Passive Acoustic Monitoring in the Mariana Islands: Density Estimation of Beaked Whales along the West Coast of Guam

Final Report

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14. ABSTRACT
A total of six Rockhopper passive acoustic recording units were deployed off the west coast of Guam in the Mariana Islands Training and Testing (MITT) study area to acoustically monitor beaked whales and mid-frequency active sonar (MFAS). Five units were deployed in an array configuration with a 1 kilometer (km) baseline in the northern part of the survey area to locate beaked whale echolocation clicks and derive a probability of detection function necessary for estimating density. An additional sixth unit was deployed approximately 15 km south of the array to investigate spatiotemporal variability in beaked whale encounters in the survey area.
Acoustic data was collected from 26 May 2022 to 22 November 2022. An additional ~three months of data (7 December 2022 through 14 March 2023) was collected at Site S02.The beaked whale analysis was performed using PAMGuard, while MFAS signals were detected in the data set using an algorithm developed by Naval Information Warfare Center (NIWC)/Naval Undersea Warfare Center (NUWC) that runs within the Raven-X software.
A total of 132 beaked whale encounters were registered across the two sites. Goose-beaked whales comprised 122 encounters and occurred almost exclusively at night. Using regression modeling, a comparison of beaked whale daily encounter rates at the two sites was performed. Results showed a higher number of detections in the first half of the deployment and variability in the number of detections between the single site and the array instruments.
The density of goose-beaked whales was estimated using spatial capture-recapture (SCR). Average densities ranged from 0.83 animals per 1,000 square kilometers (km^2) (coefficient of variation [CV]: 9.62%) in September 2022 to 6.41 animals per 1,000 km^2 (CV: 7.30%) in June 2022. Distance sampling was also investigated for goose-beaked whales

through acoustic localization, though the method could not be reliably applied due to the low sample size and violation of key modeling assumptions.

A total of 16 MFAS encounters were recorded, 9 of which were detected at both sites. Six MFAS encounters were only registered at the southern (single-unit) site and one at the array site. Most of these encounters were characterized by a low signal-to-noise ratio (SNR), suggesting that these signals were likely emitted in deeper water to the south and southeast of Guam. The signals comprising the nine encounters detected at both sites occurred at distances too far from the units to obtain localizations with reasonable accuracy. For this reason, only direction-of-arrival (DoA) was calculated. To improve sonar localization, the array configuration would need to be significantly altered (additional units and a larger baseline).

In contrast to the beaked whale detections, most MFAS detections occurred during the day. No beaked whale detections occurred in close temporal proximity to the MFAS detections. However, it should be noted that the detection ranges for both signal types differ vastly.

A second 6-month deployment took place in early 2024. For this deployment, the locations of the array and the single unit were swapped in order to investigate the variability of the probability of detection for beaked whales in the survey area. This is an important step to enable scaling up the monitoring effort to the larger MITT in the future. Results from the second deployment will be presented in a separate report.

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Abstract

A total of six Rockhopper passive acoustic recording units were deployed off the west coast of Guam in the Mariana Islands Training and Testing (MITT) study area to acoustically monitor beaked whales and mid-frequency active sonar (MFAS). Five units were deployed in an array configuration with a 1 kilometer (km) baseline in the northern part of the survey area to locate beaked whale echolocation clicks and derive a probability of detection function necessary for estimating density. An additional sixth unit was deployed approximately 15 km south of the array to investigate spatiotemporal variability in beaked whale encounters in the survey area.

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A total of 132 beaked whale encounters were registered across the two sites. Goose-beaked whales comprised 122 encounters and occurred almost exclusively at night. Using regression modeling, a comparison of beaked whale daily encounter rates at the two sites was performed. Results showed a higher number of detections in the first half of the deployment and variability in the number of detections between the single site and the array instruments.

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List of Acronyms and Abbreviations

µPa	micropascal
AIC	Akaike's Information Criterion
BWC	Cross Seamount Beaked Whale
CUI	controlled unclassified information
CV	coefficient of variation
dB	decibel
DoA	direction-of-arrival
GAM	Generalized Additive Model
GCMP	Guam Coastal Management Program
GPS	global positioning system
Hz	Hertz
IPI	inter-pulse-interval
kHz	kilohertz
km	kilometer(s)
km^2	square kilometer
LMR	Living Marine Resources Program
m	meter(s)
M/V	motor vessel
MFA	mid-frequency active
MFAS	mid-frequency active sonar
min	minute(s)
MITT	Mariana Islands Training and Testing
ms	millisecond(s)
NIWC	Naval Information Warfare Center
NUWC	Naval Undersea Warfare Center
ONR	Office of Navy Research
PAM	passive acoustic monitoring
ROCCA	Real-time Odontocete Call Classification Algorithm
SCR	spatial capture-recapture
sec	second(s)
SNR	signal-to-noise ratio
TB	terabyte
TDoA	time difference of arrival
U.S.	United States

1. Project Overview and Objectives

As part of this project, passive acoustic monitoring (PAM) was conducted in the Mariana Islands Training and Testing (MITT, **Figure 1**) study area in order to determine 1) the occurrence of beaked whales in the region, 2) the approximate locations of beaked whale PAM detections, 3) the estimated abundance and density of detected beaked whales, and 4) the presence and approximate locations of any sonar detections in the PAM data.

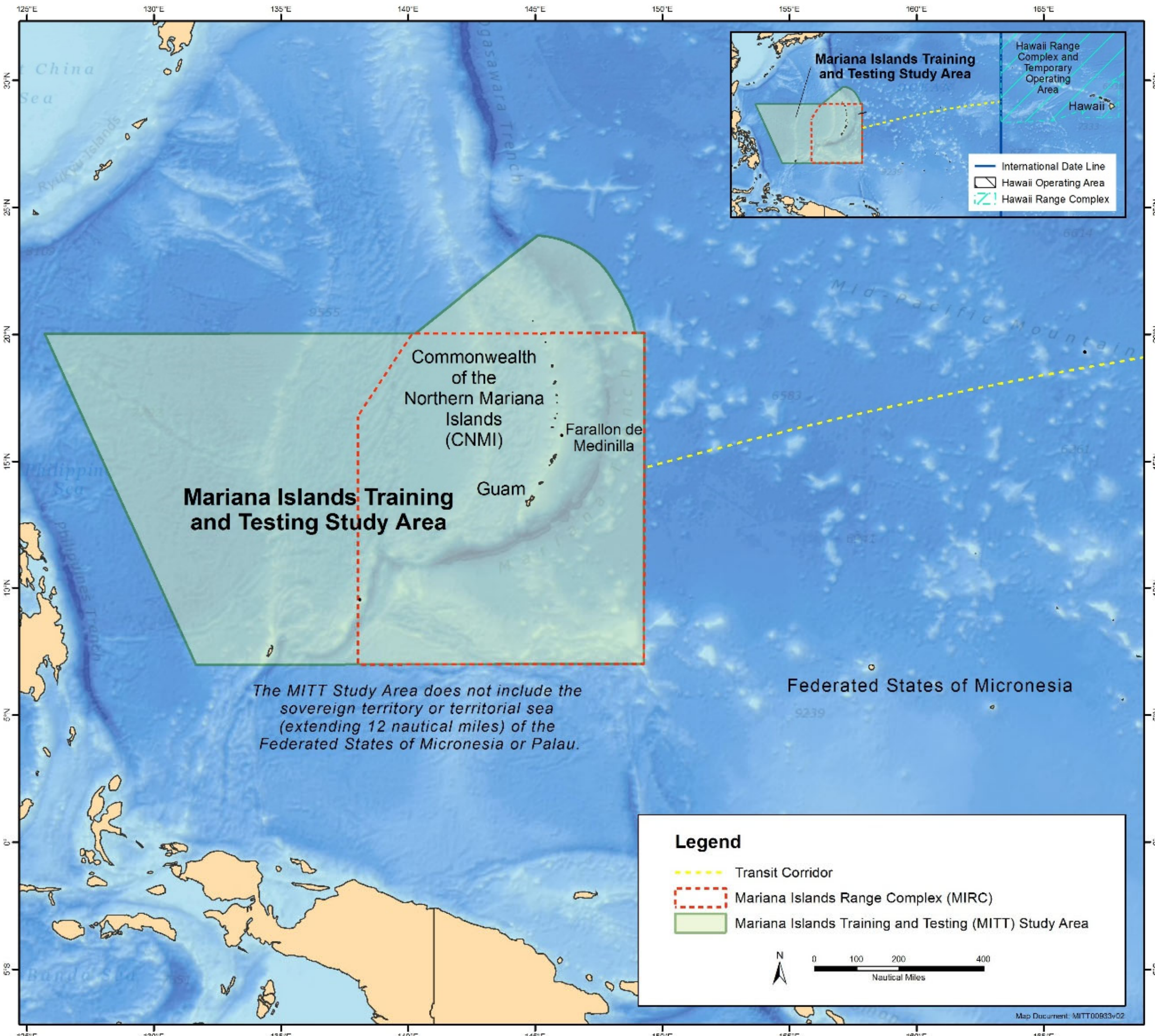


Figure 1: Mariana Islands Training and Testing Study Area. Source: DoN 2020.

To achieve these objectives, an array of five bottom-mounted receivers was deployed to estimate the probability of detecting the highly directional echolocation clicks emitted by beaked whales as a function of distance from the array. Detection probability is a key parameter required for animal density estimation (e.g., Buckland *et al.* 2001) and can be estimated using various methods such as distance sampling and spatial capture-recapture (e.g., reviewed in Marques *et al.* 2013). This project aims to assess whether beaked whale detection probability can be estimated from the data collected by the array, which will help inform the design of future surveys to estimate beaked whale densities.

Based on data from previous acoustic surveys (McCullough *et al.* 2021), five beaked whale species are expected to occur in the project area (**Table 1**). The vocalizations of all five species have been described in the literature and were used to aid in species identification.

Table 1: List of five beaked whale species that may occur in the proposed survey area*.

Species, common name	Species, scientific name	Description
Goose-beaked whale	*Ziphius cavirostris*	Zimmer *et al.* 2005
Dense-beaked whale	*Mesoplodon densirostris*	Madsen *et al.* 2013
Indo-Pacific beaked whale	*Indopacetus pacificus*	Rankin *et al.* 2011
Deraniyagala's beaked whale	*Mesoplodon hotaula*	Baumann-Pickering *et al.* 2014
Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	Baumann-Pickering *et al.* 2014

*An acoustic signal from an unknown beaked whale species has been detected frequently in the Marianas. This frequency-modulated (FM) pulse is known as the Cross Seamount beaked whale (BWC), BWC signal, or BWC-FM pulse (Manzano-Roth *et al.* 2023).

In addition, PAM data was analyzed for occurrences of mid-frequency active sonar (MFAS), and, when feasible, the direction of the vessels emitting the MFAS signals was acoustically determined.

2. Data Collection

2.1. Array Configuration Modeling

In the initial phases of the project, John Spiesberger, Scientific Innovations, Inc., modeled and assessed suitable array configurations to locate vocalizing beaked whales.

For modeling purposes, it was assumed that each receiver location could be acoustically surveyed within ±3 meters (m), about the same as is possible with modern acoustical surveying technology and using a plurality of global positioning systems (GPS) and GPS-like satellites. Synchronization across receivers (±0.04 seconds [sec]) was achieved through acoustic pingers attached to each hydrophone mooring emitting synchronization signals at least hourly.

The chosen array configuration consisted of four receivers on the vertices of a square with a side length of 1 km. A fifth receiver was located in the center of the square. A minimum of four receivers is necessary to accurately determine the source location. The deployment of the fifth receiver safeguarded the project in case of a unit failure. The selected array configuration was similar to a beaked whale localization array of High-Frequency Acoustic Recording Package receivers described by Gassmann *et al.* (2015) in the San Clemente Basin, California, U.S.

Modeling results incorporating anticipated local sound propagation conditions and ambient noise levels indicated that beaked whales could be located 2–3 km from the array.

2.2. Equipment Specifications

The acoustic data was collected with Rockhopper marine recording units (**Figure 2**Figure 1) developed by Cornell University, Ithaca, New York (Klinck *et al.* 2020). One person can easily deploy the Rockhopper units from a small vessel, including those previously used by Hill *et al.* (2020) for marine mammal work in the Marianas region. There are no mechanical aids (winch, a-frame, etc.) required for deployment and recovery. The lithium battery-powered units can be deployed at a depth of up to 3,500 m and continuously record calibrated acoustic data at high sampling rates for over 6 months.

