in 2018, with the numbers increasing slightly in 2019 (Figure 7, a).

There is a clear seasonal pattern, with the number of GVPs per hour-hydrophone peaking in January, followed by December and May. They reach a low point in September, and there is a smaller dip in numbers in March (Figure 7, b).

Spatial Distribution & Depth: The number of GVPs per hour-hydrophone increases when moving west with increasing longitude, reaching a peak at a longitude of about -119.0°, and then decreasing slightly (Figure 7, d). This longitude peak is about the center of the western half of the range. There is more variation in the number of GVPs per hour-hydrophone with latitude, although it increases as you come onto the range from the north, from about 33.1° to about 33° (Figure 7Figure 7, e). The highest number of GVPs is at about 32.73°, which is in the southern half of the range.

Therefore, Cuvier's beaked whales forage primarily in the west, and somewhat less so in the northernmost part of the range, as has been observed during field tests. The number of GVPs per hour-hydrophone also increases with increasing water depth, though there is a dip at 1400 m, and the number of GVPs are more constant from about 1600 to 1800 m (Figure 7, f).

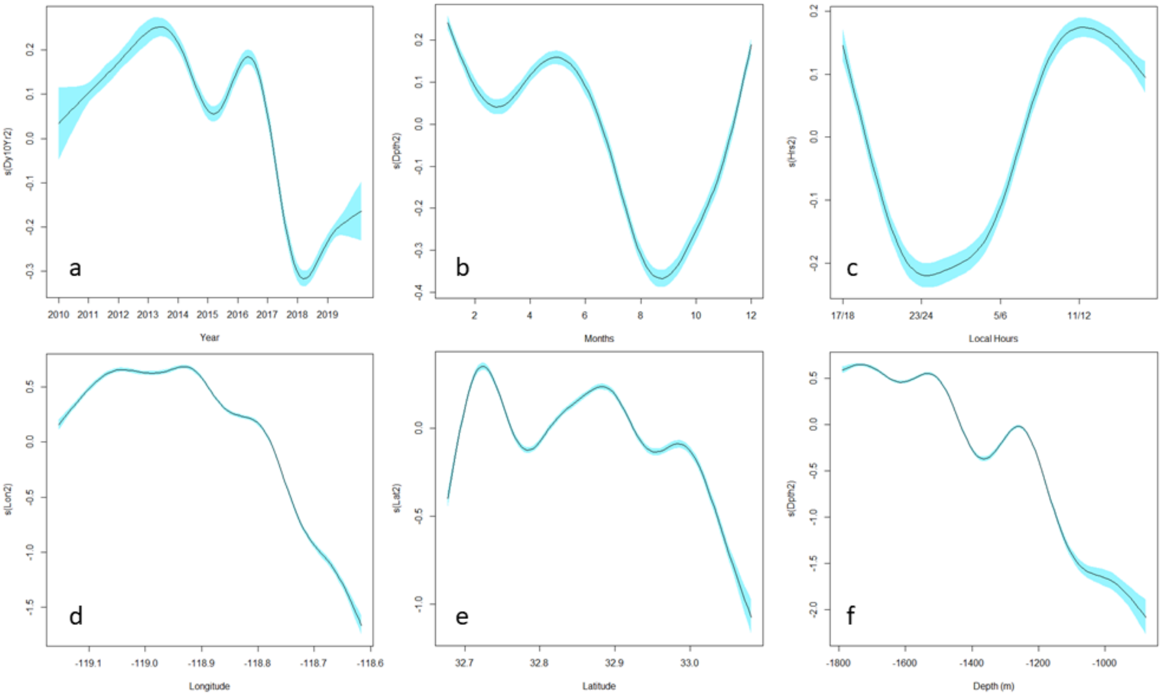


Figure 7. Smooths of the predictors for the number of GVPs_HrHyd
a) Long-term trend (Dy10Yr), b) Seasonal (Mnths), c) Diel (Hrs), d) Longitude (Lon), e) Latitude (Lat), and f) Depth (Dpth).

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 for 2010 to 2020 peaks in May at 61 animals, followed by a peak in January of 58 animals. The mean abundance is lowest in September at 21 animals, with another smaller drop in abundance in March to 42 animals (Table 7; 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).

Table 7. Mean monthly Cuvier's beaked whale abundances at SOAR averaged from 2010 to 2019.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
upper CI	67.15	56.37	54.37	57.97	73.15	57.34	41.23	31.20	25.33	54.29	44.86	66.10
mean abundance	57.52	48.17	42.29	51.67	60.97	50.59	34.58	27.38	21.18	37.44	38.17	54.65
lower CI	47.89	39.97	30.22	45.37	48.80	43.84	27.93	23.56	17.02	20.59	31.47	43.20

Over the 10-year time period the mean abundance in any month has varied from a high of 110 animals in October of 2019 to a low of 6 in March of 2018 (Table 8; Figure 8, right).

Table 8. Monthly SOAR Cuvier's beaked whale abundances 2010 - 2020.
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	25.35	27.80	17.99	48.63	64.64
2011	78.51	42.34	44.40	61.09	76.21	NA	31.38	38.03	7.64	19.43	29.62	45.68
2012	69.82	72.25	75.64	52.33	64.12	NA	15.79	20.55	NA	42.50	30.56	16.94
2013	NA	NA	NA	NA	105.12	69.39	49.19	19.98	17.12	22.74	32.13	64.00
2014	58.78	46.95	59.04	66.58	67.01	58.83	26.80	26.45	20.64	31.46	60.94	59.86
2015	55.38	34.19	39.95	46.56	42.67	41.43	24.99	19.20	26.30	39.78	39.92	89.71
2016	80.34	60.05	47.77	61.59	50.43	47.10	48.32	33.71	25.69	NA	44.46	50.68
2017	53.58	NA	34.22	47.51	39.20	NA	32.35	30.76	23.51	21.87	26.81	50.13
2018	47.05	33.26	6.25	36.17	45.46	39.46	42.16	26.36	28.00	31.33	30.42	50.20
2019	41.92	38.87	31.07	41.53	58.55	47.32	40.25	33.39	13.87	109.84	NA	NA
2020	32.27	57.48	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

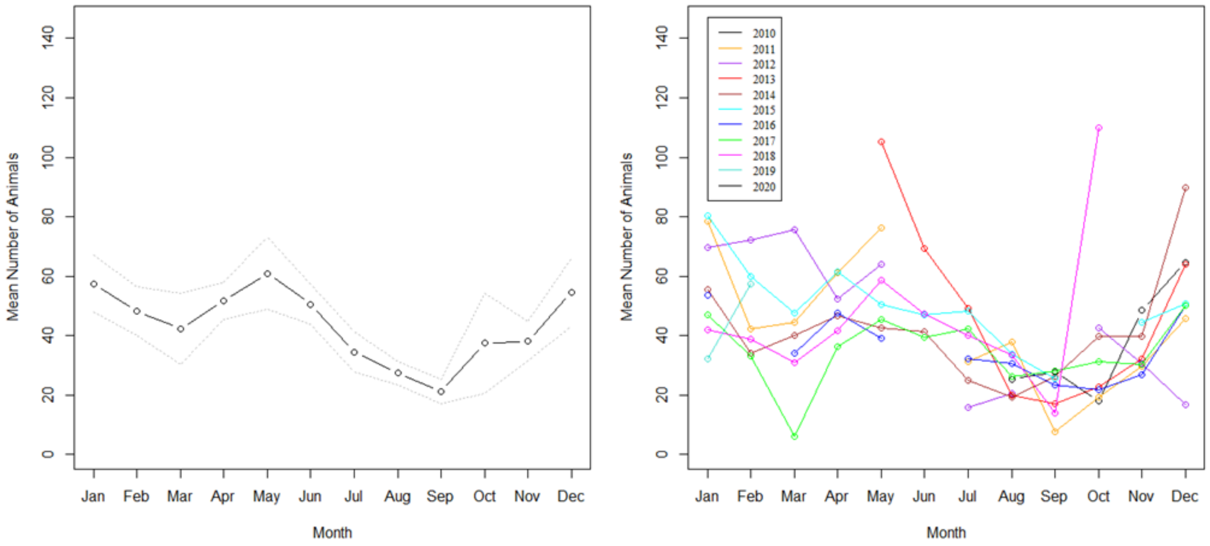


Figure 8. Mean monthly Cuvier's beaked whale abundance at SOAR
***Left:* averaged between 2010 and 2019, *Right:* for the years 2010 through 2019. Dashed lines indicate 95% confidence intervals.**

2.3.2 PMRF

2.3.2.1 PMRF: Blainville's beaked whale distribution

2.3.2.1.1 PMRF: Overview

Blainville's beaked whale distribution was analyzed using PMRF archives from 2015 through 2020. A total of 19,889 hours of data were processed, with the number of hours per year varying from a low of 110 hours in 2015 to a high of 7,855 hours in 2017 (Table 9).

Table 9. PMRF: Total number of hours of effort per year in which data were recorded.

2015	*2016*	*2017*	*2018*	*2019*	*2020*
110	473	7855	5661	5029	761

2.3.2.1.2 PMRF: ANOVAs for the number of GVPs per hour-hydrophone

An ANOVA of the number of GVPs per hour-hydrophone as a function of Year as a factor variable found that there was a significant difference with year ($p < 2e-16$).

Tukey's HSD test determined that all year pairs were significantly different at least at the p=0.01 level except 2016-2015 and 2020-2018 (Table 10).

Table 10. PMRF 2015-2020: Significance level results from Tukey's HSD test between pairs of years.

Tukey's HSD significance levels between year pairs: PMRF 2015-2020				
2016-2015	2017-2016***	2018-2017***	2019-2018**	2020-2019**
2017-2015***	2018-2016***	2019-2017*	2020-2018	
2018-2015***	2019-2016***	2020-2017***		
2019-2015***	2020-2016***			
2020-2015***				
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				

Similarly, using Month as a factor variable found a significant difference with month (p=2.19e-08), though many months were not significantly different per Tukey's HSD test. September was significantly different from all other months (at least at the 0.05 level), except for October and November. October was significantly different from February, and both October and November were significantly different from April and June (Table 11).

Table 11. PMRF 2015-2020: Significance level results from Tukey's HSD test for pairs of months.

Tukey's HSD significance levels between year pairs: PMRF 2015-2020										
2-1	3-2	4-3	5-4	6-5	7-6	8-7	9-8*	10-9	11-10	12-11
3-1	4-2	5-3	6-4	7-5	8-6	9-7***	10-8	11-9	12-10	
4-1	5-2	6-3	7-4	8-5	9-6***	10-7	11-8	12-09*		
5-1	6-2	7-3	8-4	9-5**	10-6**	11-7	12-8			
6-1	7-2	8-3	9-4***	10-5	11-6*	12-7				

7-1	8-2	9-3*	10-4**	11-5	12-6					
8-1	9-2***	10-3	11-4*	12-5						
9-1*	10-2*	11-3	12-4							
10-1	11-2	12-3								
11-1	12-2									
12-1										
Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1										

2.3.2.1.3 PMRF: GAM with Poisson distribution for the number of GVPs per hour-hydrophone

All predictors were significant for determining the number of GVPs per hour-hydrophone on the range ($p<2.2e-16$ for $\mathrm{Dy6Yr}$, Xlon, Ylat and Dpth; $p= 1.70e-05$ for Hrs; and $p=2.35e-07$ for Mnths). When models with each of these factors individually were compared, the model using Dpth as a predictor was best; however, when all predictors were considered together, the full model had the lowest AIC. The smooths for each predictor are shown in Figure 9.

Temporal Distribution: Aside from the early data in 2015, which was sparse, the number of GVPs per hour-hydrophone has remained relatively consistent through 2020, with slight fluctuations from year to year (Figure 9, Dy6Yr). There is seasonal pattern to the Blainville’s beaked whale GVP detections somewhat similar to that for Cuvier’s beaked whales at SOAR. The number of GVPs are lowest in September to October, with a second dip around March; and they are highest in December, January, and about June to July (Figure 9, Mnths).

