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Passive Acoustic Monitoring in the Mariana Islands: Density Estimation of Beaked Whales along the West Coast of Guam (Part 2)

Final Report

for the

U.S. Navy Marine Species Monitoring in the Mariana Islands Archipelago

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Prepared by:

Cornell University, EcoSound Bioacoustics, Inc., University of St Andrews, and HDR, Inc.

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6. AUTHOR(S)
Holger Klinck
Tina Yack
Irina Tolkova
Daniel P. Salisbury
Danielle Harris

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell University
EcoSound Bioacoustics, Inc.
University of St Andrews
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14. ABSTRACT
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 monitor beaked whales and mid-frequency active sonar (MFAS). Five units were arranged in an array with a 1-kilometer (km) baseline in the southern part of the survey area to determine a detection probability function through spatial capture-recapture (SCR) analysis, which is crucial for estimating density. An additional sixth unit was deployed about 15 km north of the array to investigate spatiotemporal variability in beaked whale encounters within the survey area. This deployment configuration is reversed from the 2022 survey (Klinck et al., 2024) to study spatial variability.
Acoustic data were collected from March 7, 2024, through September 4, 2024. The beaked whale analysis was performed using PAMGuard, while MFAS signals were detected in the data set using an algorithm developed by the Naval Information Warfare Center/Naval Undersea Warfare Center that runs within the Raven-X software.
A total of 192 beaked whale encounters were registered across the two sites (up from 132 in 2022). Goose-beaked whales comprised 115 encounters (down from 122 in 2022) and, as previously observed, occurred almost exclusively at night. Compared to 2022, there was a significant increase in Cross Seamount beaked whale (BWC) detections. A total of 70 encounters were registered across the two sites, with detections predominantly occurring during daylight hours, indicating niche partitioning with goose-beaked whales.
The density of goose-beaked whales was estimated by applying an SCR framework. Average densities ranged from 1.48 animals per 1,000 square kilometers (km2) (coefficient of variation [CV]: 8.99 percent) in August 2024 to 11.64 animals

per 1,000 km2 (CV: 7.01 percent) in March 2024. These numbers fall within the same range as those reported for the 2022 survey. The monthly estimates indicated higher densities in spring, decreasing over summer into fall. This pattern was also observed in 2022, suggesting some possible consistency between years, though more data are needed to establish a longer-term trend.

While a detection probability function was derived for BWC, densities could not be estimated due to a lack of auxiliary information (e.g., group size).

Sonar activity was low, with only two brief (3–4 hours) MFAS encounters observed. The direction-of-arrival analysis indicated that the signals came from due west of the deployment site. There were no beaked whale detections close in time to the MFAS events. However, it is important to note that detection ranges for both signal types differ greatly.

Overall, this study demonstrated that an array configuration with a 1 km baseline is effective for SCR beaked whale density estimation and should be maintained for similar tasks in future projects. Additionally, a hybrid setup combining arrays with single units could be used to enhance beaked whale monitoring and density estimation in the larger MITT, including the Northern Mariana Islands.

Lastly, minor adjustments to the analysis code during this effort resulted in updates to the deployment 1 results (Klinck et al., 2024). The revised beaked whale density estimates are presented in Appendix C of this report.

15. SUBJECT TERMS

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Abstract

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 monitor beaked whales and mid-frequency active sonar (MFAS). Five units were arranged in an array with a 1-kilometer (km) baseline in the southern part of the survey area to determine a detection probability function through spatial capture-recapture (SCR) analysis, which is crucial for estimating density. An additional sixth unit was deployed about 15 km north of the array to investigate spatiotemporal variability in beaked whale encounters within the survey area. This deployment configuration is reversed from the 2022 survey (Klinck *et al.*, 2024) to study spatial variability.

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The density of goose-beaked whales was estimated by applying an SCR framework. Average densities ranged from 1.48 animals per 1,000 square kilometers (km^2) (coefficient of variation [CV]: 8.99 percent) in August 2024 to 11.64 animals per 1,000 km^2 (CV: 7.01 percent) in March 2024. These numbers fall within the same range as those reported for the 2022 survey. The monthly estimates indicated higher densities in spring, decreasing over summer into fall. This pattern was also observed in 2022, suggesting some possible consistency between years, though more data are needed to establish a longer-term trend.