Acoustic data was continuously recorded at a rate of 197 kilohertz (kHz) and with 24-bit resolution (FLAC file format), optimized to capture signals in the 10 Hertz (Hz) to 80 kHz frequency range. This frequency range was sufficient to record the signals of all beaked whale species presumed to be present in the area (**Table 1**). In addition, each mooring was equipped with an acoustic pinger (model EMT-01-3, Sonotronics, Inc., Tucson, Arizona) to synchronize the recording units in the array. Each pinger emitted a unique sequence of pings (between 34 and 38 kHz) with a source level of approximately 160 decibel(s) (dB) referenced to 1 micropascal (µPa) at 1 minute (dB re 1 µPa @ 1m). The pingers were programmed to ping sequentially, resulting in a short synchronization signal (a series of short pings emitted at a 1-sec interval) being emitted every 15 minutes (min). The maximum operating depth of the pingers was 1,000 m.

During the 6-month deployment period, each Rockhopper unit typically collects approximately 6 terabytes (TB) of data, stored internally on two 4 TB SSD drives. After recovery of the units, the Rockhoppers were shipped to Ithaca, New York, where the data was extracted and handled following the negotiated controlled unclassified information (CUI) data handling protocol. The units' system sensitivity and noise floor can be found in Klinck *et al.* (2020).

Figure 2: The Rockhopper marine recording unit developed by the K. Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology, Cornell University, Ithaca, New York, U.S.

2.3. Rockhopper Deployments

The final deployment configuration is shown in **Figure 3**: a five-element localization array and a single Rockhopper unit were deployed on the western side of the island of Guam. The deployment and recovery operations were executed using the motor vessel (M/V) *Liquid Soul* (Rockstar Charters, Inc., Hagtna, Guam, U.S.). The maximum deployment depth of the array unit was limited to 1,000 m because of the maximum operation depth of the synchronization pingers. While a deployment depth of at least 1,000 m is recommended to monitor especially goose-beaked whales, a study by Simonis *et al.* (2020) conducted in the MITT reported a higher number of detections for this species at an instrument deployed at ~650 m compared to an instrument deployed at ~1,000 m. In addition, the array was not configured to track individuals or groups of beaked whales but rather to collect suitable data to enable beaked whale density estimation.

Before the fieldwork commenced, a deployment permit was obtained from the Guam Coastal Management Program (GCMP).

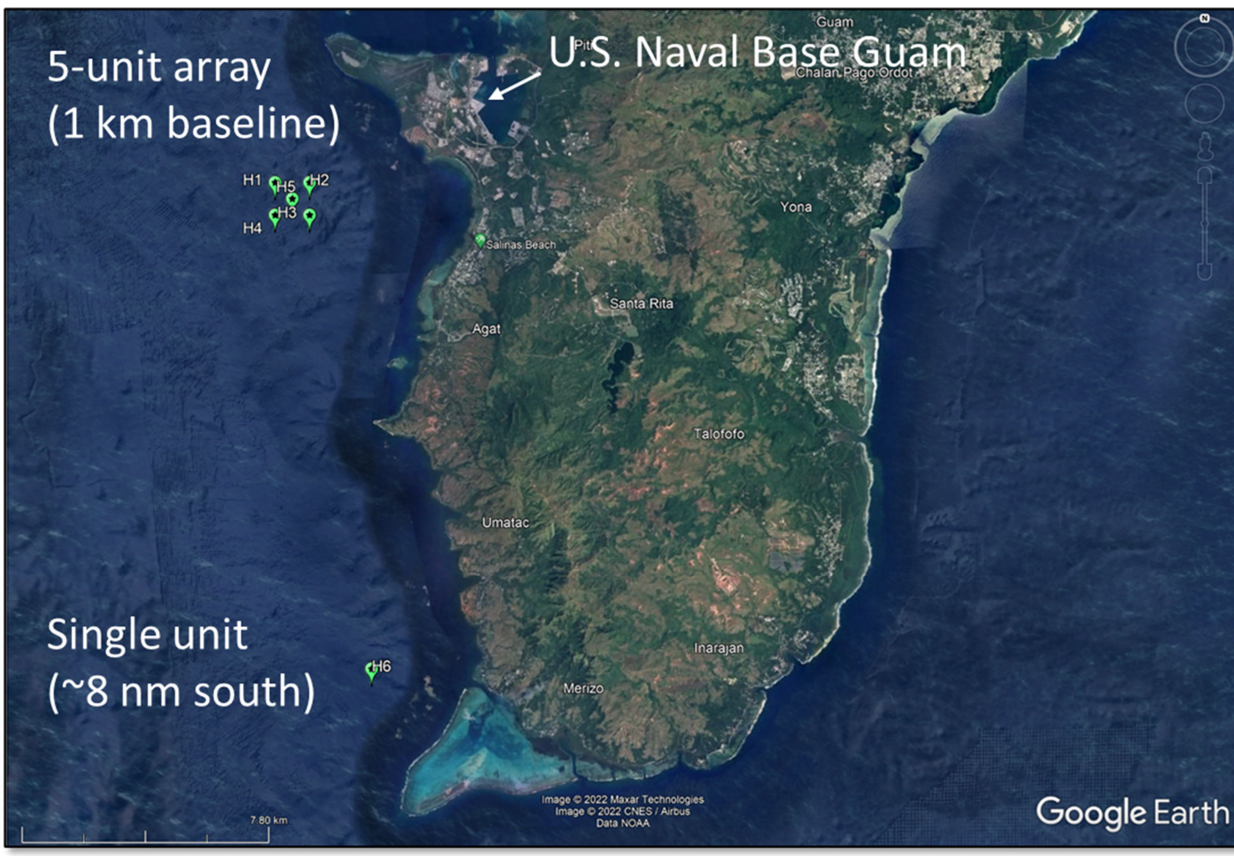


Figure 3: Final deployment configuration. Note: Map source: Google Earth.

After deployment of the units, the sensor locations were surveyed, following the procedure outlined in Russel *et al.* (2019), to accurately determine the final deployment locations and depth (see **Table 2**).

Acoustic data was collected from 26 May 2022 to 22 November 2022. An additional ~three months of data (7 December 2022 to 14 March 2023) was collected at Site RH02.

Table 2: Rockhopper deployment locations

Site	Lat [N]	Lon [E]	Depth [m]
RH01 (array, NW corner)	13.40288	144.60390	913.5
RH02 (array, NE corner)	13.40306	144.61397	636.0
RH03 (array, SE corner)	13.39431	144.61423	742.9
RH04 (array, SW corner)	13.39388	144.60421	980.9
RH05 (array, center unit)	13.39822	144.60934	833.2
RH06 (single unit)	13.26864	144.63148	900.3

2.4. Issues Encountered

Approximately one month (on 19 October 2022) before the recovery of the units, the Rockhopper deployed at location RH02 surfaced prematurely. Over the next several months, the unit drifted about 2,500 km in a north-northwesterly direction and eventually was picked up by someone close to the Babuyan Islands in the Philippines. Because of the remoteness of the islands and the lack of infrastructure, getting in touch with the finder was challenging. By the time communication was established and the field operations team arrived in the Philippines, the finder had completely disassembled the unit. However, the drives containing the recorded data, the acoustic release, and the hydrophone could be returned to the U.S.

3. Data Analysis

3.1. Beaked Whale Detection and Classification

Data from the Rockhopper deployments were post-processed using PAMGuard software (64-bit Version 2.01.05; Gillespie *et al.* 2008) to detect the acoustic presence of beaked whales known to occur in the area (see **Table 1**). PAMGuard was configured with customized click classifiers to classify impulsive signals as goose-beaked whale, dense-beaked whale, Indo-Pacific beaked whale, Deraniyagala's beaked whale, Ginkgo-toothed beaked whale (BW43 call type), and the 'BWC' call type (species unknown). This post-processing results in 'binary files' (a proprietary PAMGuard file type) and a populated SQLite database that was used to analyze data further using PAMGuard's ViewerMode. PAMGuard ViewerMode was used to verify and log the start and end times of beaked whale encounters. Encounters were identified using a combination of the click detection time/amplitude display, a scrolling spectrogram, the Wigner plot, and the data map (a condensed display showing all the click detections for the month). An encounter was defined as a period of time in which beaked whale clicks were present with less than a 30-min inter-detection interval. Encounter logs were exported for each month of data at each site and combined for each location using a custom R script (R Core Team 2021).

Additionally, the PAMGuard Real-time Odontocete Call Classification Algorithm (ROCCA) module (Oswald and Yack 2015) was used to measure and extract click features (e.g., peak frequency, -

10 dB bandwidth, duration, and inter-pulse-interval [IPI]) required for species classification for each beaked whale encounter. Beaked whale echolocation clicks were classified to species level based on time and frequency characteristics (Baumann-Pickering *et al.* 2013; Yack *et al.* 2013).

Four features of clicks were used to classify encounters to species (Department of the Navy [DoN] 2014):

- Click duration (range for beaked whales: 182 to 585 microseconds [μs])
- Peak frequency (e.g., goose-beaked whale = 38-40 kHz and dense-beaked whale = 34-36 kHz)
- IPI (e.g., goose-beaked = 0.34 s and dense-beaked = 0.28 s)
- Presence of an upsweep on the Wigner-Ville transform (e.g., see
- **Figure 4**, right panel)

a) **b)** **c)**

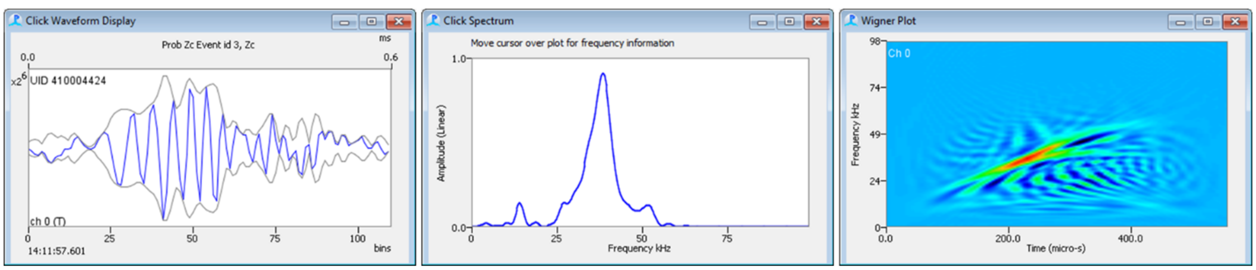


Figure 4: Graphical examples of important beaked whale echolocation click features.

Notes: (Left panel) A waveform depicts time (x-axis) versus amplitude (y-axis) for data from one of the deployed Rockhopper units. (Center panel) Frequency (x-axis) versus amplitude (y-axis) demonstrates the frequency of peak energy in each click. (Right panel) A Wigner plot of echolocation clicks, depicting time (x-axis) versus frequency (y-axis), with energy represented by color. The Wigner plot (i.e., Wigner-Ville transform) represents time and frequency in greater detail than possible from a traditional spectrogram. It provides a simple way to view short-duration signals, such as echolocation clicks.

Plots of median peak frequency vs. median IPI of each beaked whale acoustic encounter and boxplots of relevant ROCCA click measures were used to formally classify encounters to the species level (e.g., see **Figure 5**). Median values instead of means and percentiles instead of standard deviations were used because beaked whale click data typically exhibits a non-normal distribution, often with numerous outliers.

A data analyst experienced with beaked whale click classifications reviewed and classified all unidentified beaked whale click encounters to the lowest taxonomic level possible (similar to the methods outlined in McCullough *et al.* 2021). In addition, occurrence patterns for each species and location were produced using a custom R Script. Verified detector outputs and the associated raw acoustic data were used for localization analysis.

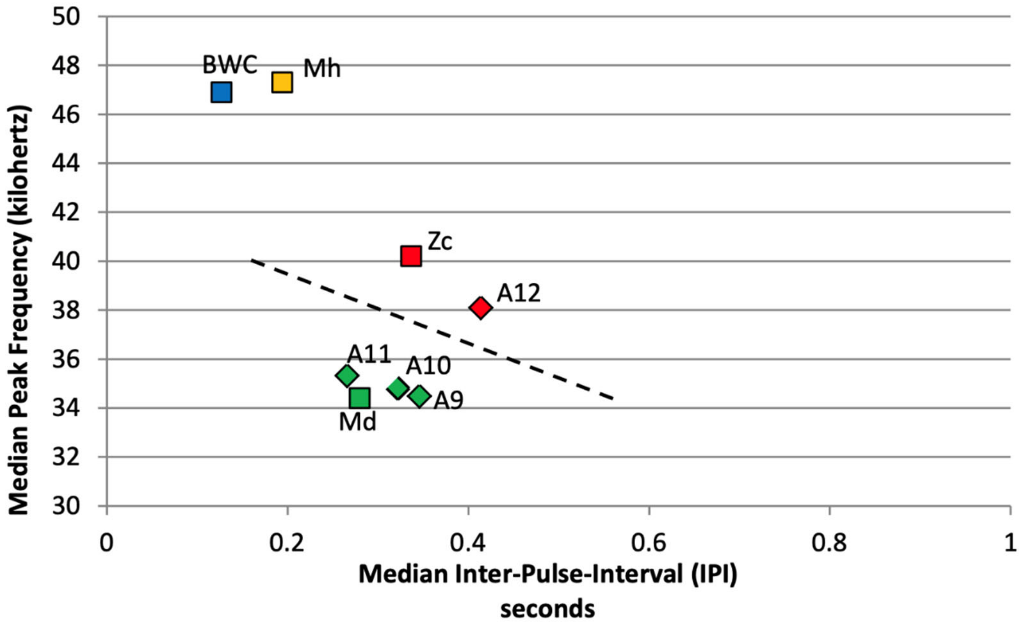


Figure 5: Beaked whale echolocation click median peak frequency vs. IPI for species identification.