Spatial Distribution & Depth: The number of GVPs per hour-hydrophone remains about the same from -158.5° to -159.5° longitude, and then decreases when moving west with increasing longitude (Figure 9, Xlon). This corresponds roughly to most detections occurring around the center or center-west of the range. The smooth for latitude with this model shows the number of GVPs are consistent from 22.1° to 22.3° latitude, and then increase north of 22.3° (Figure 9, Ylat). However, the smooth for the model that only includes latitude had the opposite trend, decreasing north of 22.3° while remaining consistent from 22.1° to 22.3°. This was the only predictor with a smooth that was significantly different in the single-predictor model from the full model. In either case, Blainville’s beaked whales primarily forage in the central and center-western portions of the range over the BARSTUR, and to some extent BSURE hydrophones, as is seen during field tests. The number of GVPs per hour-hydrophone appears to be consistent from 100 to 2000 m depth, dropping off with depths over 2000 m (Figure 9, Dpth).

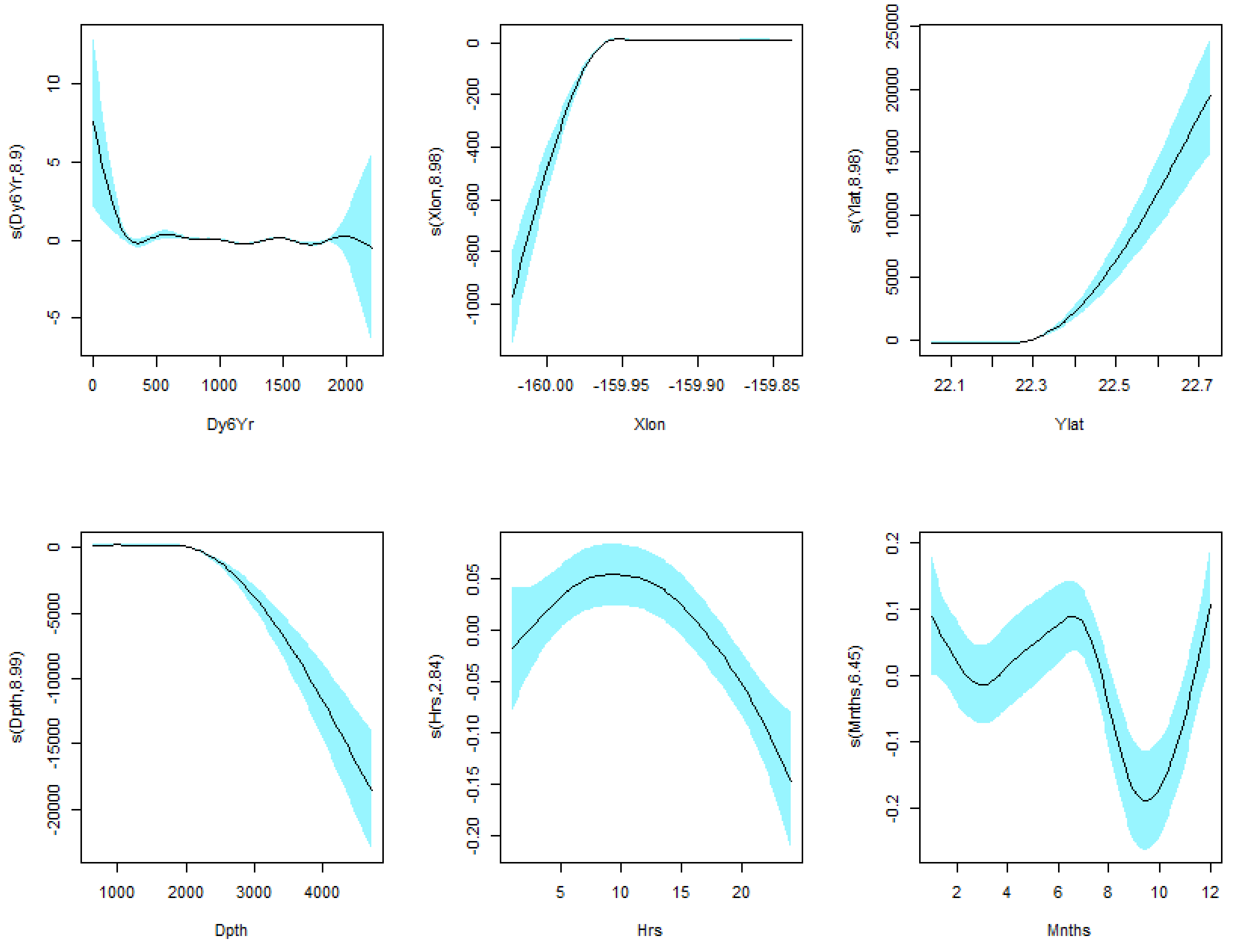


Figure 9. Smooths of the predictors for the number of GVPs_HrHyd.
Clockwise from upper left: Long-term trend (Dy6Yr), Longitude (Xlon), Latitude (Ylat), Depth (Dpth), Diel (Hrs), and Seasonal (Mnths)

2.3.2.2 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 monthly Blainville's beaked whale abundance for 2015 to 2020 is relatively constant through the year. The mean abundance peaks in May at 28 animals and is lowest in August at 20 animals (Table 12; Figure 10, left).

Table 12. Mean monthly Blainville's beaked whale abundances at PMRF averaged from 2015-2020.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
upper CI	26.95	28.32	26.40	31.95	31.68	34.99	32.99	27.21	27.71	28.95	25.89	30.46
mean abundance	25.57	22.25	24.03	24.92	27.53	23.83	25.47	19.84	23.24	25.62	21.17	22.67
lower CI	24.19	16.19	21.66	17.89	23.37	12.68	17.96	12.47	18.78	22.28	16.45	14.87

Over the six year time-period the mean abundance in any month has varied from a high of 38 animals in June of 2017 to a low of 10 in June of 2019 (Table 13; Figure 10, right).

**Table 13. Monthly PMRF Blainville's beaked whale abundances 2015-2020.
NAs indicate periods without data.**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2015	NA	NA	NA	NA	NA	NA	NA	NA	29.66	29.36	NA	NA
2016	NA	13.70	NA	NA	NA	NA	NA	10.46	NA	NA	NA	NA
2017	NA	25.83	26.33	34.31	27.20	37.47	35.79	20.19	19.56	26.36	22.83	29.56
2018	24.09	15.61	20.69	16.89	32.88	24.43	23.22	28.87	20.52	21.12	26.06	NA
2019	27.46	32.07	25.06	23.55	22.50	9.60	17.41	NA	NA	NA	14.62	15.78
2020	25.15	24.07	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

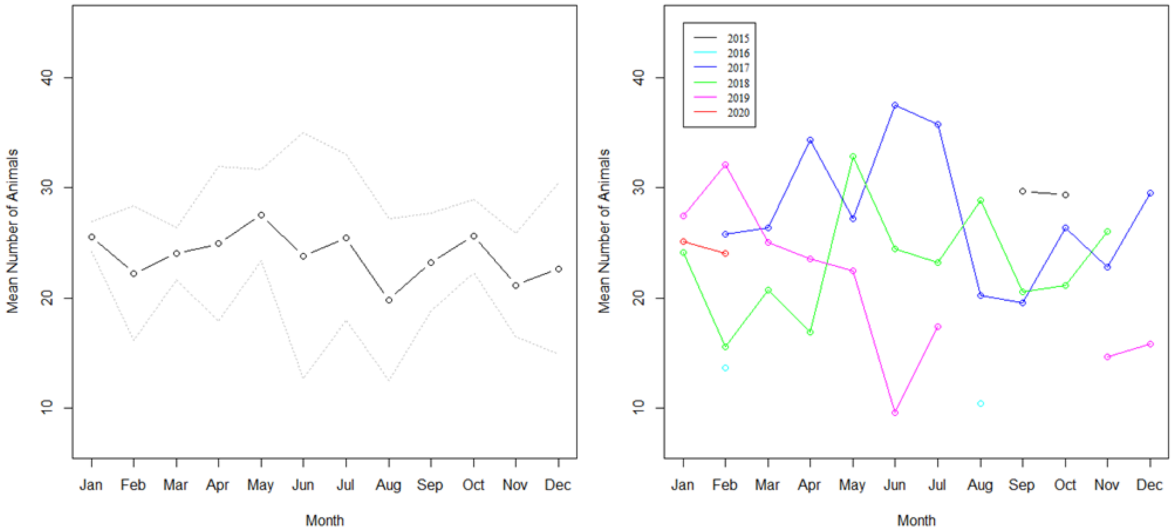


Figure 10. Mean monthly Blainville's beaked whale abundance at PMRF
Left: **averaged between 2015 and 2020,** ***Right:*** **for the years 2015 through 2020. Dashed lines indicate 95% confidence intervals.**

2.4 Discussion

2.4.1 SOAR

Our results support observations during field tests since 2006, that Cuvier's beaked whales prefer foraging in the western part of the range. This is consistent with a home range analysis conducted by Schorr (et al. 2019) in San Nicolas Basin from 2008-2017, which found that within SOAR there is a preference for the center to western portion of the basin and SOAR. Sightings and satellite tag locations of Cuvier's beaked whales in 2018 also indicate they primarily use the central to western portion of the SOAR range (Schorr et al. 2018). Previous studies (Benoit-Bird et al. 2016, Southall et al. 2019) examined, over four days in September 2013, the distribution of potential Cuvier's beaked whale prey items, squid and fish, in two parts of the northern SOAR, an eastern and western portion, along with an area off-range to the northwest. Active acoustic sampling from ship-based and autonomous underwater vehicle (AUV) echo-sounders found that the percentage of squid targets was significantly different among the sampling zones, with the western being the highest, followed by the off-range zone, and then the eastern zone. There was not a significant difference with sampling zone for fish targets. As the sampling zones in their study did not cover the full extent of the range, and the number of GVPs per hour-hydrophone increases with decreasing latitude, the southwestern portion of the range may provide an even richer foraging habitat than those evaluated in the echo-sounder survey. This is also an area where a high amount of beaked whale activity is observed during field tests. Benoit-Bird (et al. 2016) was limited in temporal scale covering only four days in September, the month typically with the lowest abundance of Cuvier's beaked whales. As noted by Benoit-Bird (et al. 2016) and Southall (et al. 2019), animals are likely exposed to sonar in all three of their survey zones, though the use of sonar would be higher on SOAR due to the training and test activities. The presence of the high-quality foraging habitat on SOAR is likely an important motivator for beaked whales to use those portions of the range, despite the presence of sonar.

The number of GVPs per hour-hydrophone also increased with increasing water depth, from 1 to 1.8 km. These depths are consistent with, and in some cases higher than numerous studies of these deep-diving cetaceans. In the Central Tyrrhenian Sea, Arcangeli (et al. 2016) analyzed data from two time periods and found that the preferred depths of Cuvier's beaked whales were 1131 m and 989 m for the 1990s and 2000s, respectively. From visual sighting data in the Pelagos Sanctuary in the north-western Mediterranean Sea, 48% of the Cuvier's beaked whales were found in water depths of 756 to 1389 m, though higher encounter rates were observed at depths between 1389 and 2021 m (Moulins et al. 2007). Griffiths and Barlow (2016), using drifting acoustic recorders in the southern California Current, documented beaked whale detections over abyssal plains and not associated with slope or seamount features. Ferguson (et al. 2005) surveyed a very large area in the eastern tropical Pacific Ocean, and found that the habitat typically considered as preferred for beaked whales, including features such as continental slopes, seamounts, and canyons, was likely too restrictive, as they encountered beaked whales over the abyssal plain as well as the continental slope. The mean water depth in which Cuvier's beaked whales were sighted was 3.4 km, with a maximum of over 5.1 km, considerably deeper than the deepest parts of the SOAR range (Ferguson et al. 2005). Ongoing Cuvier's beaked whale tagging at SOAR over 10 years have found tagged Cuvier's beaked whales utilizing the deeper waters of SOAR, primarily in the western part of the range (Schorr et al. 2018). Recent results from a study of 19 satellite tagged Cuvier's beaked whales off southern California found the mean foraging dive was to 1182 m, while the mean of the maximum depths for foraging dives was 1427 m (Barlow et al., 2020).