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List of Acronyms and Abbreviations

μPa	micropascal
BWC	Cross Seamount Beaked Whale
CV	coefficient of variation
dB	decibel
DoA	direction-of-arrival
DON	Department of the Navy
FM	frequency-modulated
GAM	Generalized Additive Model
GPS	global positioning system
Hz	Hertz
IPI	inter-pulse-interval
kHz	kilohertz
km	kilometer(s)
km^2	square kilometer(s)
LMR	Living Marine Resources Program
m	meter(s)
MFAS	mid-frequency active sonar
min	minute(s)
MITT	Mariana Islands Training and Testing
Navy	United States Navy
PAM	passive acoustic monitoring
ROCCA	Real-time Odontocete Call Classification Algorithm
ROV	remotely operated vehicle
SCR	spatial capture-recapture
sec	second(s)
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 carried out 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 estimated abundance and density of the detected beaked whales, and 3) the presence and approximate direction of arrivals of any sonar detections in the PAM data.

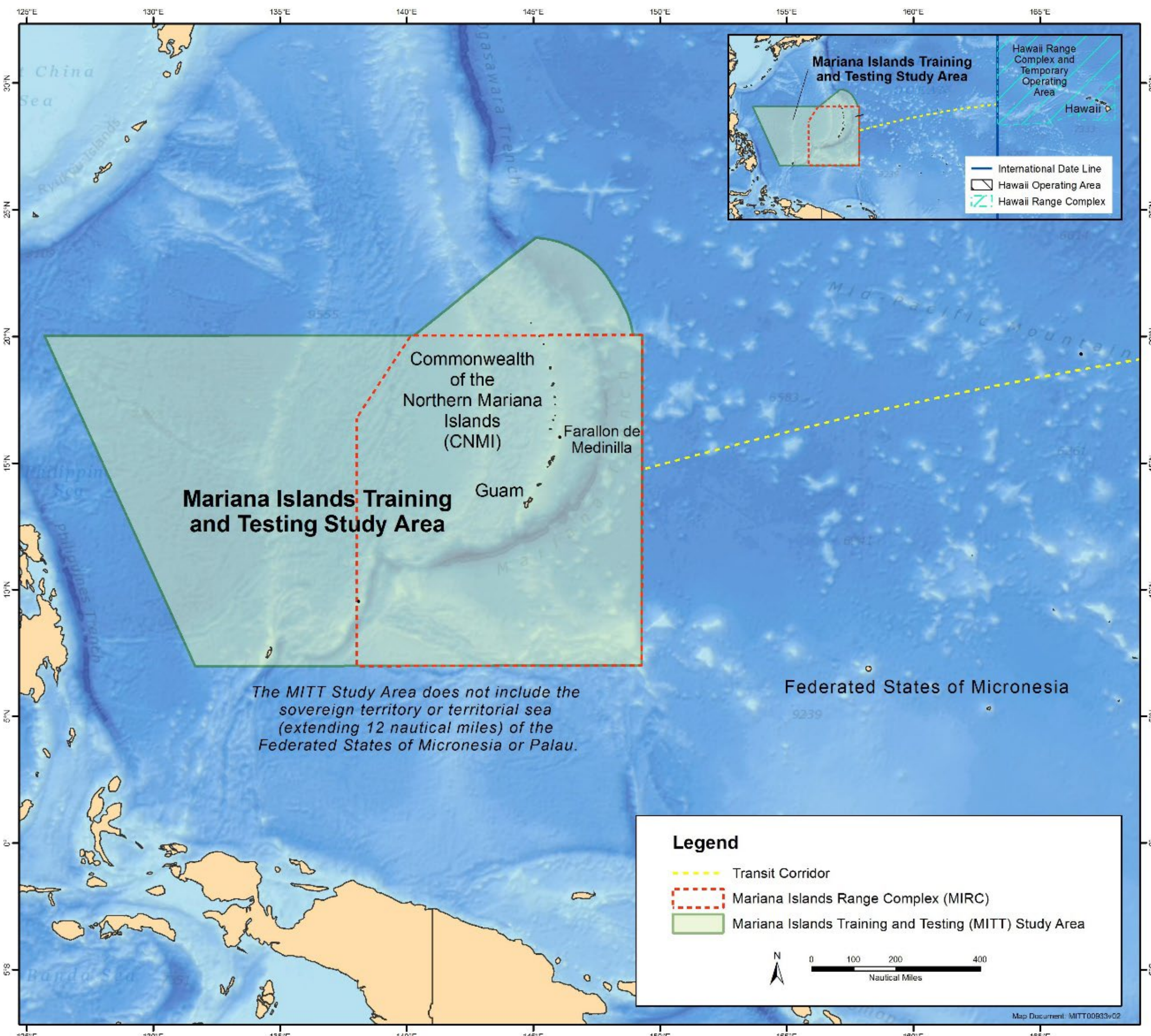


Figure 1: Mariana Islands Training and Testing Study Area (MITT). Source: DON 2020.

To achieve these objectives, an array of five bottom-mounted acoustic 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. A sixth unit was placed 15 kilometers (km) north of the array in this deployment.

Detection probability is a key parameter for animal density estimation (e.g., Buckland *et al.*, 2001) and can be estimated using methods such as distance sampling and spatial capture-recapture

(SCR) (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 assist with 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).

Additionally, PAM data were analyzed for occurrences of mid-frequency active sonar (MFAS), and when possible, the direction of the vessels emitting the MFAS signals was acoustically identified.

2. Data Collection

2.1. Array Configuration Modeling