Notes: Median peak frequency (kilohertz; y-axis) is plotted against IPIs for each beaked whale acoustic encounter and reported values of species of beaked whales expected to occur in the study area. Goose-beaked whales (Zc), Dense-beaked whales (Md), Deraniyagala's beaked whale (Mh), and an unidentified beaked whale click type from the tropical Pacific (BWC) (Baumann-Pickering *et al.* 2013). The A numbers (A9–A12) are the acoustic detections from a Marianas survey. Image source: Figure K-2 from DoN, 2014.

The encounters were processed to produce beaked whale detections in 10-sec time segments. The use of 10-sec segments corresponds with the time segments used in the localization work described in Section 3.2. A regression analysis was used to investigate the spatial and temporal patterns of the encounters at the different locations. A Generalised Additive Model (GAM) was used, and the number of 10-sec segments with species-specific detections per day was the response variable. The response variable was initially assumed to follow a Poisson distribution, though quasi-Poisson and negative binomial distributions were subsequently considered to address overdispersion in the data. Day of year, month, species, and instrument were considered as predictor variables. Day of year and month were considered to be continuous variables, while species and instrument were included in the model as factor variables. Collinearity between the predictor variables was assessed using variance inflation factor scores, and influential data points were investigated using Cook's Distance scores. Model selection between variables was performed using hypothesis tests (specifically F tests) and associated p-values (at a level of 0.05). T-tests or z-tests (depending on the model) were used to investigate differences between factor levels for a given factor variable. Model fit, and assumptions of constant error variance, error independence, and normality were tested through diagnostic plots. All stages of the modeling analysis were performed using R software, version 4.3.1 (R Core Team 2023). The GAM was fitted using the mgcv package (version 1.8-42, Wood 2017).

3.2. Beaked Whale Localization

The primary goal of this task was to generate a sufficient number of high-confidence beaked whale localizations to enable density estimation (as opposed to tracking whales). The individual Rockhopper recordings were synchronized through a semi-automated pipeline with manual verification. Within each hour-long interval, all emitted pings were identified with an energy-based detector at the peak frequency range associated with each pinger (34–38 kHz +/- 0.25 kHz). Next, the measurement of each emitted ping on all other units was detected by cross-correlation. As spurious peaks could occur due to noise or misalignment, a custom interactive interface was designed to visually verify and/or correct any errors in these detections. If two units both emitted and measured pings within the same continuous recording interval, the empirical travel time between the two units could be calculated. These travel times were compared against expected times to validate the sound speed and temporal calculations used in the localization algorithm. Lastly, after accounting for travel time, the relative drift was calculated for each measurable emitter/receiver pair (relative to the center unit), and the median value was used to align the five audio channels.

Following synchronization, the locations of beaked whales near the array were calculated with a custom implementation of likelihood surface localization (Nosal, 2013). Likelihood surface localization relies on calculating an intersection of hyperbolic surfaces representing the locations at which the theoretical time difference of arrival (TDoA) of a signal recorded at two units most closely corresponds to the measured TDoA. Theoretical TDoAs were calculated assuming direct arrival at a constant sound speed profile. To ensure confidence in click association across channels, measured TDoAs were calculated for partial click trains in 10-sec segments rather than individual clicks. Specifically, after bandpass filtering the time-domain signals to 35–45 kHz, high-amplitude clicks were detected with peak-finding over the Teager-Kaiser operator. For each pair of units, the time differences between all pairs of peaks were 'histogrammed' with a resolution of 0.01 sec. TDoAs with a count of 5 or more (empirically derived) were then incorporated into the localization algorithm with a likelihood surface corresponding to the hydrophone pair (Morrissey *et al.* 2006). The final likelihood distribution of the sound source was determined through the multiplication of all likelihood surfaces representing TDoAs identified across hydrophone pairs, and the output of the algorithm was the discrete coordinate corresponding to the maximum of the likelihood distribution. A standard deviation-of-error parameter of 0.05 sec was chosen based on conservative error estimates across synchronization, sound propagation, and TDoA measurement. The synchronization and localization pipeline was validated by localizing signals emitted during the ranging of the Rockhoppers at the start of the deployment, as described in Appendix A. While localization was implemented in 2D, multiple feasible depth values (from 400 to 1,000 m, in increments of 100 m) were tested, and the highest likelihood result was selected. Lastly, only localizations detected at four or more units were retained, and localizations with a low likelihood (maximum likelihood <0.1) or with high uncertainty (likelihood sum >100) were excluded from further analysis. This process was applied to all 10-sec segments within the synchronized files for which beaked whale clicks were detected on the center unit. Finally, through a manual review, about a third of the intervals were found to be dominated by noise and non-beaked-whale (particularly dolphin) clicks, and these localizations were thereby excluded from the results.

3.3. Beaked Whale Detection Function Estimation

The primary method to estimate the beaked whale detection function was acoustic spatial capture-recapture (e.g., Stevenson *et al.* 2015). This method requires a record (known as 'capture history') on which hydrophones the same beaked whale clicks were detected. Initially, detections across all the instruments in the array were binned into 10-sec segments and used to create capture histories. Additional data, such as TDoA and signal strength, can be used to supplement the analysis.

The estimated detection functions were used to estimate the densities of beaked whales around the array using the estimator:

$$\widehat{D} = \frac{n(1-\hat{c})\hat{s}}{k\hat{v}\hat{\lambda}} \qquad \text{(Eqn. 1)}$$

Where:

$\widehat{D}$ is estimated animal density, n is the number of 10-sec segments containing beaked whale detections, $\hat{c}$ is the estimated false positive proportion, $\hat{s}$ is the estimated group size, k is the total number of 10-sec time segments, $\hat{v}$ is the estimated effective detection area (which includes the detection probability estimated from the detection function), and $\hat{\lambda}$ is the estimated probability of a beaked whale group clicking in a 10-sec segment.

Variance and associated confidence intervals around the density estimates were estimated using the Delta method (Seber 1982). Detection functions and density estimates were estimated for goose-beaked whales only, given the larger sample size and available auxiliary information needed for density estimation. While $\hat{c}$ and $\hat{P}$ could be estimated from the collected data, information about $\hat{s}$ and $\hat{v}$ were taken from the literature. The group size of goose-beaked whales was assumed to be 2.45 animals (CV: 0.05). This estimate was reported by Badger *et al*. (2024) and was derived from visual sightings from several Pacific studies (Baird 2019; Yano *et al*. 2022). The probability of a beaked whale group clicking in a 10-sec segment was derived from an expression in Barlow *et al.* (2021), where the probability of clicking in a time segment is estimated as:

$$\hat{\lambda} = \frac{t_a+d}{t_a+t_u} \qquad \text{(Eqn. 2)}$$

Where:

t_a is the time spent clicking, d is the length of the time segment, and t_u is the time spent not clicking. Note that $(t_a + t_u)$ can be defined as the deep dive cycle of an animal, including non-clicking periods nearer the surface. Barlow *et al.* (2021) state that the instantaneous probability of being detected is $\hat{\lambda}' = t_a/(t_a + t_u)$.

Barlow *et al.* (2020) provided data on $\hat{\lambda}'$ and $(t_a + t_u)$, which enabled $\hat{\lambda}$ to be estimated for a 10 sec time segment, with associated uncertainty. An assumption of these calculations, however, is that animals in a group click synchronously.

Using the above auxiliary information, goose-beaked whale density was estimated using spatial capture-recapture (SCR) in the ascr R package vs. 2.2.4 (Stevenson 2022). Multiple sessions were used in the analysis to reflect that the number of available instruments changed in the array in September and November. Using a buffer of 10 km and assuming homogenous density across space, a half-normal and a hazard rate detection function were both fitted to the capture history data. Model selection was performed using Akaike's Information Criterion (AIC). A secondary analysis was conducted using distance sampling (Buckland *et al.* 2001) to estimate the detection function. The localizations from Section 3.2 were the input data for the distance sampling analysis. Half-normal, uniform, and hazard rate detection functions with associated adjustment terms (cosine and polynomial) were fitted to the data. Model goodness of fit was assessed using hypothesis tests (Kolmorogov-Smirnov and Cramer von Mises tests) with associated p-values (at a level of 0.05) and diagnostic quantile-quantile plots. AIC was used to perform model selection.

3.4. MFAS Detection Analysis

The U.S. Navy sonar analysis was performed with a highly efficient detector developed by Naval Information Warfare Center (NIWC) and Naval Undersea Warfare Center (NUWC) under the Living Marine Resources Program (LMR)-funded project 'Standardizing Methods and Nomenclature for Automated Detection of Navy Sonar (Project #LMR-34)'. This detector runs on the Raven-X platform (Dugan *et al.* 2015), developed with Office of Navy Research (ONR) funding. Raven-X is based on a high-performance computing framework that enables users to analyze large amounts of acoustic data in short periods of time. Detector outputs of Raven-X were provided in Raven Pro selection tables (see **Figure 6**). An experienced analyst reviewed and verified the detections visually and aurally.

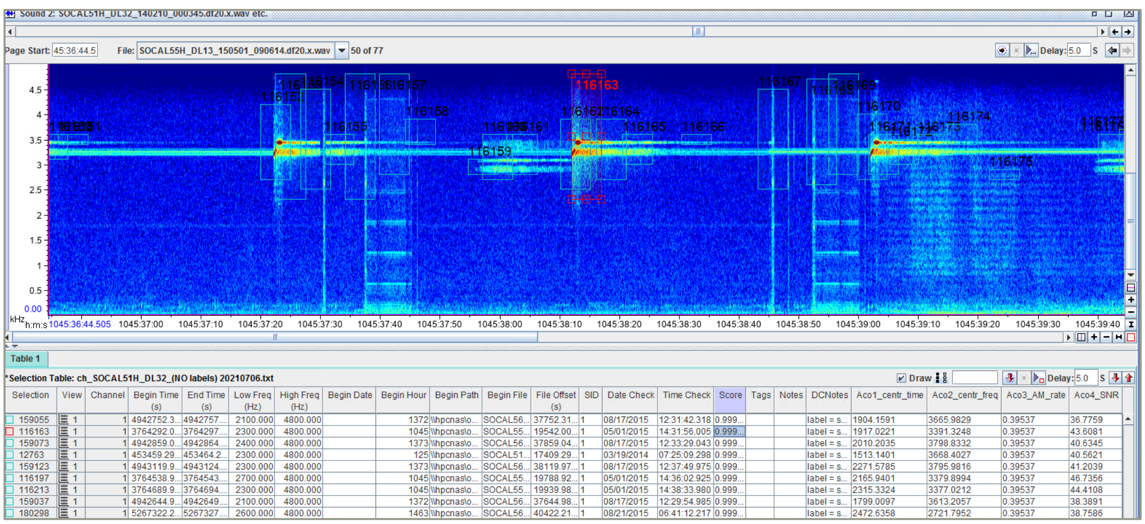


Figure 6: Screenshot of U.S. Navy mid-frequency active sonar detections (from a different dataset) generated with Raven-X and displayed in Raven Pro.

Verified detector outputs and the associated raw acoustic data were used for the sonar localization analysis described in the following section.

3.5. MFAS Direction-of-Arrival Estimation

For each of the nine sonar events detected on the array and the single unit and the single event detected on the array, associated audio recordings were synchronized, and times-of-arrival of individual sonar signals were manually annotated to obtain TDoAs across channels. As localization accuracy inherently falls with the distance of a source from the array and is infeasible for distant sources, direction-of-arrival (DoA) was instead estimated for detected MFAS events. While TDoA localization assumes an acoustic monopole emitting a spherical wave, DoA estimation assumes a far-field source propagating as a plane wave. Accordingly, the likelihood-surface algorithm was adapted for numerical DoA estimation by modifying the theoretical TDoAs across recording units to represent expected time delays for a source at an angle θ relative to the center of the array. In all, this approach yields curves quantifying likelihood as a function of θ that can be visualized in a polar representation.

For sonar events occurring late in the deployment, only units at sites S01, S03, and S05 within the array were actively recording, creating left-right directional ambiguity. The unit at site S06 was opportunistically synchronized to resolve the ambiguity for MFAS events during this period. Synchronization was achieved using sonar pings emitted north of the array, creating a known time delay between units at sites S05 and S06 that was independent of source distance.