Though there are fluctuations in the number of Cuvier's beaked whale GVPs per hour-hydrophone, there appears to be a slightly decreasing trend from 2010 through 2019, though the presence of a trend has not yet been statistically quantified. They appear to have peaked in 2013 and 2015-2017, and reached a low point in 2017.

The GVPs per hour-hydrophone vary seasonally, with a peak in January, followed by peaks in December and May. The peak in the beginning of the year coincides with a period in which there are typically no sonar exercises occurring on the 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) show a similar low point in September (Baumann-Pickering et al. 2014). The sites shown by Baumann-Pickering are located to the northwest and southeast of SOAR.

The temporal distribution was initially examined with the number of GVPs per hour scaled by the number of active hydrophones. This resulted in fractional values for the response between 0 and 0.1667, including a large number of zeros, and therefore a gamma distribution with an identity link function was found to be the best GAM model for the data. However, when the additional spatial predictors were added, a data structure was used with the original counts of GVPs per hydrophone and hour. In both cases, and particularly with the count data, there are a very large number of zeros, in part because of the hourly scale used. There are also a large number of NAs in the dataset. The model may be improved by using a zero-inflated or hurdle model, and possibly by using a coarser scale, such as daily data.

Another consideration is that the CS-SVM classifier was updated in 2014. The Cuvier's beaked whale foraging click class remained the same, but the combination of potential classes was modified, and it should be investigated whether that change could have had an impact on the detectability of Cuvier's beaked whale echolocation clicks.

2.4.2 PMRF

While acoustically monitoring for animals during field tests at PMRF, Blainville's beaked whales are generally found over the BARSTUR and southern BSURE hydrophones. This field experience is consistent with the results of the GAM, which found the most beaked whale foraging in the center and center-west of the range over BARSTUR, and to some extent on the lower BSURE hydrophones. The depths of most Blainville's beaked whale detections at PMRF are consistent with the median depth of 1155 m for island-associated Blainville's beaked whales found by Baird off Hawai'i (Baird 2019).

The number of Blainville's beaked whale GVPs at PMRF appears to be relatively consistent over the past six years. As the number of GVPs is directly proportional to abundance, this would indicate that the abundance has remained stable from 2015 to 2020. There appears to be a seasonal pattern to the GVP s, which is in contrast to Martin (et al. 2020), which found no clear seasonal pattern in Blainville's beaked whale abundance between August 2018 and August 2019. The pattern found at PMRF is similar to that found for Cuvier's beaked whales at SOAR, with peaks in January, December and June, and the lowest numbers detected in September.

3 Behavioral response of beaked whales to mid-frequency sonar

3.1 Introduction

Beaked whales have been documented to respond to mid-frequency sonar (DeRuiter et al. 2013, Falcone et al. 2017, Manzano-Roth et al. 2016, McCarthy et al. 2011, Tyack et al. 2011). The goal of these analyses was to examine the effect of recent opportunistic exposure to Navy training and testing events on foraging beaked whales.

3.2 Methods

3.2.1 Data Processing

3.2.1.1 Overview

Data from SOAR in 2019, and from PMRF in 2018 and 2019, were used for this analysis. The FFT detector reports were processed through an automated sonar detector that outputs the occurrence of MFAS signals, or pings, within a specified frequency band and time duration. The start time, number of FFT bins, duration, peak frequency and peak level for signals that exceeded the frequency and duration (number of consecutive FFT bins) thresholds were provided. The MFAS detector created a record for any signal with a duration longer than 1 second within the MFAS frequency bands; the actual signals transmitted during MFAS operations are not fixed, but are selected based on daily conditions and the objective of the operation. Therefore, false positive detections (particularly of delphinid whistles) were common. Additionally, the detector reports all detections on any hydrophone; it does not correlate detections of the same signal across multiple hydrophones. To filter out false detections, only detection reports with a peak magnitude level above a certain threshold were retained. This threshold ensured that the detections were likely to be from sonar on the range. Periods with sonar were compared to the SOAR or PMRF event schedule to determine type of event. Events were broken into three types: (1) events that involved primarily hull-mounted surface ship sonar, (2) events that primarily involved helicopter-deployed dipping sonar, and (3) events that involved both types of sonar. Time was grouped into one-hour periods, and each period was marked for the presence or absence of sonar at some point during the time window.

3.2.1.2 SOAR

The 2019 SOAR event schedule was used to isolate testing and training events that coincided with sonar use. A total of 53 events were categorized as follows: (1) 12 events that involved primarily hull-mounted surface ship sonar, (2) 32 events that primarily involved helicopter-deployed dipping sonar, and (3) nine events that involved both types of sonar. Periods with sonar detections were then compared to the SOAR event schedule to determine type of event. Before and after periods were designated as ten one-hour time windows without sonar surrounding time windows encompassing the event with sonar. The before time period was considered a baseline.

The following information about the event groups was annotated: date of detections, time of detections, GVP, location: non-edge only groups (0) or edge only groups (1), period_bda, event number, and event type (Table 14).

Table 14. SOAR and PMRF response and explanatory variables used in the statistical modelling.

SOAR		PMRF	
Variable	**Description**	**Variable**	**Description**
GVP	# of GVPs per hour	**GVP**	# of GVPs per hour
Period_BDA	1=before sonar 2=during sonar 3=after sonar	**BDA**	1=before sonar 2=during sonar 3=after sonar
EventType	1=hull-mounted sonar (n=12) 2=helicopter-deployed dipping sonar (n=32) 3=both (n=9)	**Type**	1=hull-mounted sonar (n=9) 2=helicopter-deployed dipping sonar (n=6)

3.2.1.3 PMRF

The 2018 and 2019 PMRF range schedules were cross-referenced with total hourly sonar detections across the PMRF range to determine sonar detections associated with scheduled test events. For all exercises during which there were sonar detections, the date and time of the first and last detection were used to define the start and end time of the exercise. The number of hours with no sonar detections before and after the exercise was also recorded.

Events during which sonar detections were recorded, and which were preceded and followed by 10 or more consecutive hours with no sonar detections, were selected for further analysis. The 10-hour period before the exercise was used to establish baseline conditions. These selection criteria resulted in 15 events in 2018 and 2019: nine of which were type 1, or hull-mounted sonar (ship) and six of type 2, or dipping sonar (helo).

The number of GVPs per hour were recorded for the before, during, and after periods, and exercises were classified based on sonar type (Table 14).

3.2.2 Statistical Modelling

3.2.2.1 SOAR

Generalized Linear Models (GLMs) were used in R (glm function, R version 3.5.3) with a Gamma distribution and the default inverse link function to model the number of GVPs per hour on range as a function of the $\mathrm{Period\_BDA}$ and $\mathrm{EventType}$ (Table 14). Since the Gamma distribution does not allow zero values for the GVPs, a small offset (0.00001) was added to the data. For both SOAR and PMRF the before and after periods were each 10 hours in length, and were periods that included no significant sonar. The during periods varied in length, and may not have had significant sonar detections in each hour. The best models were chosen as those with the lowest AIC values.

An ANOVA, followed by Tukey's HSD, was then conducted for these two sets of explanatory variables (R functions aov and $\mathrm{TukeyHSD}$) to determine if they had a significant effect on the number of GVPs detected, and if so, which levels of the factor variables contributed to the number of GVPs detected.

3.2.2.2 PMRF

GLMs were fit with the poisson family and the default log link function to model the number of GVPs per hour on range as a function of the period BDA and event Type (Table 14). No significant interactions were found between BDA and Type, and models with the lowest AIC were chosen using the AICtab

function in R. The best model used BDA as a factor variable as the only predictor, followed by a model that used both BDA and Type as factor variables.

An ANOVA, followed by Tukey's HSD, was then conducted for these two sets of explanatory variables.

3.3 Results

3.3.1 SOAR

A total of 53 events were analyzed, with each event consisting of a before, during and after period (Figure 12). Since the during time periods were variable in duration depending on the length of the event, the overall event durations also varied (**Figure 11**).

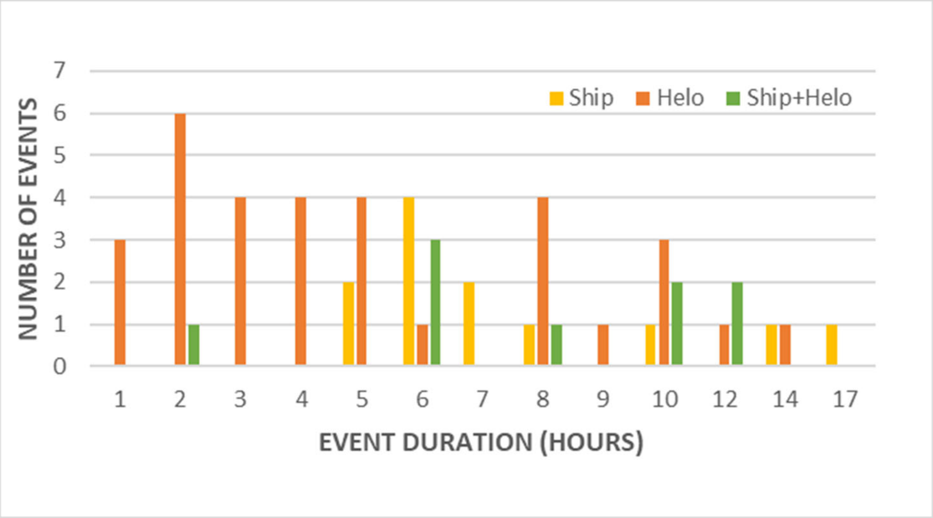


Figure 11. SOAR sonar event durations.

When only EventType was used as a predictor in the GLM, both the hull-mounted sonar (p<2e-16) and helo-dipping sonar (p=2.52e-06), had significant effects on the number of GVPs detected. When both types of sonar were present there was also a statistically significant effect, but at a lower significance level (p=0.0273).

When both EventType and Period_BDA were used in the model, both were significant for predicting the number of GVPs detected. All periods were statistically significant, as were all event types, though the highest levels of significance were for the before period and hull-mounted sonar (p<2e-16), and for the before period and the helo-dipping sonar (p=3.45e-06).

Results of an ANOVA also showed that both the EventType (F=5.324, p=0.00497) and Period_BDA (F=11.413, p=1.21e-05) were statistically significant for determining the mean number of GVPs detected per hour on the range. For EventType, the difference between hull-mounted and helo-dipping sonar was the only significant factor (p<0.001). For Period_BDA, there were significant differences between before and after (p=0.0134005) and before and during (p=0.0177938). There was not a significant difference between the during and after periods (Figure 12).

Overall, the EventType appears to have more of an impact on the number of GVPs detected than the Period_BDA. For the EventType, hull-mounted sonar appears to have been more significant than helo-dipping sonar, and for Period_BDA, there were significant differences between before and both during and after, but not between during and after.