In the initial phases of the project, John Spiesberger of Scientific Innovations, Inc., modeled and assessed suitable array configurations for locating 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 by acoustic pingers attached to each hydrophone mooring, which emitted 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 determine the source location accurately. 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, United States (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

Acoustic data were collected with Rockhopper marine recording units (**Figure 2**) developed by Cornell University, Ithaca, New York (Klinck *et al.*, 2020). A single person can easily deploy the Rockhopper units from a small vessel, including those previously used by Hill *et al.* (2020) for marine mammal research in the Marianas region. No mechanical aids (e.g., winches or A-frames) are required for deployment or recovery. The lithium battery-powered units can be deployed to 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**). Additionally, each mooring was equipped with an acoustic pinger (model EMT-01-3, Sonotronics, Inc., Tucson, Arizona) for relative synchronization of 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 decibels (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 gathers approximately 6 terabytes (TB) of data, which is stored internally on two 4 TB SSD drives. After recovery, the units were shipped to Ithaca, New York, where the data was extracted and managed in accordance with the negotiated controlled unclassified information data handling protocol. The system sensitivity and noise floor of the units are described in Klinck *et al.* (2020).

Figure 2: The Rockhopper marine recording unit developed by the K. Lisa Yang Center for Conservation Bioacoustics at 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 period was from March 7, 2024, through September 4, 2024. The deployment and recovery operations were executed using the motor vessel *Liquid Soul* (Rockstar Charters, Inc., Hagåtña, Guam, U.S.). The maximum deployment depth of the array unit was limited to 1,000 m due to the maximum operational depth of the synchronization pingers. While a deployment depth of at least 1,000 m is recommended to monitor especially goose-beaked whales (*Ziphius cavirostris*), 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.