4. Results

4.1. Beaked Whale Occurrence Patterns

Beaked whale occurrences are initially reported on an encounter basis (though the regression modeling, localization, and density estimation analyses focused on a finer temporal scale). Encounters are periods of vocal activity separated by at least 30 min of silence (see **Figure** 7).

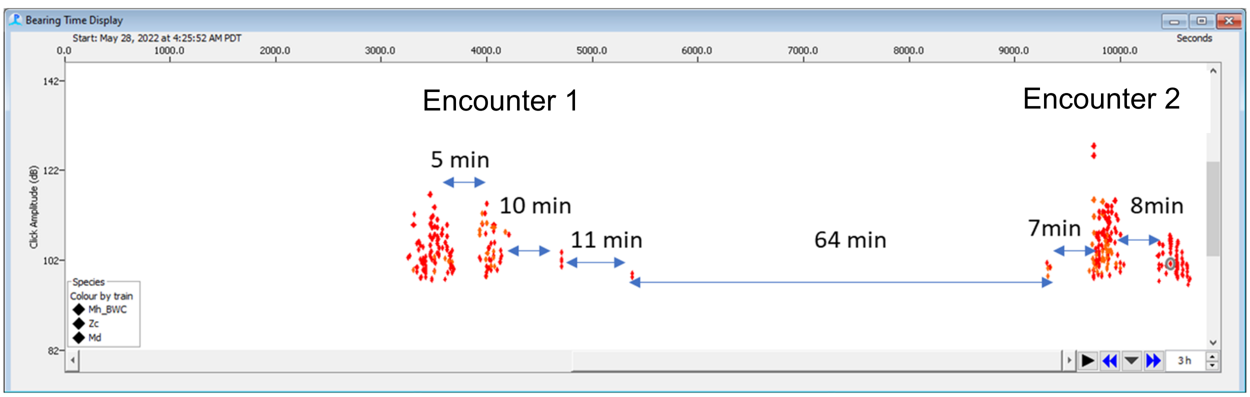
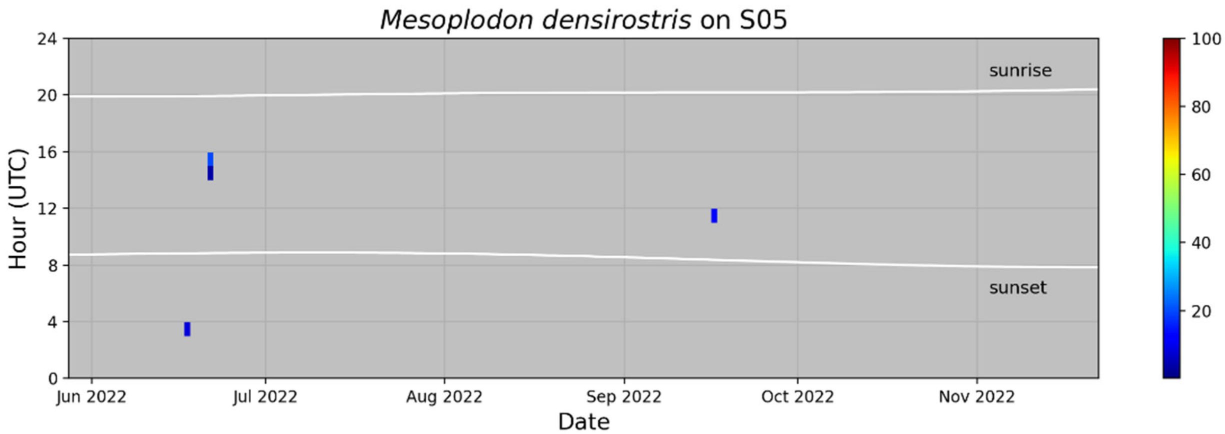
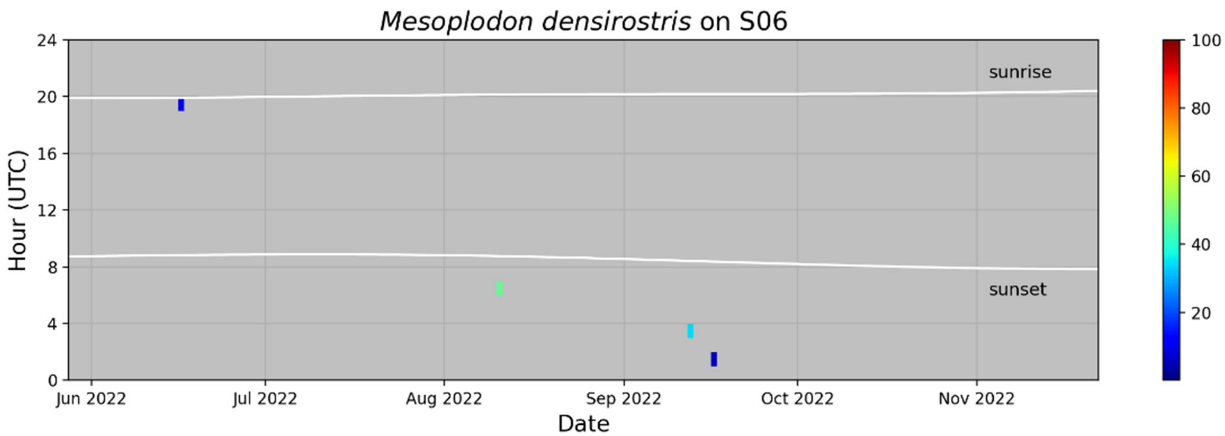
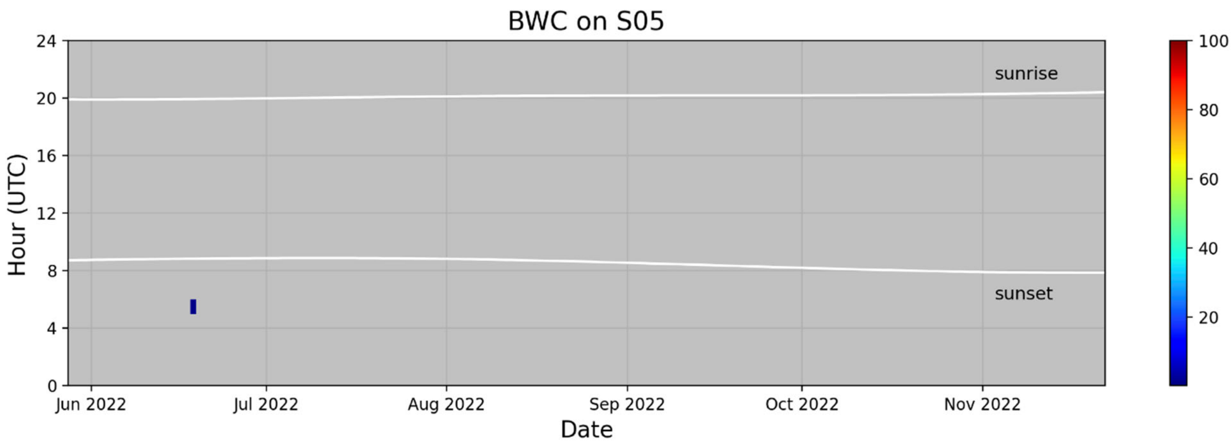


Figure 7: Two encounters of goose-beaked whales.

At the array site (S05), a total of 66 encounters (62 encounters of goose-beaked whales) were registered. At the single-unit site (S06), the number of encounters was identical (n = 66) and also primarily driven by occurrences of goose-beaked whales (n = 60). The remaining encounters were associated with dense-beaked whales (n = 4), BWC beaked whales (n = 1), and unidentified beaked whales (n = 1). Details are presented in **Figure 8** below.


Mesoplodon densirostris on S05
Hour (UTC)
Date
sunrise
sunset
Jun 2022
Jul 2022
Aug 2022
Sep 2022
Oct 2022
Nov 2022


Mesoplodon densirostris on S06
Hour (UTC)
Date
sunrise
sunset
Jun 2022
Jul 2022
Aug 2022
Sep 2022
Oct 2022
Nov 2022


BWC on S05
Hour (UTC)
Date
sunrise
sunset
Jun 2022
Jul 2022
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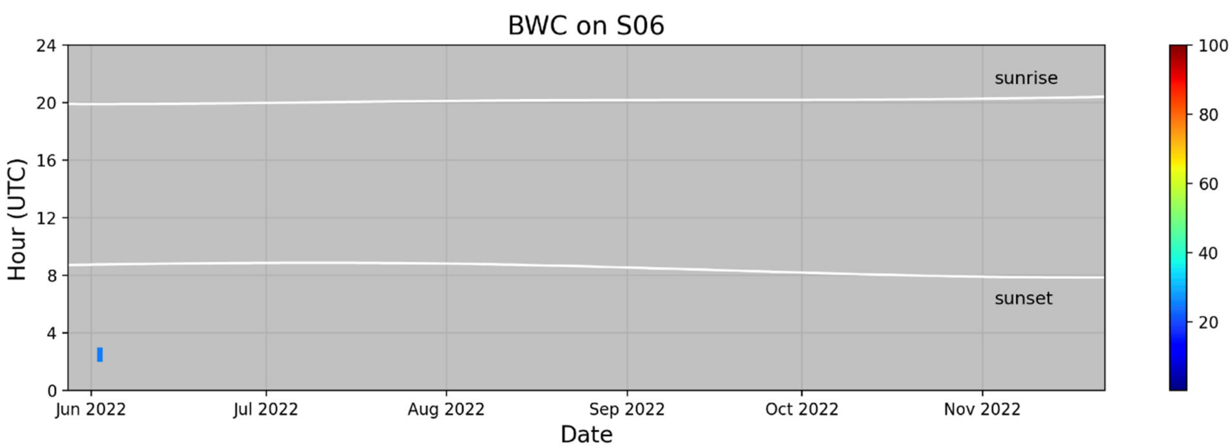
Sep 2022
Oct 2022
Nov 2022

1


BWC on S06
Hour (UTC)
Date
sunrise
sunset
Jun 2022
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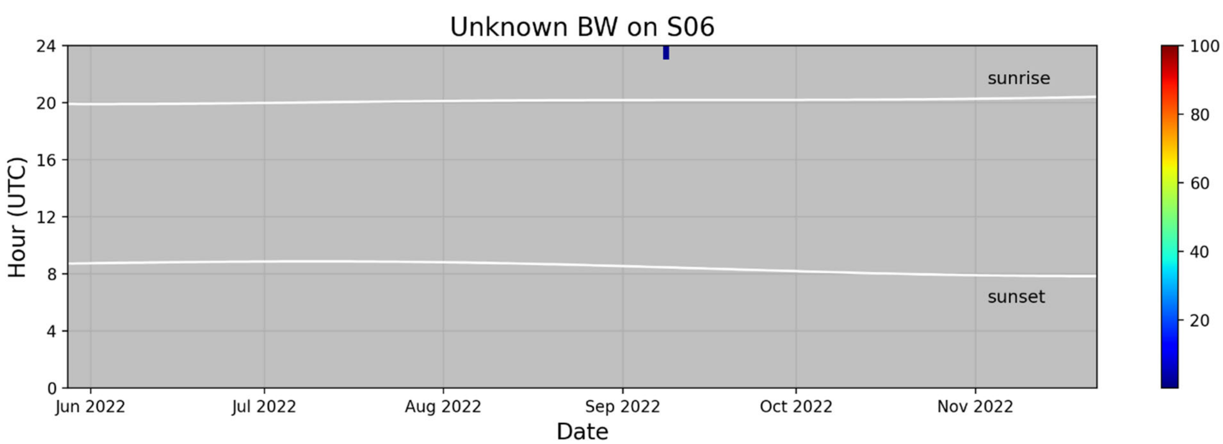
Oct 2022
Nov 2022

2


Unknown BW on S06
Hour (UTC)
Date
sunrise
sunset
Jun 2022
Jul 2022
Aug 2022
Sep 2022
Oct 2022
Nov 2022