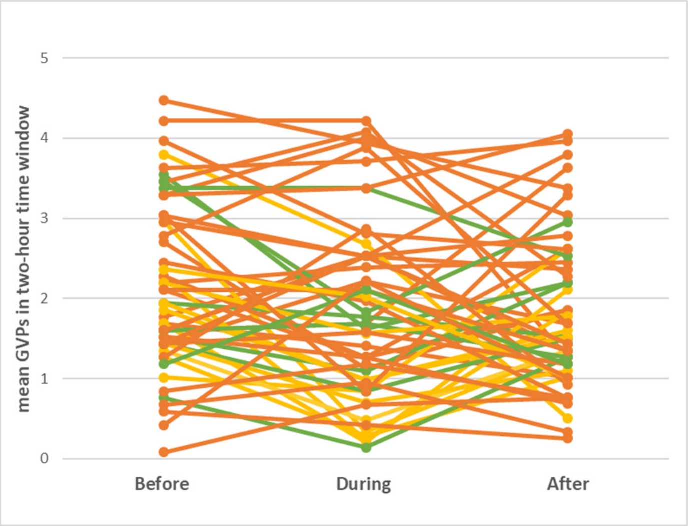


Figure 12. Mean number of GVPs per one hour time window before, during, and after a sonar event
***Yellow*: a hull-mounted sonar event, *orange*: a dipping sonar event, *green*: an event with both types of sonar**

3.3.2 PMRF

For PMRF 15 events were analyzed (Figure 13). The best model only included BDA as a predictor variable, while the model with the next lowest AIC included both BDA and Type. No significant interaction effects were found between BDA and Type.

When considering only the BDA period, the differences between before-during (p=3.54e-06) and before-after (p=0.00106) were statistically significant.

When both BDA period and event Type were considered, only the BDA was statistically significant in explaining the number of GVPs detected, with the before period significantly different from both the during period (p=3.78e-06) and the after period (p=0.00108). There was no significant effect found on the number of GVPs by the type of sonar, likely due to the low sample size.

ANOVAs also indicated that only the period BDA had a statistically significant effect on number of GVPs on range (p=3.2e-05), as was found with the GLMs.

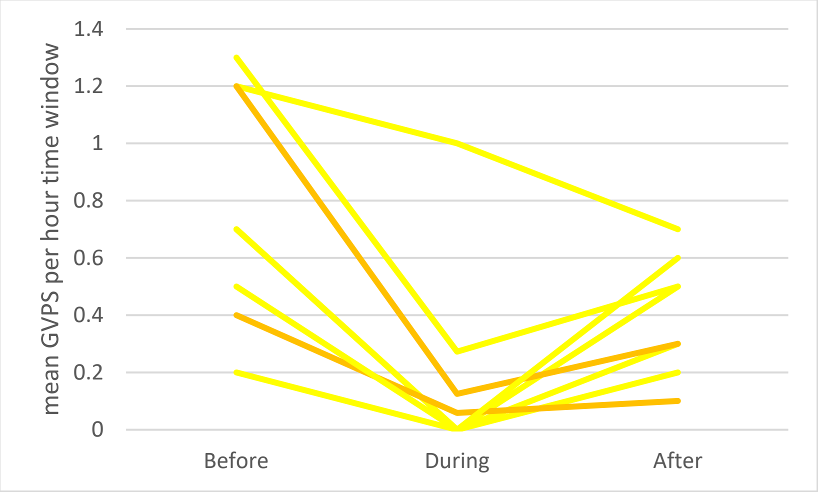


Figure 13. Mean number of GVPs per one hour time window before, during, and after a sonar event
***Yellow*: a hull-mounted sonar event, *orange*: a dipping sonar event, *green*: an event with both types of sonar**

Tukey's HSD test indicated that there was no significant difference between sonar types, and that the only statistically significant differences for period BDA were between before and during (p=0.0000308) and before and after (p=0.0031632) (Figure 14).

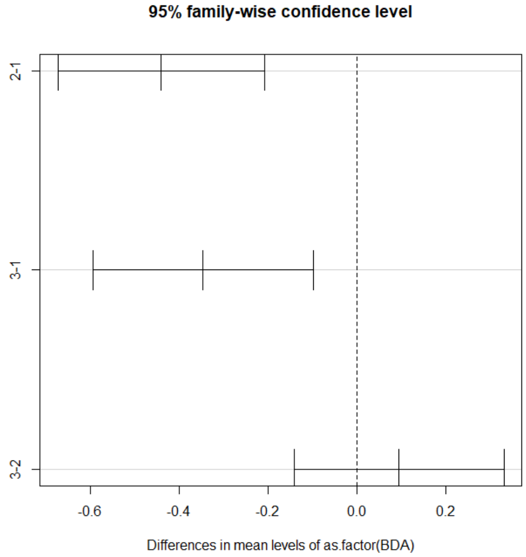


Figure 14. PMRF: Difference in means for period BDA

3.4 Discussion

The data presented here show a consistent result of changes in detections of foraging beaked whales of two different species in the presence of MFAS. There was a statistically significant difference between the before period and both the during and after periods for species on both ranges. The decrease in detections of foraging animals could be a result of increased inter-deep dive interval observed by Falcone et al. (2017) in the presence of MFAS. At SOAR, the hull-mounted sonar appears to have been more significant than the helo-dipping sonar for determining the number of GVPs detected on range, but at PMRF there was not a statistically significant difference between sonar types. The lack of difference in type of sonar was likely due to low sample size, due to the restricted years of the analysis.

Additional years should be added to the analysis to improve the resolution of results. Additionally, the lack of a significant difference between the during and after periods at both SOAR and PRMF indicate that the after period was not long enough to capture the return to foraging behavior. In a recent analysis on the duration of the response to sonar by Cuvier’s beaked whales at SOAR, Schorr et al. (2020) found that it could take up to two days for the Cuvier’s beaked while dive behavior to return to baseline after MFAS exposure, supporting the notion that our analysis did not include a long enough period after exposure. Additional time post sonar events should be included in future analyses.

4 Low-frequency detector algorithm at SOAR

4.1 Introduction

The purpose of the project was to conduct the first systematic review of the localizations of low-frequency (LF) calls automatically generated by the M3R system installed at SOAR. M3R does not currently have any classifiers for baleen species. The premise for looking at localization data was that LF localizations, which requires reception of the same signal on three or more hydrophones, might provide a robust indication of presence/absence of baleen species, particularly fin whales (*Balaenoptera physalus*).

M3R's current LF localization capability was developed under the Advanced Instrumentation Systems Technology (AIST) Marine Mammal Effects of Test and Evaluation on Ocean Ranges (METEOR) program and incorporated into M3R's real-time processing stream in 2015. 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 routine 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 animal localizations ('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 (*Eschrichtius robustus*), humpback whales (*Megaptera novaeangliae*) and blue whales (*Balaenoptera musculus*).

4.2 Methods

The methodology employed for this project was straightforward. First, we collected M3R archive files from multiple 24-hr periods spread across the year (Table 15). We originally intended to use the files as they are stored on the M3R central data server but COVID-19 restrictions on the Naval Undersea Warfare Center (NUWC) base access meant we had to copy the files from the server to portable media to conduct the analysis. Next, we used M3R Java post-processing tools (ReadSPC.jar) to review each archive file and extract just the localization reports. This actually represents a significant amount of processing as each file contains a gigabyte of M3R binary detection report data (1147 files = 1.147 TB in all). The localizations were sorted by their 'whale type' number (2 = Cuvier's beaked whale clicks, 3 = dolphin clicks, 4 = sperm whale clicks, 6 = high frequency/dolphin whistles and 21 = LF calls), and the numbers of raw localizations per type per time period were determined.

Table 15. SOAR SPC archive files used for low-frequency detector analysis

Year	*Start Day*	*Start Time (Z)*	*Stop Day*	*Stop Time (Z)*	*SPC Archive Series*	*Files*
2019	4 Jan	03:52:21	5 Jan	03:53:19	spc-20181221-185315	1,401-1,563
2019	15 Jan	00:06:47	16 Jan	00:35:04	spc-20181221-185315	2,737-2,840
2019	4 Apr	23:38:28	6 Apr	00:02:00	spc-20190129-230531	7,327-7,532

2019	16 Apr	15:40:48	17 Apr	15:53:27	spc-20190129-230531	8,619-8,700
2019	4 July	15:46:27	5 July	15:44:46	spc-20190619-211452	1,797-1,902
2019	14 July	15:50:21	15 July	15:51:23	spc-20190711-193245	327-492
2019	5 Oct	11:26:46	6 Oct	11:29:28	spc-20191004-152728	95-274
2019	15 Oct	15:42:43	16 Oct	15:50:43	spc-20191010-190744	803-934

M3R's multilateration localization assumes direct path reception of all calls within a set of seven hexagonally adjacent hydrophones. In fact, the hydrophone layout for undersea tracking ranges is intentionally designed to assure direct path reception of high-frequency tracking pings used by training participants on the 7-hydrophone hexagonal arrays. LF baleen calls propagate well and can be well received by hydrophones several baselines away. That distant array of hydrophones still assumes all signals received are local and attempts to solve for position using direct path assumptions. Often, in such cases, the solution would not converge, but sometimes the solver does still converge which results in bogus solutions. We filtered out suspect solutions for all species by requiring the calculated posit to be within the direct path radius (~5.5 km) of the center, or master, hydrophone of the array used. Figure 15 shows histograms of the distance of all raw posits from the center hydrophone of the array used for localization and Table 16 lists the number of filtered posits for each whale type per day.

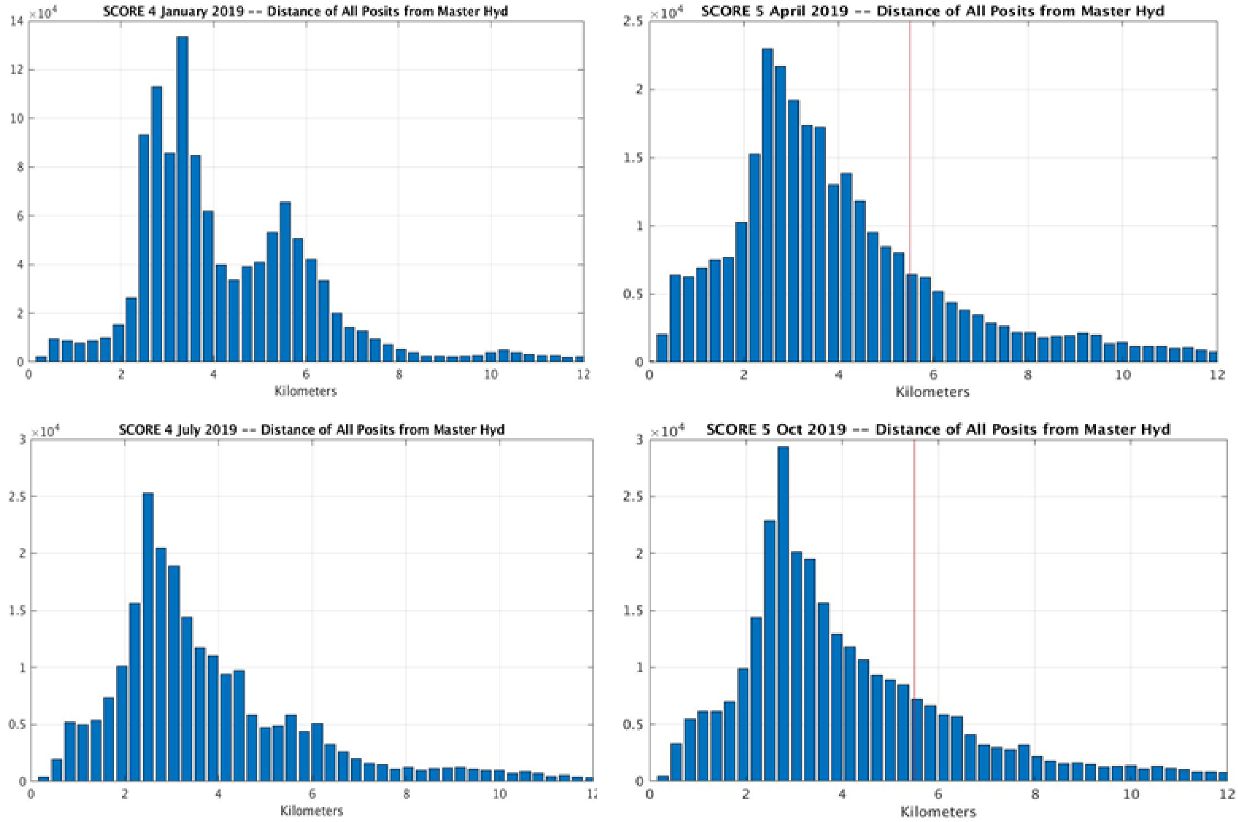


Figure 15. Histograms of the distance of all raw posits from the center hydrophone of the array. Vertical red line indicates the direct path radius distance of 5.5 km from the master hydrophone. The baseline spacing between hydrophones varies somewhat with depth across the range but averages approximately 4 km.

Table 16. Filtered localizations by whale type

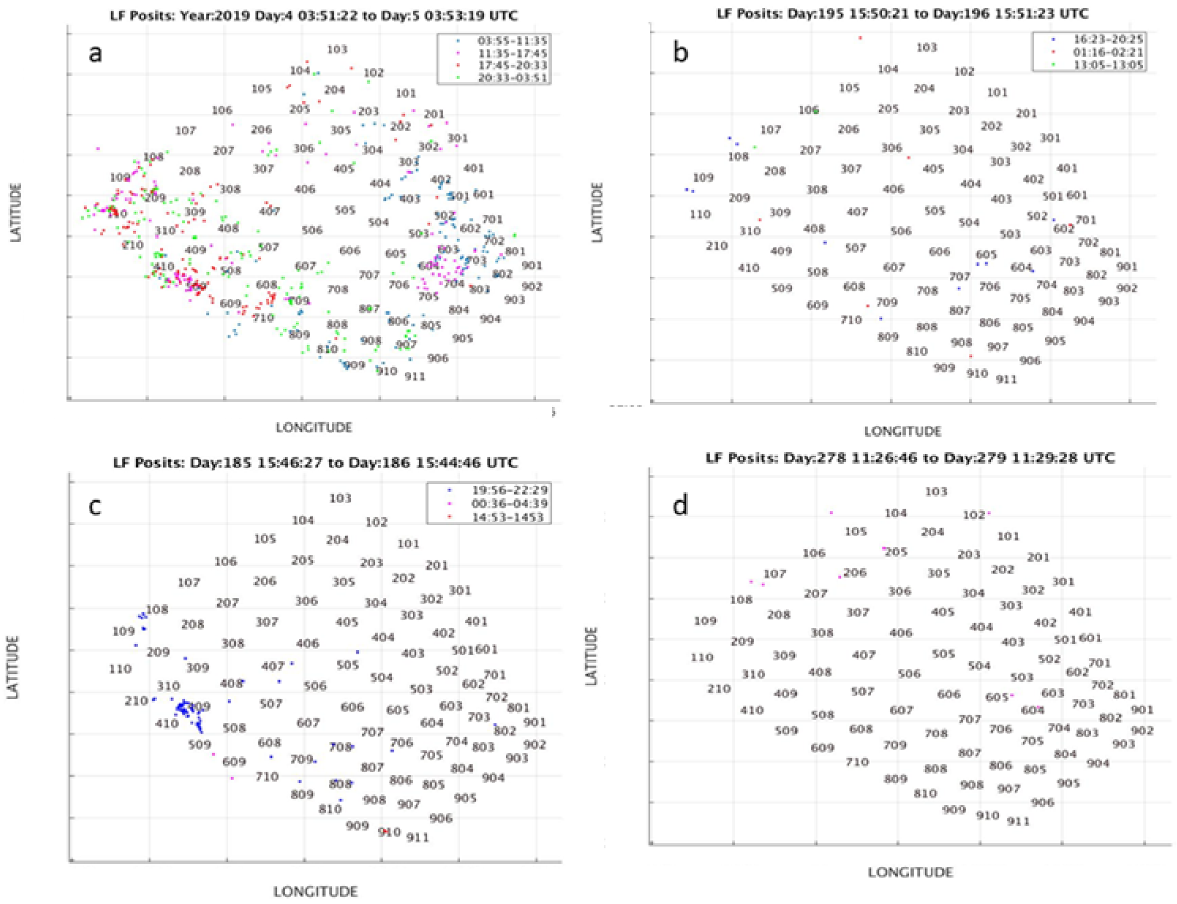
Date	*Raw Posits*	*Total Filtered*	*Filtered Cuvier's beaked whale clicks*	*Filtered Dolphin clicks*	*Filtered Sperm whale clicks*	*Filtered Dolphin Whistles*	*Filtered LF calls*	*Day of the Week*
4-5 Jan	1,268,905	900,057	23,260	68,8597		126,349	663	Sat-Sun
4-5 Apr	309,291	228,696	6,766	67,487	6	149,652	4,785	Thu-Fri
4-5 Jul	244,264	190,931	5,789	109,589	0	75,430	123	Thu-Fri++
5-6 Oct	309,985	226,290	401	104,988	74	120,817	10	Sat-Sun
15-16 Jan	1,030,084	767,400	14,099	682,958	38	58,317	11,988	Tue-Wed
16-17 Apr	758,677	574,698	15,938	509,794	24	3,7640	11,302	Tue-Wed
14-15 Jul	362,332	272,266	2,624	150,185	7	119,424	26	Sun-Mon
15-16 Oct	420,724	313,844	1,949	304,730	0	0*	7,165	Tue-Wed

++ Holiday
* Dolphin whistle localization intentionally disabled

4.3 Results

Initially, posit data from four 24-hr periods (4-5 January, 4-5 April, 4-5 July and 5-6 October) were extracted and analyzed. When it was noted that 3 of the 4 days were either weekend or holiday periods without range activity, the second set of four 24-hr periods was extracted to have more data from days where there was likely to be range activity. We expected that range activity such as noisy surface ships could generate energy in the region below 600 Hz and possibly result in 'false LF posits'. We have previously noted during on-site monitoring exercises that M3R can sometimes track noisy surface vessels like freighters. However, we had no way of knowing a priori how likely range activity was to cause LF posits. Figure 16 and Figure 17 show the range-filtered LF localizations for both weekend and weekday study days, respectively.

The number of LF call posits varies greatly, from 10 to nearly 12000, over the study days, with the higher number of posits generally occurring on the mid-week days. After plotting the localizations, we first assumed that the high number of mid-week LF localizations were due to range activity and that finding LF localizations that came from baleen calls might be a needle/haystack problem.


LF Posits: Year:2019 Day:4 03:51:22 to Day:5 03:53:19 UTC

LF Posits: Day:195 15:50:21 to Day:196 15:51:23 UTC

LF Posits: Day:185 15:46:27 to Day:186 15:44:46 UTC

LF Posits: Day:278 11:26:46 to Day:279 11:29:28 UTC

Figure 16. LF localizations on weekend or holidays days without apparent range activity. (a) January, (b-c) July, and (d) October

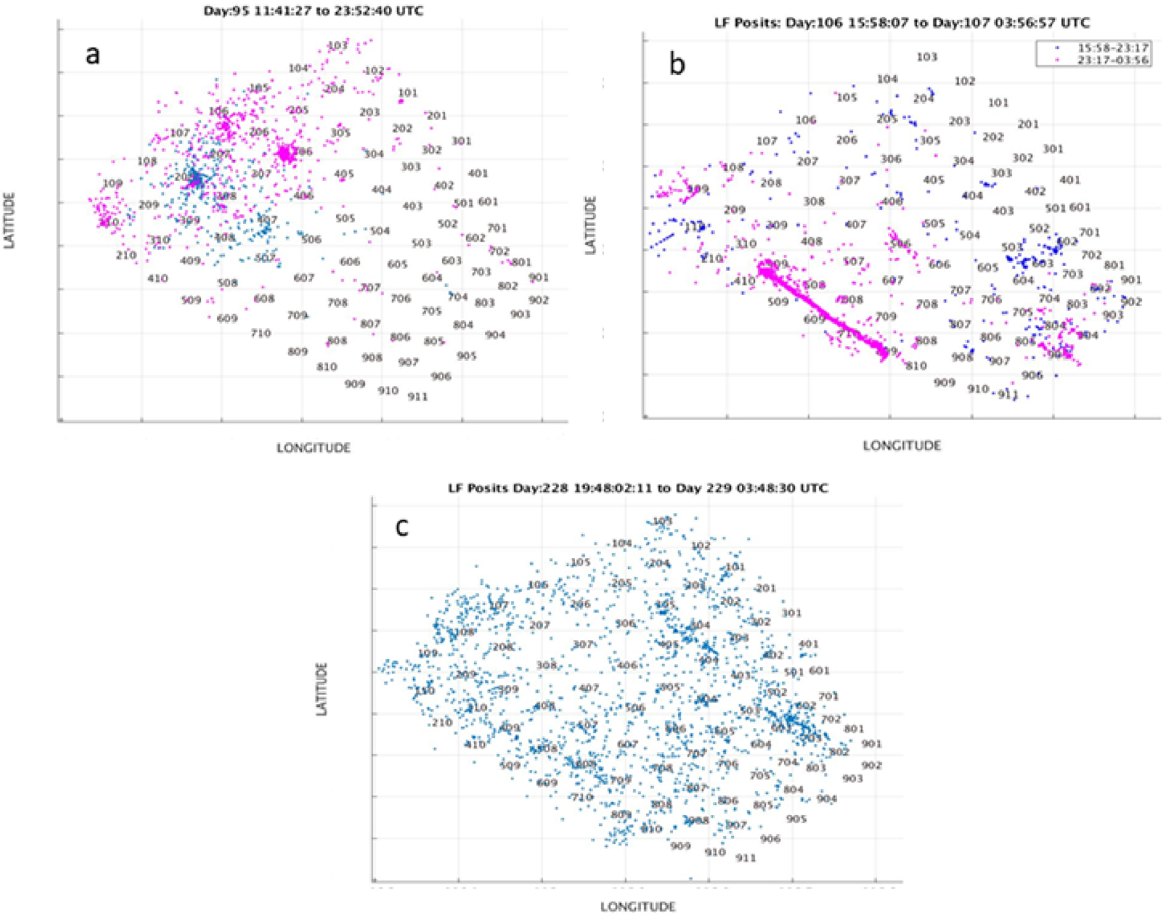


Figure 17. High number of LF posits on mid-week days, initially thought to be from range activity.

Table 17 is a listing of LF localizations from 14-15 July 2019. Tables of LF localizations like this one were created for each of the study days. These times of localization were then used to index into the archive files for that day. The original plan was to manually validate a large number of LF posits against the M3R LF FFT spectrogram displays to estimate the percentage of LF posits associated with different species/sources (e.g. fin, humpback, man-made). However, due to time constraints and the very large number of LF posits found on some study days only a few manual spot checks of spectrogram versus time of localization were conducted for both weekend and mid-week days (Figure 18 through Figure 20). The assignment of species for the calls given in Figure 18 through Figure 20 are based on experience monitoring M3R displays during verified sightings. Interestingly, the only localization from an apparently anthropogenic sound was from 14 July, a weekend day with very few LF localizations.