3

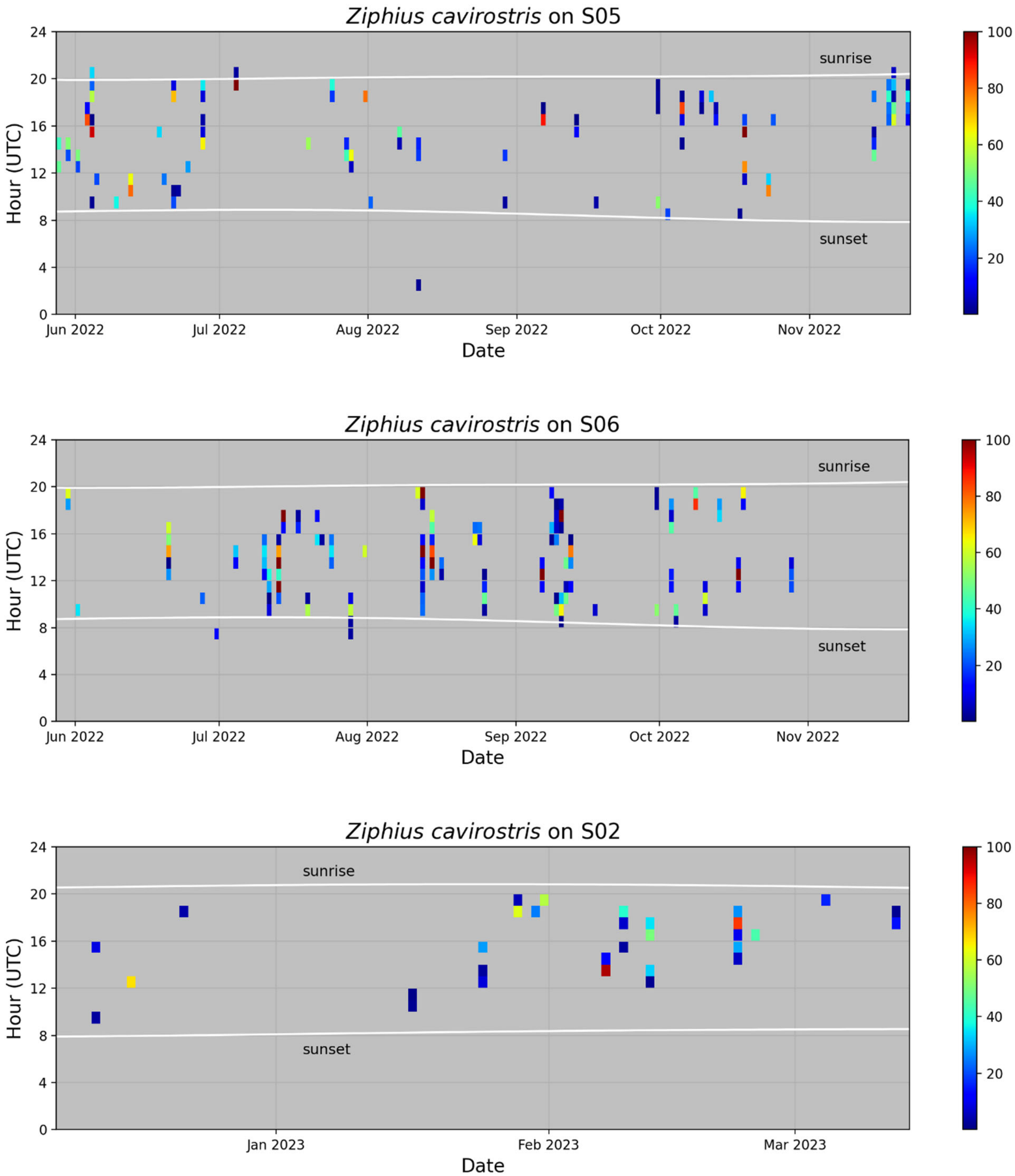


Figure 8: Beaked whale occurrence patterns for the array (S05) and the single-unit (S06) by species.

Notes: The date is shown on the x-axis. The y-axis represents the time of the day (sunrise and sunset times shown with white lines). The color bar represents the number of 10-sec windows with detections for each hour. The acoustic data was collected from 26 May 2022 to 22 November 2022. Results from the array (S02) were included for goose-beaked whale detections for additional data collected from 7 December 2022 to 14 March 2023 (Note: no sonar detections occurred during this time period).

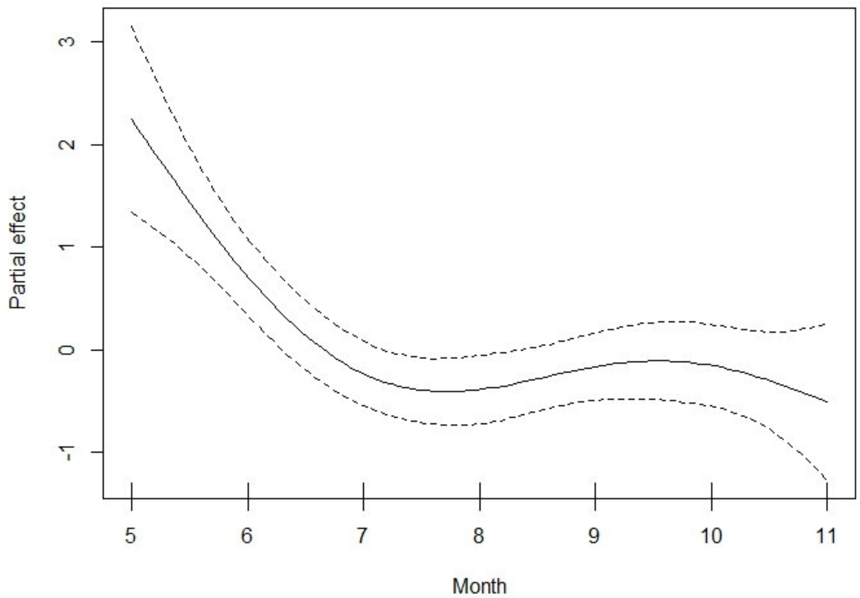
Beaked whales were detected every month at both sites, except for the month of November at the single-unit site. Unexpectedly, almost all goose-beaked whale detections occurred at night. This may be caused by the diel movement patterns of beaked whales in the area. The final regression model used to model the daily numbers of beaked whale detections as a function of species, instrument, and month used a negative binomial distribution to account for overdispersion. Day of year was collinear with the month, so was not included in the model. The negative binomial was selected in preference to the quasi-poisson distribution due to improved diagnostic plots relating to constant error variance. Further, evidence of temporal correlation (up to a lag of three days) resulted in an AR1 correlation structure being fitted to the GAM. Model selection resulted in instrument, species, and month being retained as predictor variables (**Figure 9, Table 3**). While there was little difference between instruments in the array (though RH02 showed increased detections) the single instrument showed an increased number of 10-sec time segments with detections per day.

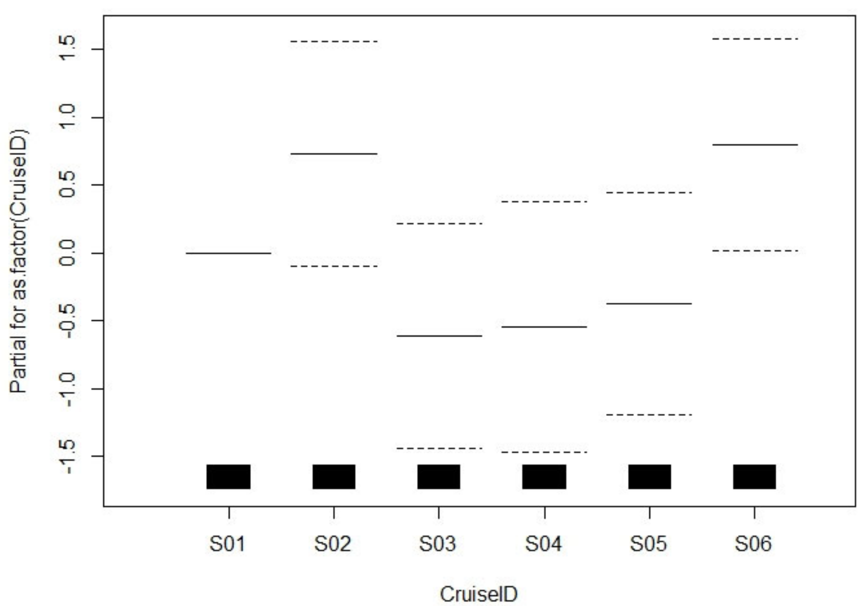
Table 3: Results from the final GAM.

Predictor variable	Effective degrees of freedom	F value	p-value
Instrument	5	4.51	0.0004
Species	3	159.74	<0.0001
Month	3.18	8.10	<0.0001

Goose-beaked whales had the highest daily number of 10-sec time segments with detections. The "unknown" species category had the lowest number of segments per day compared to the other species (**Figure 9**). Detections appeared to be higher at the start of the deployment (**Figure 9**, **Table 3**). The final model explained 49.4% of the deviance and showed some evidence of non-constant error variance, though other assumptions were met.

It should be noted that the frequency of the synchronization pings is within the hearing range of beaked whales (Pacini *et al.* 2011) and could have impacted the behavior of the studied animals. However, as the source level is fairly low, the area over which these signals are audible to the whales is much shorter than the detection ranges for beaked whale signals. In addition, it is reassuring that the observed occurrence patterns of the single unit (which does not have a pinger) are similar to the array site.


Partial effect
3
2
1
0
-1
5
6
7
8
9
10
11
Month


Partial for as.factor(CruiseID)
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1.0
0.5
0.0
-0.5
-1.0
-1.5
S01
S02
S03
S04
S05
S06
CruiseID

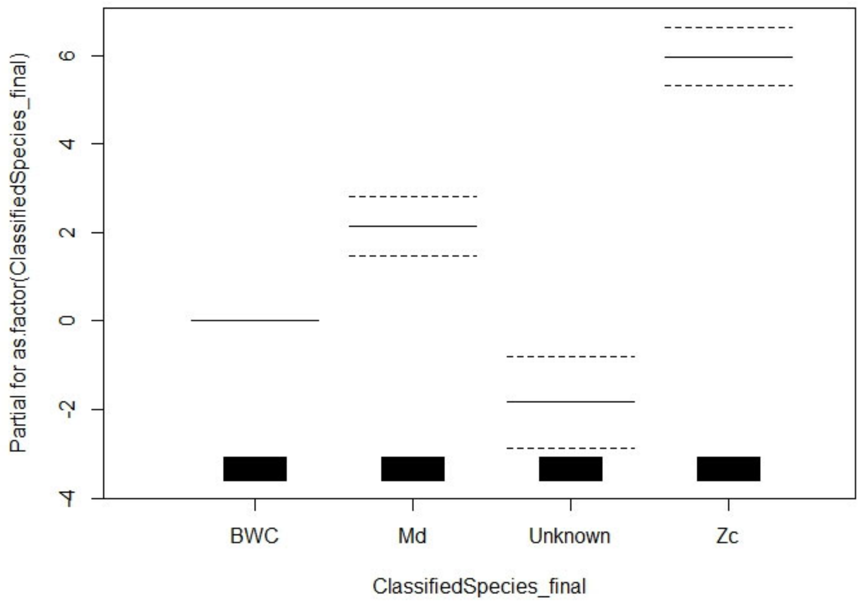

Figure 9: Results from the final GAM model showing relationships between the response variable and three predictor variables.

4.2. Beaked Whale Localizations

Emitted pings from all corner units were reliably measurable on the center unit (S05). Conversely, over 90% of pings emitted by the center unit were measurable on the corner units. The measured travel times between pairs of units were highly consistent, with standard deviations across measurements under 0.01 sec. Notably, the travel times indicated that pings received at and from S01 and S02 were surface reflections rather than direct arrivals. At a sound speed of 1,500 m/s, the measured travel times agreed with theoretical travel times with a root-mean-squared error below 0.01 sec; this sound speed was consequently used for localization. The relative drift between the corner units and the center unit remained below 1 sec for the duration of the acoustic survey. The localization focused on goose-beaked whales, given their large sample size. In all, synchronization of time periods containing verified goose-beaked whale detections yielded 87 aligned 10-min files, which were further processed into 10-sec segments.

Likelihood surface localization initially yielded locations for 377 x 10-sec segments. After filtering to high-likelihood, low-uncertainty detections at four or more units, followed by a manual review to remove non-beaked whale localizations, we obtained 49 locations with 201 associated distances (**Figure 10**), representing detections across 14 distinct days spanning the deployment duration.