Table 17. LF localizations versus time and master hydrophone 14-15 July 2-19

Time (Z)	*Time (sec)*	*Hydrophone*	*Latitude*	*Longitude*	*Depth (m)*
16:23:11	16820591.3246	508	32.84313	-118.983	0
16:23:16	16820595.8883	501	32.87078	-118.696	0
16:23:17	16820596.5977	706	32.81769	-118.781	0
16:23:21	16820600.8376	501	32.87078	-118.696	0
16:23:21	16820601.2220	703	32.80827	-118.722	0

Time (Z)	*Time (sec)*	*Hydrophone*	*Latitude*	*Longitude*	*Depth (m)*
16:23:22	16820601.5471	706	32.81769	-118.781	0
16:23:23	16820602.5804	807	32.78728	-118.815	0
16:23:26	16820606.1713	703	32.80827	-118.722	0
17:33:35	16824814.6345	108	32.96334	-119.093	0
17:33:36	16824816.1869	107	32.97052	-119.103	0
17:33:41	16824821.1362	107	32.97052	-119.103	0
17:33:55	16824834.9800	808	32.75053	-118.913	0
17:34:11	16824850.5133	604	32.81697	-118.791	-487.8
20:24:45	16835085.3406	109	32.90601	-119.149	0
20:24:50	16835090.4699	110	32.90779	-119.156	0
1:16:14	16852574.1165	910	32.70456	-118.8	0
1:16:19	16852579.0659	910	32.70456	-118.8	0
1:16:34	16852593.5669	209	32.8709	-119.065	-31.528
1:18:01	16852681.2141	601	32.86467	-118.675	-536.253
1:18:02	16852681.5049	608	32.76622	-118.929	-66.389
1:18:22	16852701.7486	104	33.09269	-118.939	0
2:21:21	16856481.4659	305	32.94651	-118.878	-645.605
2:21:26	16856486.4153	305	32.94651	-118.878	-645.605
13:05:04	16895103.7475	206	33.00275	-118.994	0
13:05:05	16895104.8202	108	32.95945	-119.071	0
13:05:09	16895108.6968	206	33.00275	-118.994	0
13:05:09	16895108.6968	206	33.00275	-118.994	0

Notes: HYD is the hydrophone at the center of the array used to form the localization. WT is the M3R Whale Type number, 2=Cuvier's beaked whale clicks, 3=dolphin clicks, 4=sperm whale clicks, 6=high frequency/dolphin whistles and 21= LF calls. HT (m) is height of the posit and is equal to -1*depth. Posits where the height (or depth) equals 0 correspond to 3-hydrophone (X-Y only) solutions. Posits with a non-zero depth were generated from 4 or more hydrophones. Accuracy of the depth is unknown but the estimated X-Y accuracy of M3R localization is ~±100m. Depth accuracy is likely at least this coarse as depth estimates suffer most from the effects of geometric dilution of precision (GDOP) inherent in multilateration localization.

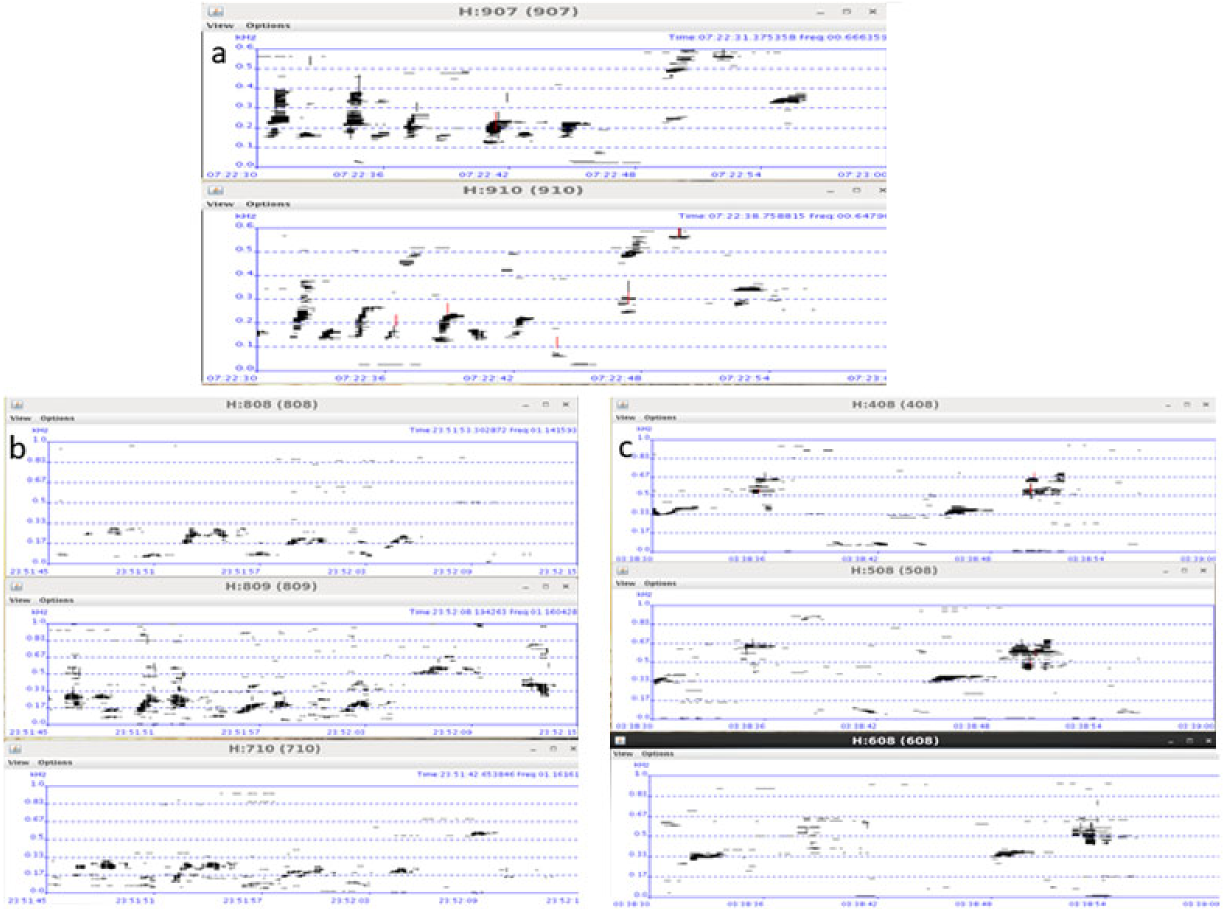


Figure 18. Manual review of M3R binary LF spectrogram displays for randomly selected LF posits. (a) 4 January 2019 07:22Z possible gray whale; (b-c) 14-15 April 2019 23:51-03:38 possible gray whale. These spectrograms are from the start and end of the straight track visible in Figure 16 b.

Figure 19. Manual review of M3R binary LF spectrogram displays for randomly selected LF posits. (a) 4 July 2019 19:56Z probable fin whale, (b) 4 April 2019 16:28Z probable fin whale, (c) 4 October 2019 16:28Z probably fin whale.

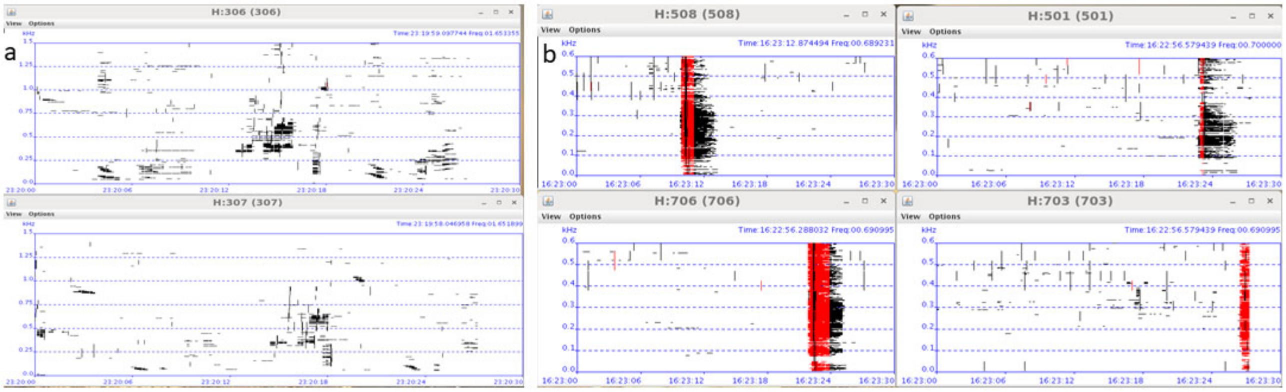


Figure 20. Manual review of M3R binary LF spectrogram displays for randomly selected LF posits. (a) 4 April 2019 23:30Z possible humpback, (b) 14 July 2019 16:23Z, probable anthropogenic sound.

Histograms of the number of LF posits versus time of day were generated, but because the number of localizations per study day varied so greatly, as did the calling species, and the validation of the localizations was so sparse, it was difficult to draw meaningful insight (Figure 21).

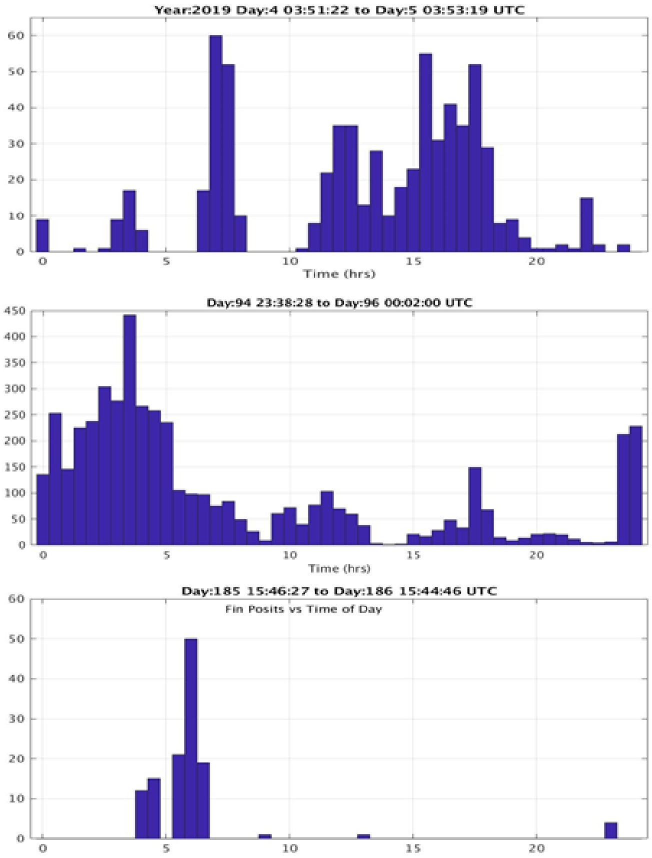


Figure 21. Histograms of number of LF localizations per hour for 4 January, 4 April and 4 July 2019.

4.4 Discussion

In this analysis we conducted a preliminary review of LF localizations from M3R archive data collected at SOAR. Our initial hypothesis was that we could quantitatively describe the relationship between occurrence of LF posits and the presence/absence of baleen species such as fin whale. The sheer number of LF posits recorded on some the study days made an exhaustive, quantitatively significant review impossible. A manual review of M3R LF spectrogram data from the times of select localizations was done instead. Of the 20 spectrogram/posit test cases considered (eight are shown in Figure 18 through Figure 20) only one appeared to be from a man-made source while the others appear to be calls from either fin whales, gray whales, or humpback whales. Originally, the straight ‘track’ of LF posits stretching from hydrophone 809 to hydrophone 409 (in excess of 15 km) evident in Figure 17b was thought to be caused by range activity. After review of the LF spectrograms it appears the track, which formed over ~4.5 hrs, is from gray whale(s).

The results of this project demonstrate that M3R's LF localization routine can effectively localize calls from several baleen species, and that the SOAR is sometimes home to considerable baleen call activity. The number of LF call posits per day varied widely from a low of 10 to almost 12000 per 24-hour period. However, because the localizations are based upon simple energy detection in the band <600Hz, localization reports alone do not contain enough information to differentiate between calls from different species. Additional post-processing or modification of M3R’s current LF detection and localization algorithms would be required. One straightforward approach, going forward, would be for the LF localization routines to report the frequency of peak energy in the spectrograms used to determine TDOA. A better solution would be to add a dedicated detector-classifier capability, one which uses the M3R LF spectrogram as its input, to differentiate among low-frequency calls and species. The times of detection from the classifier could then be passed to the multilateration localization algorithm.

5 Detection statistics for Blainville's beaked whales at PMRF

5.1 Introduction

Blainville's beaked whale detection statistics for the Autogrouper at PMRF were derived by comparing the output to a manual review of a set of systematic random samples of the data. The beaked whale groups determined by manual review were considered 'truth,' and the probability of detection (PD), percent of false-negatives (FNs), and percent of false-positives (FPs) were calculated. The BARTSUR and BSURE refurb hydrophones were used for the analysis.

5.2 Methods

5.2.1 Manual Review

One hundred systematic random 1-hour samples were identified between 2011 and 2015, and 17 of these random samples were manually reviewed for the presence of Blainville's beaked whales. All GVPs that began on range within the one-hour sample period were tabulated.

A two-step process was used to manually identify the GVPs. First, the BARSTUR and BSURE refurb hydrophones were manually reviewed for the potential presence of Blainville's beaked whale foraging clicks. After the hydrophones were reviewed, those identified in the first pass as potentially Blainville's beaked whales were plotted on a map of the range, and formed into groups based on the temporal and spatial overlap of the click-trains. A group typically included hydrophones within a baseline of the hydrophone with the highest click density, and with a group vocal period of less than one hour. At times neighboring groups ensonified some common hydrophones. At the conclusion of the second pass the number of GVPs, along with start and stop times of the GVPs, were recorded for each of the samples.

5.2.2 Autogrouper Algorithm (AG)

The Autogrouper algorithm was run on the output of the CTP program. Only CS-SVM Blainville's beaked whale foraging clicks and click trains with an ICI between 0.23 and 0.4 sec were used. Prior to comparison with the manual groups, the AG output was filtered in R so that all GVPs had to have a total number of clicks between 360 and 64,800, and a duration between 5 and 90 min.

5.2.3 Comparison of Manual and AG GVPs

For each sample the manual and AG GVPs were placed into one of four categories: (a) exact matches, (b) 'confused' matches, (c) manual only (false negatives, FN), or (d) AG only (false positives, FP). A group was considered an exact match if: (1) the groups had at least one hydrophone in common, (2) the hydrophones were not part of another group, and (3) the time periods overlapped. The 'confused' matches occurred when all or some of the same hydrophones were identified by both the manual process and the AG program, and the time periods overlapped, but the number of groups and/or the hydrophone combinations forming the groups were not the same.

5.2.4 Derivation of Detection Statistics and Correction Factors

Detection statistics were then calculated from 17 random one-hour samples (Table 18). Correction factors were also calculated to derive the ‘true’ number of Blainville’s beaked whale GVPs present from the number of AG groups detected. The PD was calculated as the number of GVPs correctly detected by the AG divided by the number of manual GVPs. The percentage of FNs (GVPs missed by the AG) was the number of FNs divided by the number of manual GVPs; and the percentage of FPs (GVPs misidentified by the AG) was the number of FPs divided by the number of AG GVPs.

FP and FN correction factors for the AG GVP results were then derived as follows, using all samples combined:

1. The FP correction factor = 1 – (number of FP / number of AG GVPs)
2. The FN correction factor = 1 + (number of FN / (number of AG GVPs * FP correction factor)).

Table 18. Data used to calculate the PMRF detection statistics.

AutoGrouper									
				# Confused Matches					
Sample #	Total # Manual GVPs	Total # Auto GVPs	# Exact Matches	# Manual GVPs	# Auto GVPs	Min of Confused	Correctly Detected	# GVPs Manual Only (FN)	# GVPs Auto Only (FP)
46	6	2	0	5	2	2	2	3	0
160	7	3	2	2	1	1	3	1	0
217	5	4	0	3	3	3	3	2	1
331	2	1	1	0	0	0	1	1	0
388	5	0	0	0	0	0	0	5	0
445	4	0	0	0	0	0	0	4	0
502	1	2	1	0	0	0	1	0	1
559	4	0	0	0	0	0	0	4	0
616	3	2	1	2	1	1	2	1	0
673	4	1	1	0	0	0	1	3	0
730	3	3	2	0	0	0	2	1	1
787	6	0	0	0	0	0	0	6	0
844	2	3	0	0	0	0	0	2	3
2212	4	1	0	3	1	1	1	1	0
2269	3	2	1	0	0	0	1	2	1
2383	3	3	2	0	0	0	2	1	1
2554	7	0	0	0	0	0	0	7	0
Sum	**69**	**27**	**11**	**15**	**8**	**8**	**19**	**44**	**8**

5.3 Results

The detection statistics and correction factors are reported in Table 19.

Table 19. PMRF AutoGrouper detection statistics/correction factors for Blainville's's beaked whales.

n	Probability of Detection (PD)	False Negative (FN)	False Positive (FP)	Correction Factors	
				FP	FN
17	0.28	0.64	0.30	0.704	3.316

5.4 Discussion

The Autogrouper algorithm only correctly detects about one third of the Blainville's beaked whale groups at PMRF, which is a much lower PD that that for Cuvier's beaked whales at SOAR (PD=0.76, cv=0.05) or Blainville's beaked whales at AUTEC (PD=0.86,cv=0.91). There are a high number of false negatives (0.64, or cases in which the Blainville's beaked whale groups were missed by the Autogrouper), and the false positive percent is 0.28 (Table 19). However, as long as the detection statistics and correction factors are appropriately applied to the data, the correct abundance values should be recovered.

One potential factor impacting the PD is that the data was run with a different version of CTP, whose output feeds the Autogrouper. It is currently being rerun with the same version of CTP as had been used at SOAR, and the statistics will be recalculated. Additional samples will be added, as well. The Autogrouper program clearly needs to be tuned for the different ranges, and in particular for PMRF. For example, often times it appears that, for a given group, fewer clicks are detected at PMRF as compared to AUTEC and SOAR; therefore, the restriction on the minimum number of clicks necessary to declare a group present may need to be lowered for PMRF. In reviewing the archives the clicks were often correctly detected on the hydrophones, but the total click requirement was not met, and the group was not included. A new version of Autogrouper is currently being developed, and these issues will be addressed in the new version.

6 Ambient noise calculation using the FFT archives

6.1 Introduction

6.1.1 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). Ambient noise level trends in other ocean basins are unknown; however, increases in seismic activity in the Atlantic Ocean are likely impacting ambient noise levels in that ocean as well (Klinck et al. 2012, Nieukirk et al. 2012, Miksis-Olds et al. 2014). The M3R program has collected multi-year datasets at three of the Navy's undersea ranges, AUTEC, SOAR, and PMRF. These deep water ranges are located in the Atlantic and Pacific Ocean basins. These datasets can be used to evaluate long-term ambient noise trends on the ranges and to compare ambient levels across different ocean basins.

Changes in the ocean acoustic ambient 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. This 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 ambient noise curves will be extracted from these datasets over multiple years, and the ambient noise will be analyzed for any diel or seasonal patterns, or long-term trends.

The goals of this project are as follows:

1. *FY20:* Develop tools to extract ambient noise data from M3R data archives.
2. *FY21:* Perform analysis for the three deep water ranges: AUTEC, SCORE, and PMRF.

6.1.2 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. Fixed systems exist at multiple locations including the Bahamas at AUTEC, off the California coast at SOAR, and off the coast of the Hawaiian island of Kauai at PMRF.

M3R systems have been installed at AUTEC and data collected since 2002, SOAR since 2006, and PMRF since 2011. These systems have been in constant operation and consequently nearly continuous multi-year datasets are now available. These datasets have value for multiple analyses, including animal abundance, SONAR impact, and ambient noise analysis.

6.2 Methods

The three deep water Navy ranges each consist of a set of bottom mounted hydrophones that are cabled to a shore based processing facility. The upper frequency detectable by these hydrophones is approximately 45 kilohertz (kHz), while the lower frequency varies depending on the specific hydrophone. Hydrophones installed since 2000 typically have a lower frequency specification of 50 Hertz (Hz). Measurements of the acoustic spectrum show sensitivity below 20 Hz.

The hydrophones are digitized at the shore facility at a rate of 96 kHz and fed into the M3R processing system. A FFT-based energy detector is run on the data. A 2048 point FFT with 50% overlap is used, resulting in a per-bin frequency resolution of 46.875 Hz and a time resolution of 10.67 milliseconds (ms). The magnitude of each bin of the FFT is compared to the noise-varying threshold (NVT) for that bin (Ward et al., 2008). The resulting 'detection spectrum' is a binary representation of detection (1) or no detection (0) information per bin. A detection is reported if any of the bins have passed the threshold, and the binary FFT results are then archived to file.

In 2016, the system was extended to increase resolution at the lower frequencies. In addition to the processing steps listed above, a second FFT energy detector is run in parallel with the first. The data are first low pass filtered using a filter with a cutoff at 4 kHz. The 96 kHz data are then decimated by a factor of 8 to 12 kHz. A 4096 point FFT with 75% overlap is used, resulting in a per-bin frequency resolution of 2.92 Hz and a time resolution of 85.3 ms. Thresholding is performed identically to the case described by Ward et al. (2008).

In addition to the binary spectrogram data, the FFT detection report stores the peak amplitude and associated frequency. These data can be aggregated over time to produce an average noise spectra. This is done by noting that the NVT is chosen as low as possible without overloading the system, resulting in a significant number of reports where the system is triggered purely by noise. Noise spectra are differentiated from spectra containing acoustic events by filtering the results for 'single bin' detections. These appear as the black 'sprinkles' in the binary spectrogram displays (Figure 22).

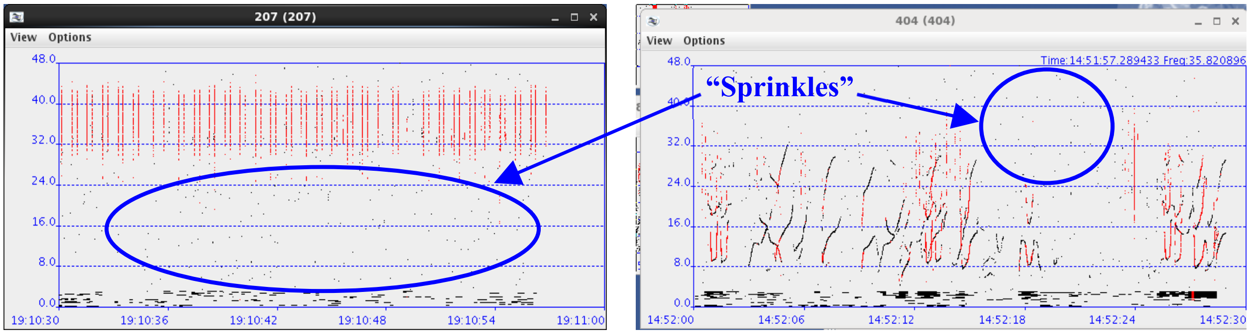


Figure 22. 'Sprinkles' in hard-limited FFT-based Whdetect report messages.
Whdetect report messages with only a single bin of the binary FFT set to '1' appear in the binary spectrogram displays as 'sprinkles.'

The peak magnitude of each bin is collected until a statistically significant number of samples has been collected for each bin. These data are then averaged to obtain an estimate for the noise level after backing out the system transfer function. The goal for FY20 was to develop code to automatically extract ambient noise data from the FFT-based detector reports. It was expected that ambient noise curves similar to those in Ward et al. (2011) would be generated (Figure 23).

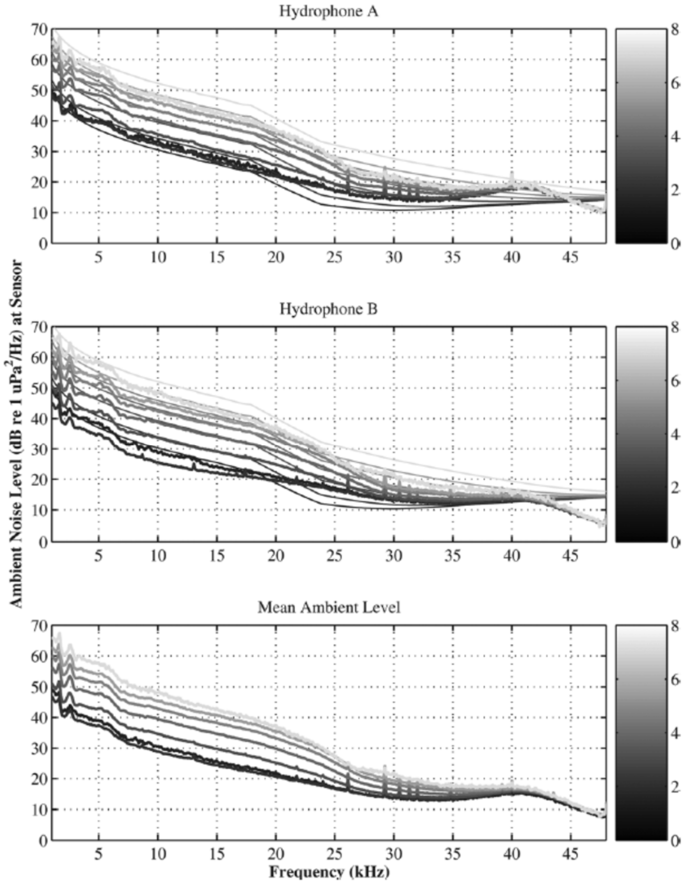


Figure 23. Modeled versus ambient noise as a function of sea-state at AUTEC.
Color bar represents sea state, thin lines represent modeled noise levels, while thick lines are empirical noise levels. From Ward et al. (2011).