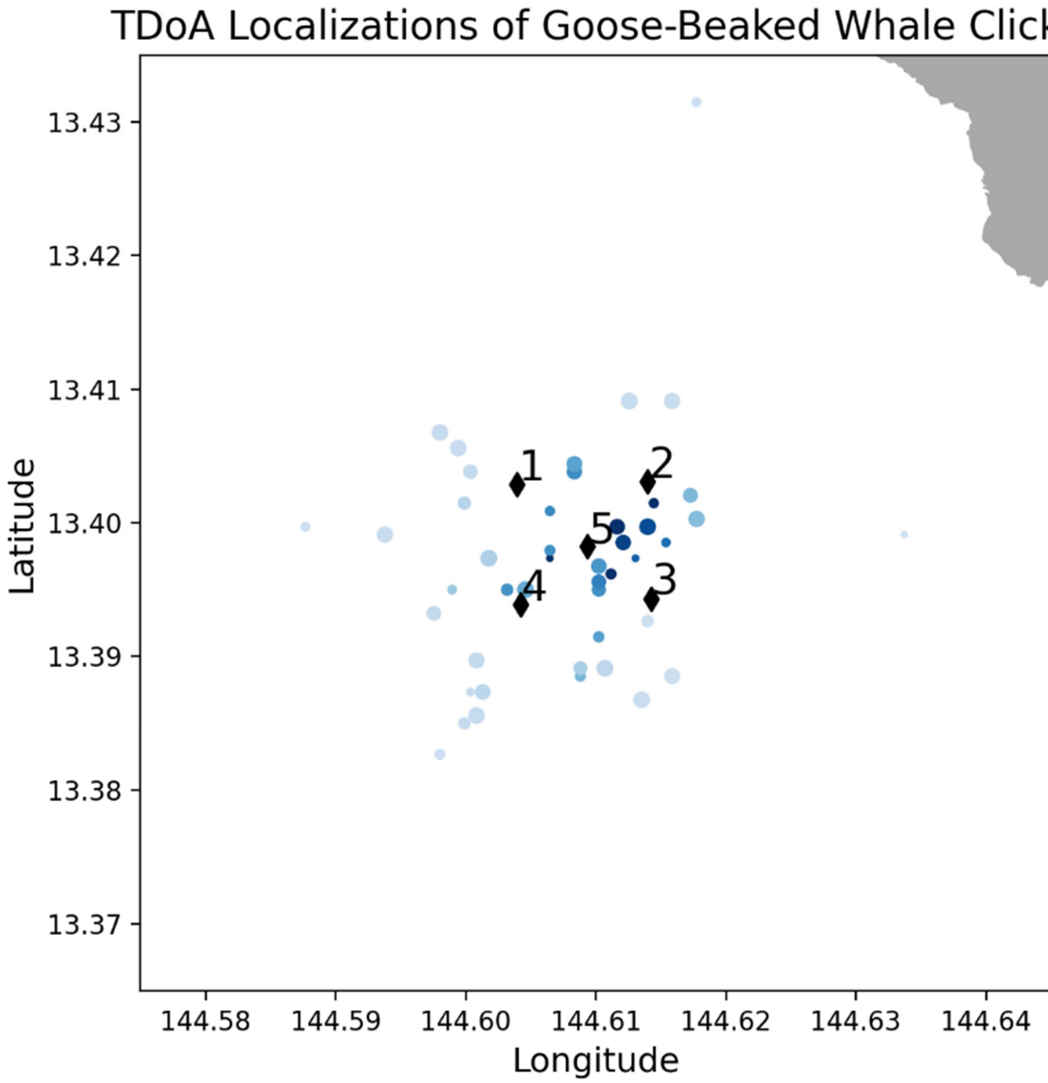

Figure 10: High-confidence goose-beaked whale locations (n = 49) derived using 4 or 5 receivers.

Notes: The color of the locations indicates the associated likelihood score (darker colors represent higher likelihood values).

4.3. Beaked Whale Detection Function Estimation

There was a total of 5,552 unique 10-sec segments containing goose-beaked whale detections across the array (instruments S01-S05) during the entire deployment. The frequency of 10-sec segments detected on 1, 2, 3, 4, or 5 instruments within the array is given in Table 4. The number of detections in each month is given in

Table 5.

Table 4: Frequency of unique 10-sec segments with goose-beaked whale detections that were detected on 1, 2, 3, 4, or 5 instruments within the array during the whole deployment.

Number of instruments	1	2	3	4	5
Number of unique 10-sec segments	3,287	1,485	625	141	14

Table 5: Number of unique 10-sec segments with goose-beaked whale detections in each session across the array (instruments S01-S05) during the whole deployment with associated density estimation results.

Session	1	2	3	4	5	6	7
Dates	26-31 May	1-30 June	1-31 July	1-31 August	1-27 September	28 September -18 October	19 October - 22 November
Number of unique 10-sec segments	380	1930	841	328	225	896	952
Total number of 10-sec segments with monitoring effort	85,800	431,400	444,600	445,800	386,400	301,800	489,600
Effective survey area (km^2)	8.59	8.59	8.59	8.59	8.59	7.44	6.27
Density (animals per 1,000 km^2)	**6.34**	**6.41**	**2.71**	**1.05**	**0.83**	**4.89**	**3.80**
Density 95% CI (animals per 1,000 km^2)	5.36 - 7.51	5.56 - 7.39	2.33 - 3.15	0.89 - 1.25	0.69 - 1.01	4.20 - 5.69	3.27 - 4.43
CV Density (%)	8.62	7.30	7.74	8.86	9.62	7.75	7.76

The false positive proportion, $\hat{c}$, was assumed to be zero, given that every detection was manually checked and verified as a goose-beaked whale detection. The total number of 10-sec segments with monitoring effort, k, was 2.59 x 10^6, with monthly totals provided in Table 5. In the SCR analysis, the preferred detection function was the half-normal detection function, as the hazard rate function had convergence issues (**Figure 11**), estimating $\hat{v}$ to be 6.27, 7.44, and 8.59 square kilometers (km^2), depending on whether there were 3, 4, or 5 instruments actively monitoring in the array. The probability of a beaked whale group clicking in a 10-sec segment was estimated to be 0.20 (CV: 3.57%). Average densities per session ranged from 0.83 animals per 1,000 km^2 (CV: 9.62%) in September 2022 to 6.41 animals per 1,000 km^2 (CV: 7.30%) in July 2022.

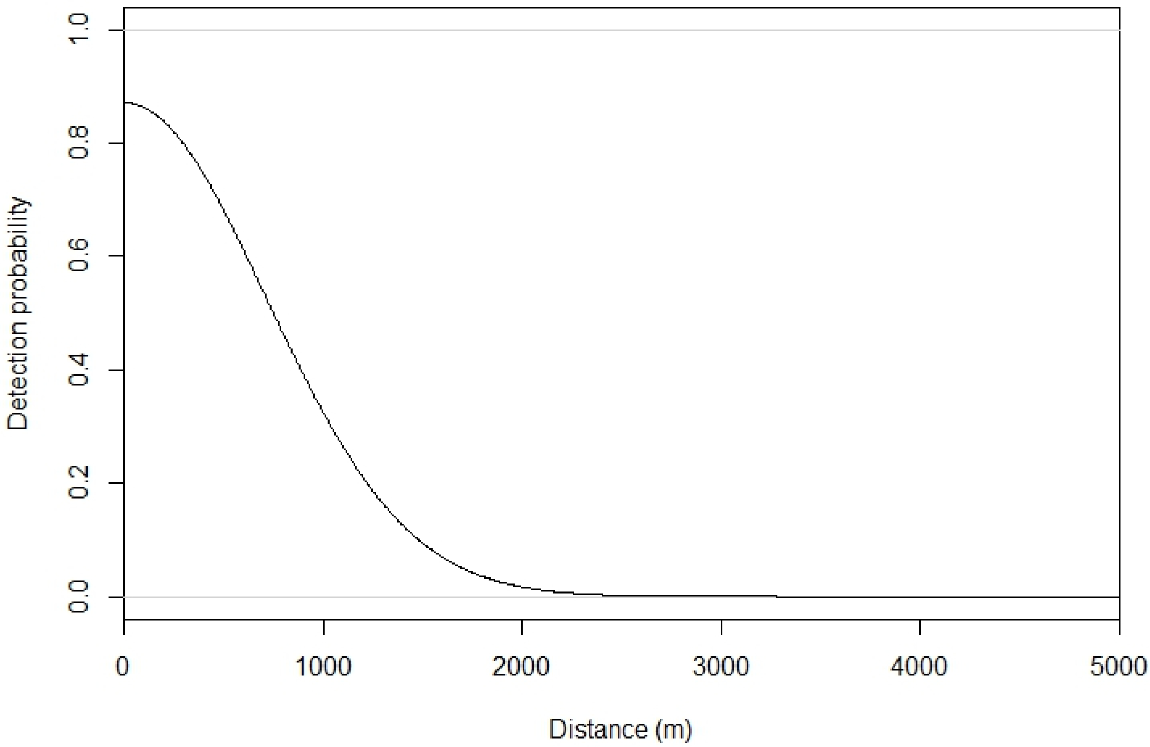

Figure 11: Estimated detection function for each single sensor from the SCR analysis. A half-normal model was selected as the preferred model.

The distance sampling analysis used 49 localizations. Given that detection on the central instrument (S05) was a condition of localization, only distances to S05 were considered for this analysis, rather than measuring the distance from each localization to all instruments that detected it (e.g., Oedekoven *et al.* 2021) (**Figure 12**). Data were truncated (a common distance sampling practice) at 3 km. The final model was a half-normal model with no adjustment terms (**Figure 12**). This was based on goodness of fit assessment; a hazard rate model with two polynomial adjustment terms had the lowest AIC but very poor goodness of fit results. The goodness of fit tests for the final model suggested an adequate fit.

Density was estimated using the same equation for the SCR analysis (Eqn. 1). The number of detections and effort were adjusted to reflect that distances were measured to S05 only. Therefore, n was 48 (after truncation), and k was 1,831,800 to represent the number of 10-sec time periods between May and September (when localization was performed). The estimated effective detection area was 4.21 km^2, and the resulting density estimate (averaged over May–September) was 0.076 animals per 1,000 km^2 (95% Confidence Interval: 0.05–0.11 animals per 1,000 km^2, percentage CV: 20.56%).

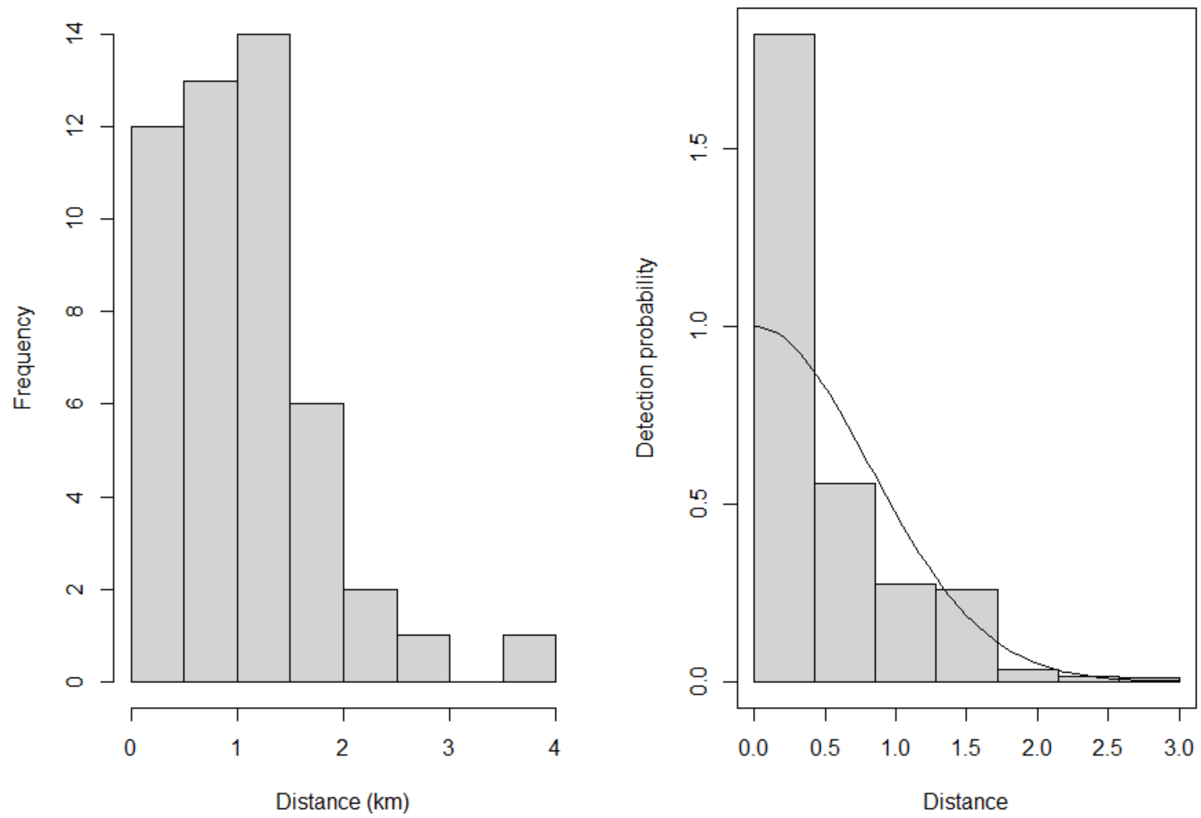

Figure 12: Distance sampling input data (left) and (right) the fitted half-normal detection function to the same data (truncated at 3 km and scaled for plotting).

4.4. MFAS Occurrence Patterns

MFAS activity (16 encounters total) was detected at both sites between August 2022 and November 2022 (see **Figure 13**). Nine encounters were recorded on both units, while six encounters were only registered on the single unit. One encounter was only registered on the array unit. Except for one encounter, MFAS occurred exclusively in the second half of the deployment between September and November 2022. Beaked whale detections did not occur during the time periods during which MFAS signals were detected. While beaked whale detections occurred primarily during the night, sonar detections were primarily detected during the day. However, it should be noted that the detection ranges for these types of signals are vastly different. While beaked whales can be detected over only a few kilometers, MFAS signals are typically detectable over many tens of kilometers. Because of the vastly different spatial scales at which these signals are being observed, no conclusions about the potential impact of MFAS on beaked whales in the area can be drawn.

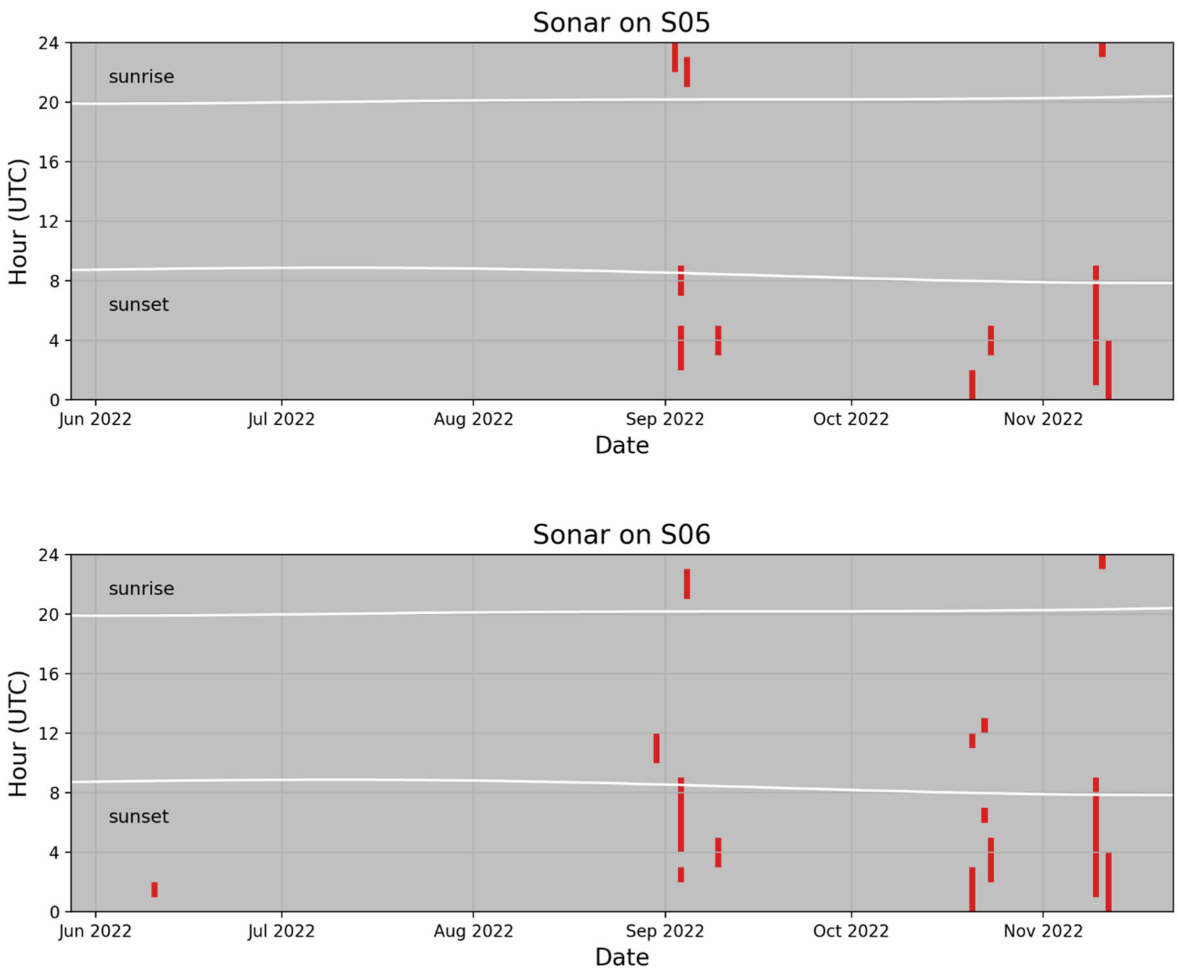

Figure 13: MFAS occurrences (red) for the array site (top) and single-unit site (bottom).

Notes: The day of the date is shown on the x-axis. The y-axis represents the time of the day (sunrise and sunset times shown with white lines). The acoustic data was collected from 26 May 2022 to 22 November 2022.

4.5. MFAS Direction-of-Arrival Estimations

Figure 14 displays polar plots of the DoA estimates for all ten sonar events detected on the array. Each curve represents an average direction over an hour-long duration, with color indicating the time of day. Overall, the events predominantly occurred to the west and north. The longest sonar event detected across the array occurred on 9 November 2022, with north-to-south movement visible over the course of the event.

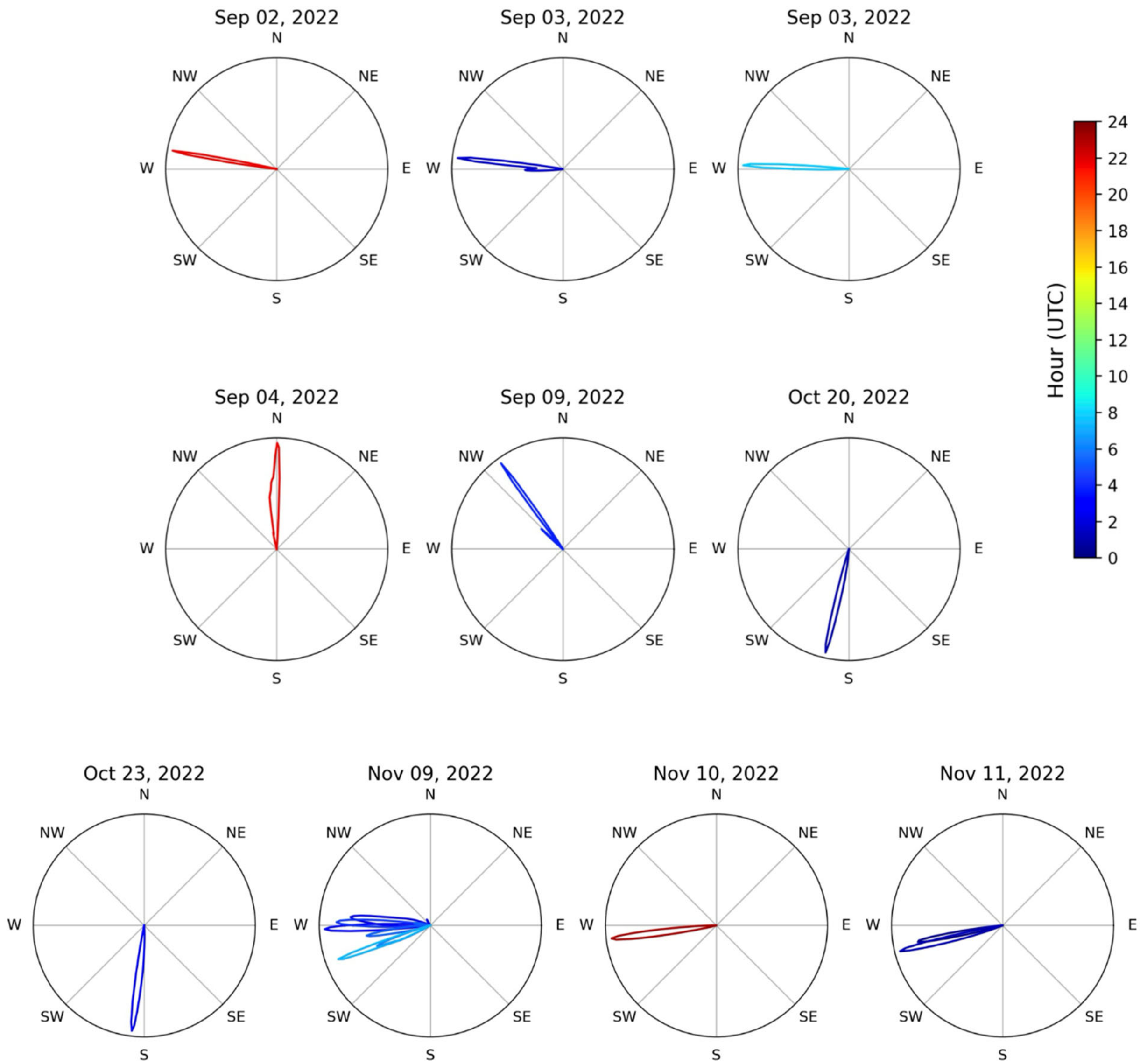

Figure 14: Direction-of-arrival estimates for all ten sonar events detected on the array.

Notes: Each curve represents the mean hourly DoA, yielding multiple curves for long-duration sonar events. The color indicates the hour (in UTC).

5. Discussion and Recommendations

The study design has yielded sufficient data to conduct an SCR analysis to estimate densities for goose-beaked whales. The next steps would be to expand the analysis to other species should the lower sample sizes allow and should suitable auxiliary information about group size and click production be available.

Goose-beaked whale was the most commonly encountered beaked whale species at both the array and single-instrument sites. This was supported by the regression analysis that investigated patterns in daily levels of beaked whale detections, measured as the number of 10-sec time segments with detections in a given day. Goose-beaked whale was the species with the highest daily levels of detection, with the unidentified beaked whale detections having the lowest detection levels (**Figure 9**). The single site (S06) had a higher daily level of detection activity than most of the array sites (**Figure 9**). An interesting finding was that goose-beaked whale detections (at both sites) almost exclusively occurred during the night. We hypothesize that the strong diel pattern we observed is related to diel movement patterns of goose-beaked whales in the area. The regression modeling was conducted at a daily level, though the modeling analysis could be expanded to investigate the observed diel patterns. The regression model could also be extended to explore species-specific differences between daily levels of detections and the predictor variables (e.g., month and site).

The goose-beaked whale densities estimated by the SCR analysis showed monthly variation and were also comparable to estimates made by Badger *et al*. (2024). The SCR analysis did make some key assumptions. First, in this initial analysis, goose-beaked whale detections were matched across 10-sec time segments using the PAMGuard detection times, and it was assumed that detections occurring in the same 10-sec time bin were the same group of animals. Using information from the localization workflow would allow (a) detections to be more accurately matched across instruments and (b) potentially allow TDoA and signal strength data to be included in the SCR analysis, which could improve the precision of the results (Stevenson *et al.* 2015). The inclusion of TDoA data would need careful consideration, however, given that multiple detections occur within a single 10-sec time period. In some cases, clicks within a 10-sec time period may originate from animals in different locations, which would complicate the analysis. Exploration of these additional data inputs would be the logical next step for the SCR analysis. Second, auxiliary information about group size and probability of producing clicks in a 10-sec time segment was mostly taken from the literature (Badger *et al.* 2024; Baird 2019; Barlow *et al.* 2020, 2021; Yano *et al*. 2022). The studies used were goose-beaked whale studies from the Pacific, but some were focused on southern California, so it is possible that the assumed parameters are not appropriate for the animals near Guam and could bias the results. The results could be updated with more regionally-specific data, should such data be available.

The distance sampling analysis produced a density estimate that was an order of magnitude smaller than the SCR results. There are likely to be several contributing factors to this. First, distance sampling assumes that detection probability is certain at zero (horizontal) distance from the instrument (see **Figure 12**). However, the SCR analysis estimated detection probability at zero distance to be less than one (see **Figure 11**). Assuming a certain detection probability when it is less than one will underestimate density (Buckland *et al.* 2001). Second, the number of localizations was much smaller than the number of unique 10-sec time periods with goose-beaked whale detections occurring on 4 or 5 instruments (see **Table 4**). This was due, in part, to the requirement for the central instrument to be included in a detection event and filtering required to ensure high-quality localizations. It is possible that the estimated detection probability could not account for all excluded detections, therefore causing an underestimate in density. Finally, the condition of including the central instrument in every localization affected a key distance sampling assumption about the assumed average distribution of detections around the instruments. This is also likely to affect the model fitting and potentially bias the estimated detection probability. Ways to improve the distance sampling analysis will be considered, though SCR is generally better suited to estimating detection probability from this particular array configuration for these target species.

For the next deployment in early 2024, we recommend making some changes to the experimental setup. Specifically, we propose to deploy the 5-element array in the south and the single unit in the north. This will allow us to better understand how the detection function may vary geographically, which is critical information for future efforts aiming at scaling monitoring up to a larger area. In addition, we detected more beaked whale species in the south. If we get sufficient samples, this may enable us to generate a detection function for additional species (other than goose-beaked whales). Overall, the array configuration with a one km baseline worked well for the density estimation task, and we propose to keep this configuration for the second deployment.

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Appendix A. Localization Algorithm Evaluation

1

The likelihood-surface localization algorithm was validated by localizing signals emitted during the acoustic ranging of all Rockhopper units on 26 May 2022. Audio files recorded across all five units during ranging were synchronized and filtered, and the times-of-arrival across channels were calculated for each signal with a simple energy-based detector. Next, likelihood-surface localization was applied to each signal, with the standard deviation parameter of 0.05 seconds and source depth set to 10m.