6.3 Results

Initial efforts have revolved around development of a set of software tools in the Python programming language to extract the desired data from a specified set of archive files and aggregate the data. The software parses the archive file report by report, looking for reports where a single frequency bin was reported. Currently the higher resolution data is ignored in the analysis to allow for comparison over the widest possible frequency range. The frequency and magnitude are extracted from the report. The software maintains a list of magnitudes received for each possible frequency bin. The hydrophone that the data originated from is currently ignored during processing so the resulting ambient is an average over all hydrophones within the study area. When the specified list of files has been processed, a single curve is produced where the level reported for each frequency bin are a root mean squared (RMS) average of the list of peak magnitudes that were compiled during processing. Figure 24 shows a preliminary plot derived using this analysis method.

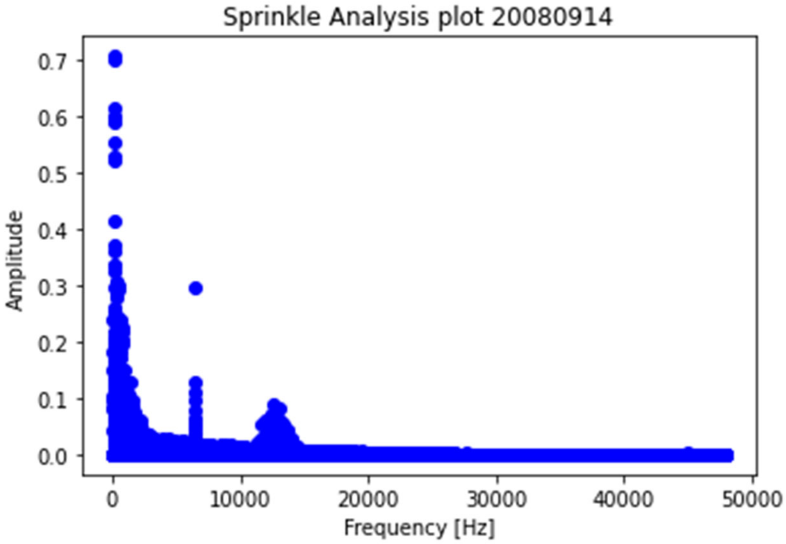


Figure 24. Plot of peak amplitude from extracted single bin FFT detections

Planned enhancements include adding the capability to limit hydrophones utilized in the analysis to a specified list to allow for more geographically specific data to be analyzed. In addition, the high resolution FFT data will be separately processed to form a more complete picture of the low frequency ambient.

Curated datasets of archives are being created for PMRF and SOAR. These datasets will be run through the analysis code in FY21.

6.4 Discussion

Initial exploration of the FFT detection reports and the generation of code to extract single detection reports were successful. Goals for FY21 include processing of long-term archives (nominally 1 day per week where archives exist on each range) to explore relative trends in ambient noise over time, and comparison of the sprinkle analysis output to ambient analysis from acoustic recordings. Additionally, the transfer function from the face of the hydrophone through the signal processing system will be calculated to enable ambient noise results to be presented in actual sound pressure level values.

7 Real-time monitoring of on-water tagging operations

7.1 SOAR

Due to COVID-19 travel restrictions, only two field tests were conducted at SOAR in 2020. M3R and Marine Ecology and Telemetry Research (MarEcoTel) carried out two field tests in support of photo-ID, biopsy, and tagging of marine mammals: one in January and a second in October. During these field tests MarEcoTel personnel work from San Clemente Island, 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) or Low Impact Minimally Percutaneous Electronic Transmitter (LIMPET) satellite tags on individuals, depending on the focus of the particular effort. The emphasis for this effort has been 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 Marine Mammal Monitoring and Localization (MMAMMAL) and WorldWind displays show 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 20 lists the cetacean species acoustically identified using the M3R system during the two field tests in 2020, along with summary information extracted from the associated SOAR field logs. More detailed information extracted from these field logs can be found in Appendix A. These tests were primarily focused on tracking Cuvier's beaked whales, except for the last day of the second field test, which was focused on fin whales. Both tests were cut short due to bad weather conditions; thus each test was only three days long.

A total of 144 acoustic sightings were logged, including 129 of Cuvier's beaked whales, nine of fin whales, two of blue whales, three of unidentified dolphins, and one unidentified baleen whale. Note that the sightings 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 were not logged. Aside from the day on which fin whales were the focus, fins and other baleen whales were not necessarily logged.

Of these acoustic sightings, there were about 37 cases in which M3R directed MarEcoTel to Cuvier's beaked whales and five instances of direction to fin whales. Additional posits were logged, but not necessarily sent to the field team, depending on conditions. MarEcoTel visually verified six groups of Cuvier's beaked whales and two to three groups of fin whales, placed a satellite tag on a Cuvier's beaked whale, and collected numerous photos, biopsies and behavioral data from both species.

Table 20. Species acoustically identified with the M3R system or visually sighted on SOAR
Data are extracted from the two field test logs in 2020.

Species			# Acoustic Sightings Logged	# Acoustic Sightings Directed	# Acoustic Sightings Visually Verified	# of Tags
ID	Common Name	Scientific Name				
Zc	Cuvier's beaked whale	*Ziphius cavirostris*	129	37	6	1
UD	unidentified dolphin	Delphinidae sp.	3	0	0	0
Bp	Fin whale	*Balaenoptera physalus*	9	5	2 to 3	0
Bm	Blue whale	*Balaenoptera musculus*	2	0	0	0
UM	unidentified baleen whale	Mysticeti sp.	1	0	0	0

7.2 PMRF

M3R conducted one field test in 2020 in conjunction with the Cascadia Research Collective (CRC), from February 7th to the 18th. 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 February 2020 field test at PMRF, along with summary information extracted from the associated field logs, are shown in Table 21. More detailed information extracted from these field logs can be found in Appendix B.

A total number of 198 acoustic sightings were logged, including 51 of Blainville's beaked whales, four of Cuvier's beaked whales, 16 of sperm whales, six of short-finned pilot whales, one bottlenose dolphin, 116 of unidentified dolphins, and four of unidentified baleen whales. Of the acoustic sightings, 25 were directed, and eight were visually verified. One satellite tag was placed on a bottlenose dolphin.

Table 21. Species acoustically identified with the M3R system or visually sighted on PMRF Data are extracted from the logs of one field test in 2020.

Species			# Acoustic Sightings Logged	# Acoustic Sightings Directed	# Acoustic Sightings Visually Verified	# of Tags
ID	**Common Name**	**Scientific Name**				
Md	Blainville's beaked whale	*Mesoplodon densirostris*	51	1	0	0
Zc	Cuvier's beaked whale	*Ziphius cavirostris*	4	0	0	0
Pm	Sperm whale	*Physeter macrocephalus*	16	0	0	0
Gm	Short-finned pilot whale	*Globicephala macrorhynchus*	6	2	0	0
Tt	Bottlenose dolphin	*Tursiops truncatus*	1	0	0	1
UD	unidentified dolphin	Delphinidae sp.	116	22	8	0
UM	unidentified baleen whale	Mysticeti sp.	4	0	0	0

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Appendix A SOAR Field Work Logs

Table 22 shows excerpts from the M3R log files from one field effort with Cascadia Research Collective in 2020 on PMRF. The excerpts show the species acoustically identified and the number of such sightings, along with the number of sightings to which the RHIB was directed, the number of species sightings verified, and the number of tags deployed. Note the sightings 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 22. Excerpts of M3R log files from two field efforts on the SOAR range in 2020.

Test Dates	# Hours Monitored	Species	# Acoustic Sightings Logged	# Acoustic Sightings Directed	# Acoustic Sightings Visually Verified	Tagged?	Notes
1/4/2020	10.5	*Zc*	33	14	2	No	Pair of *Zc* near 907; group of 3 *Zc* near 808
1/6/2020	7.5	*Zc*	26	4	2	Yes	Group of 3 *Zc* by 202: adult male, adult female, & probably juvenile subadult. Tag on adult male in 8 ft swells! Back on 202 group later.
		UM	1	0	0	No	60-100 Hz downsweeps
		UD	1	0	0	No	
1/7/2020	7.4	Zc	20	5	2	No	Group of 3 *Zc* by 302/202; probably same group as yesterday. Got photos & biopsies. One *Zc* E-SE of 206
		Bm	1	0	0	No	
		UD	1	0	0	No	
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	

Appendix B PMRF Field Work Logs

Table 23 shows excerpts from the M3R log files from two field efforts with MarEcoTel in 2020 on SOAR. The excerpts show the species acoustically identified and the number of such sightings, along with the number of sightings to which the RHIB was directed, the number of species sightings verified, and the number of tags deployed. Note the sightings 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 23. Excerpts of M3R log files from one field effort on the PMRF range in 2020.

Test Dates	*# Hours Monitored*	*Species*	*# Acoustic Sightings Logged*	*# Acoustic Sightings Directed*	*# Acoustic Sightings Verified*	*Tagged?*	*Notes*
02/07/2020	6.5	*Md*	5	0	0	No	
		Pm	1	0	0	No	
		UD	4	0	0	No	
		UM	1	0	0	No	Humpback?
		Other	3	0	0	No	
02/08/2020	0.5	*Gm*	1	0	0	No	
		UD	2	0	0	No	
		UM	1	0	0	No	LF – humpback?
02/09/2020	5.8	*Md*	8	0	0	No	
		UD	12	0	1	No	
		Other	3	0	0	No	
		UM	2	0	0	No	
		Zc	1	0	0	No	
02/10/2020	4.3	UD	4	0	0	No	
		Md	8	0	0	No	
		Pm	2	0	0	No	
02/11/2020	5.1	UD	8	0	0	No	
		Md	7	0	0	No	
		Pm	4	0	0	No	
		Zc	1	0	0	No	
		Tt	1	0	0	No	
02/12/2020	2.2	UD	18	6	3	No	Possible RT dolphin
		Gm	3	2	0	No	

		Md	4	1	0	No	
		Other	6	2	2	No	Possible pilot whale
		Pm	1	0	0	No	
		Zc	1	0	0	No	
02/13/2020	2.5	UD	6	1	0	No	Possible pilot whales
		Gm	1	0	0	No	
		Mn	6	0	0	No	
		Zc	1	0	0	No	
02/14/2020	8	UD	24	4	2	No	
		Other	1	0	0	No	
02/15/2020	7	UD	14	5	2	No	
		Gm	1	0	0	No	
		Other	3	0	0	No	
02/16/2020	5.2	*UD*	5	2	0	No	
		Md	1	0	0	No	
		Other	7	0	0	No	
		Pm	2	0	0	No	
02/17/2020	6.5	UD	15	1	0	Yes, 1	Tagged bottlenose between H-9 and G-8
		Md	4	0	0	No	
		Other	3	0	0	No	
		Pm	6	0	0	No	
02/18/2020	8.2	UD	4	3	0	No	
		Md	8	0	0	No	