Figure 15 below shows the calculated likelihood for eight ranging signals (indicated in blue) along with ground-truth locations of the deployment vessel (indicated in red). As expected, localization uncertainty and error are lowest in the interior of the array and increase with distance from the array. A measurement of distances between the maximum-likelihood location and ground-truth location yields a mean +/- SD error of 59 +/- 51 m.

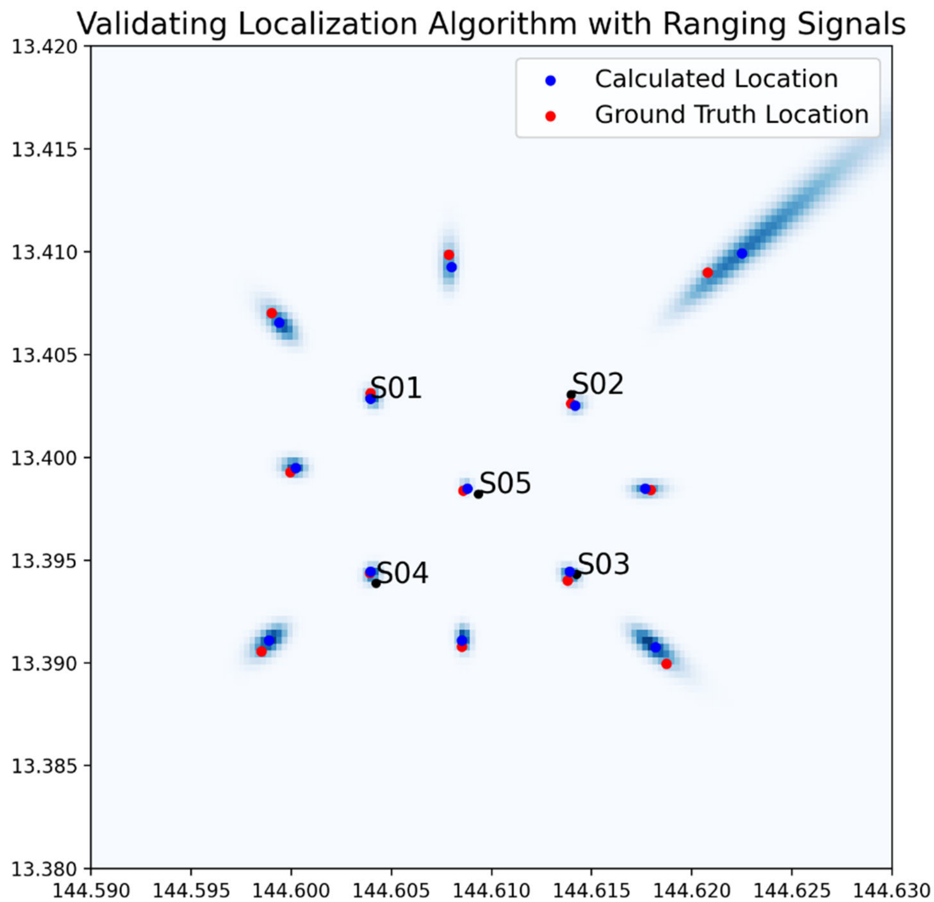

Figure 15: A validation of likelihood-surface localization for ranging signals emitted at each unit's location and around the array. The blue surfaces show superimposed likelihood surfaces for each of 13 source locations, and the blue points indicate the coordinates with maximum likelihood. Red points indicate the ground-truth source location.

Appendix B. Summary of Beaked Whale Encounters

1 **Table 6: Detected beaked whale event times for the array site.**

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]	Species
2022-05-28	12:20:01	35.33	Zc
2022-05-28	14:00:14	23.24	Zc
2022-05-30	13:28:42	75.60	Zc
2022-06-01	12:37:17	63.26	Zc
2022-06-03	16:00:50	64.80	Zc
2022-06-04	09:13:31	0.45	Zc
2022-06-04	15:06:03	74.84	Zc
2022-06-04	18:00:14	52.92	Zc
2022-06-04	19:40:28	39.89	Zc
2022-06-05	11:09:58	23.40	Zc
2022-06-09	09:18:07	38.76	Zc
2022-06-12	10:23:53	65.79	Zc
2022-06-17	03:42:28	6.23	Md
2022-06-18	05:38:47	0.03	BWC
2022-06-18	15:02:37	17.73	Zc
2022-06-19	11:03:42	15.08	Zc
2022-06-21	09:24:33	45.56	Zc
2022-06-21	14:50:09	15.46	Md
2022-06-21	18:15:15	57.51	Zc
2022-06-22	10:25:11	11.35	Zc
2022-06-24	12:01:42	41.17	Zc
2022-06-27	14:21:27	39.82	Zc
2022-06-27	15:46:01	22.81	Zc
2022-06-27	18:53:29	31.17	Zc
2022-07-04	19:00:09	60.57	Zc
2022-07-19	14:13:28	41.84	Zc
2022-07-24	18:38:47	52.76	Zc
2022-07-27	13:27:51	47.88	Zc
2022-07-28	12:51:09	40.24	Zc
2022-07-31	18:02:54	48.58	Zc
2022-08-01	09:26:13	33.42	Zc
2022-08-07	14:56:53	37.15	Zc
2022-08-11	02:05:07	5.16	Zc
2022-08-11	13:24:28	40.81	Zc

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]	Species
2022-08-29	09:43:20	0.70	Zc
2022-08-29	13:31:18	15.37	Zc
2022-09-06	16:08:15	53.10	Zc
2022-09-13	15:40:43	23.69	Zc
2022-09-16	11:08:34	13.05	Md
2022-09-17	09:33:44	3.90	Zc
2022-09-30	09:14:39	13.62	Zc
2022-09-30	17:54:58	0.07	Zc
2022-09-30	18:50:52	26.76	Zc
2022-10-02	08:34:05	12.92	Zc
2022-10-05	14:23:33	11.23	Zc
2022-10-05	16:43:17	84.14	Zc
2022-10-09	17:55:41	37.49	Zc
2022-10-11	18:24:37	28.85	Zc
2022-10-12	16:33:17	10.65	Zc
2022-10-12	17:24:49	0.74	Zc
2022-10-17	08:29:11	0.17	Zc
2022-10-18	11:46:51	52.59	Zc
2022-10-18	15:11:12	82.97	Zc
2022-10-23	10:23:10	49.15	Zc
2022-10-24	16:36:20	12.06	Zc
2022-11-14	13:24:14	60.79	Zc
2022-11-14	14:56:15	20.30	Zc
2022-11-14	18:01:50	39.68	Zc
2022-11-17	16:44:48	28.83	Zc
2022-11-17	18:07:15	22.69	Zc
2022-11-17	19:07:07	16.18	Zc
2022-11-18	16:38:03	38.57	Zc
2022-11-18	18:53:44	33.93	Zc
2022-11-18	20:27:32	9.83	Zc
2022-11-21	16:54:11	25.62	Zc
2022-11-21	17:56:31	64.40	Zc

1

Table 7: Detected beaked whale event times for the single unit site.

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]	Species
2022-05-30	18:29:27	59.41	Zc
2022-06-01	09:15:01	19.02	Zc
2022-06-02	02:34:21	19.32	BWC
2022-06-16	19:38:24	16.60	Md
2022-06-20	12:26:02	33.22	Zc
2022-06-20	13:45:29	170.69	Zc
2022-06-27	10:00:15	40.25	Zc
2022-06-30	07:23:09	9.47	Zc
2022-07-04	13:46:35	31.47	Zc
2022-07-10	12:29:45	70.65	Zc
2022-07-10	14:36:22	43.40	Zc
2022-07-11	09:00:17	69.29	Zc
2022-07-11	11:40:41	68.90	Zc
2022-07-13	10:42:30	110.74	Zc
2022-07-13	13:02:33	119.32	Zc
2022-07-14	16:39:02	67.39	Zc
2022-07-17	16:41:21	26.50	Zc
2022-07-19	09:37:53	38.83	Zc
2022-07-21	15:02:31	21.92	Zc
2022-07-21	17:11:27	12.51	Zc
2022-07-22	15:20:20	2.00	Zc
2022-07-24	13:38:52	122.51	Zc
2022-07-28	07:53:57	15.85	Zc
2022-07-28	09:36:30	34.05	Zc
2022-07-31	14:19:53	34.38	Zc
2022-08-10	06:27:56	22.73	Md
2022-08-11	19:01:21	44.76	Zc
2022-08-12	09:42:35	33.46	Zc
2022-08-12	11:41:15	38.83	Zc
2022-08-12	13:48:22	85.90	Zc
2022-08-12	18:46:47	69.89	Zc
2022-08-14	12:42:32	316.96	Zc
2022-08-16	12:56:13	22.37	Zc
2022-08-23	15:14:08	84.29	Zc

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]	Species
2022-08-24	15:54:21	30.16	Zc
2022-08-25	09:02:18	0.80	Zc
2022-08-25	10:24:15	99.04	Zc
2022-09-01	22:07:01	2.04	BWC
2022-09-01	22:46:39	16.79	BWC
2022-09-06	11:43:52	99.06	Zc
2022-09-08	15:54:35	37.79	Zc
2022-09-08	19:15:09	26.27	Zc
2022-09-08	23:05:41	28.55	Unknown_BW
2022-09-09	09:09:46	73.23	Zc
2022-09-09	15:17:54	52.65	Zc
2022-09-09	17:32:38	39.16	Zc
2022-09-10	08:59:22	39.15	Zc
2022-09-10	10:12:48	35.66	Zc
2022-09-10	16:52:53	74.89	Zc
2022-09-11	10:34:40	45.34	Zc
2022-09-11	13:05:41	39.25	Zc
2022-09-12	03:05:55	24.60	Md
2022-09-12	11:16:25	32.22	Zc
2022-09-12	13:37:46	87.15	Zc
2022-09-16	01:37:01	14.17	Md
2022-09-17	09:33:43	3.91	Zc
2022-09-30	09:14:39	13.62	Zc
2022-09-30	18:50:52	26.76	Zc
2022-10-03	11:40:43	49.12	Zc
2022-10-03	16:14:00	52.70	Zc
2022-10-03	17:52:42	46.73	Zc
2022-10-04	08:59:20	46.45	Zc
2022-10-08	18:16:30	72.35	Zc
2022-10-10	09:26:16	109.17	Zc
2022-10-13	17:21:18	60.69	Zc
2022-10-17	11:48:00	83.53	Zc
2022-10-18	18:45:18	61.48	Zc
2022-10-28	11:45:59	112.59	Zc

1

Table 8: Detected beaked whale event times for Site S02 (additional data).

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]	Species
2022-12-11	09:16:44	10.80	Zc
2022-12-11	15:21:07	14.15	Zc
2022-12-15	12:21:53	36.57	Zc
2022-12-21	18:08:37	15.92	Zc
2023-01-16	10:26:04	41.83	Zc
2023-01-24	12:46:41	26.48	Zc
2023-01-24	15:18:56	33.38	Zc
2023-01-28	18:04:25	76.04	Zc
2023-01-30	18:06:01	38.58	Zc
2023-01-31	19:00:47	28.16	Zc
2023-02-07	13:22:24	56.52	Zc
2023-02-09	15:20:06	3.24	Zc
2023-02-09	17:40:22	52.45	Zc
2023-02-12	12:53:49	27.43	Zc
2023-02-12	16:08:21	47.85	Zc
2023-02-12	17:27:13	27.77	Zc
2023-02-22	14:54:05	27.89	Zc
2023-02-22	16:51:16	107.58	Zc
2023-02-24	16:06:21	42.61	Zc
2023-03-04	19:06:14	7.64	Zc
2023-03-12	17:46:38	29.80	Zc

Appendix C. Summary of MFAS Encounters

1

Table 9: Detected MFAS event times for the array site.

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]
2022-09-02	22:28:10	51.3
2022-09-03	02:07:19	137.6
2022-09-03	07:46:33	69.0
2022-09-04	21:34:50	51.7
2022-09-09	03:32:13	30.1
2022-10-20	00:30:44	68.1
2022-10-23	03:15:12	64.6
2022-11-09	01:30:44	427.4
2022-11-10	23:29:48	71.6
2022-11-11	01:45:33	78.2

Table 10: Detected MFAS event times for the single-unit site.

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration [min]
2022-06-10	01:41:59	12.9
2022-08-30	10:57:51	16.0
2022-09-03	02:14:49	28.3
2022-09-03	04:58:35	71.7
2022-09-03	07:25:20	8.5
2022-09-03	08:33:57	21.5
2022-09-04	21:34:58	52.2
2022-09-09	03:32:29	28.3
2022-10-20	00:48:05	78.3
2022-10-20	11:27:37	30.8
2022-10-22	06:19:37	25.0
2022-10-22	12:33:12	13.4
2022-10-23	02:24:02	115.1
2022-11-09	01:30:47	427.8
2022-11-10	23:29:55	71.6
2022-11-11	01:45:41	78.2