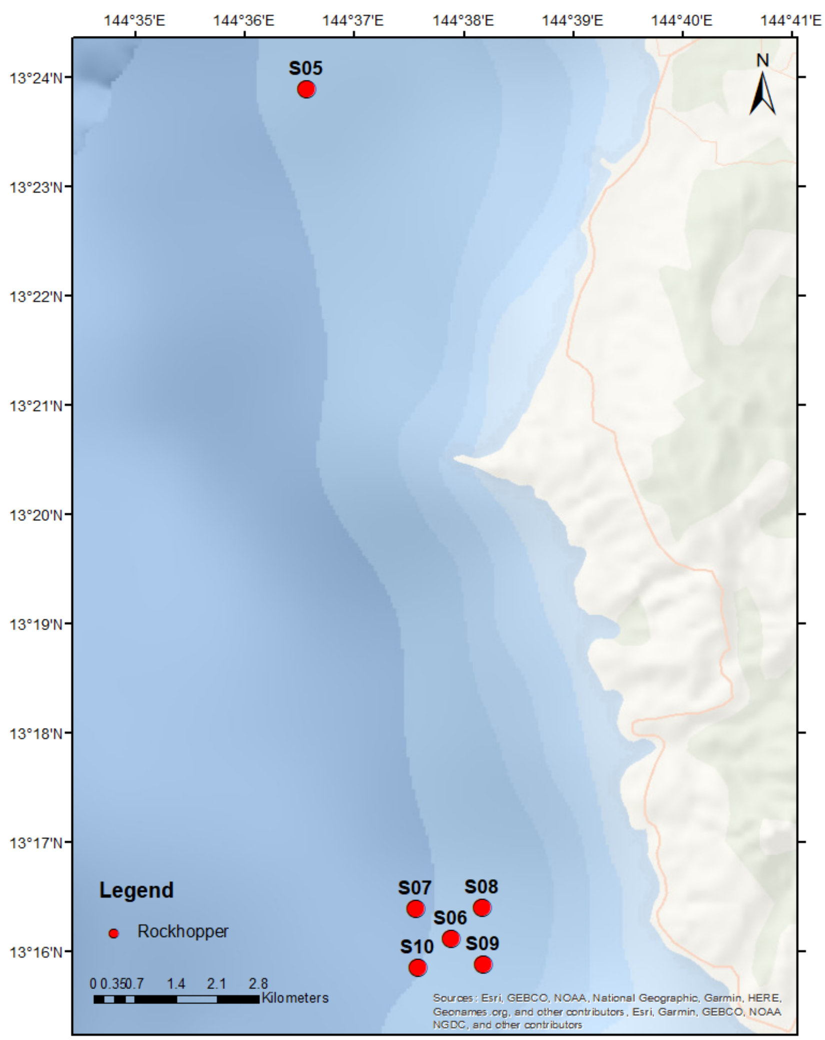


Figure 3: Final deployment configuration. The 1,000 m isobath runs through S10.

In addition, the array was not configured to track individuals or groups of beaked whales but rather to collect data suitable for estimating beaked whale density. Before the fieldwork commenced, a deployment permit was obtained from the Guam Coastal Management Program.

After the units were deployed, the sensor locations were surveyed using the procedure outlined in Russel *et al.* (2019) to accurately determine the final deployment locations and depth (**Table 2**). In short, the acoustic release is repeatedly pinged from the surface with a GPS-enabled deck box, and the 3D position of each mooring is algorithmically derived using the recorded travel times.

Table 2: Rockhopper deployment locations

Site	Lat [N]	Lon [E]	Depth [m]
RH05 (single unit)	13.39832	144.60944	-849.3
RH06 (array, center unit)	13.26943	144.63141	-923.2
RH07 (array, NW corner)	13.27277	144.62607	-1,091.5
RH08 (array, NE corner)	13.27330	144.63612	-753.0
RH09 (array, SE corner)	13.26452	144.63652	-766.9
RH10 (array, SW corner)*	13.2640	144.6260	-1,035.0

*RH10 could not be ranged, and hence the exact deployment location and depth could not be determined because of an acoustic release malfunction; the presented location is the drop location, and the depth was derived from ROV data.

2.4. Issues Encountered

Two Rockhopper units, RH05 and RH10, failed to release from their anchors during the initial recovery attempt in early September 2024. A subsequent attempt using a remotely operated vehicle (ROV) successfully recovered both units on November 25, 2024 (**Figure 4**). The recovery was conducted using ROV *Jason*, operated by Woods Hole Oceanographic Institution during the National Science Foundation-funded cruise TN438 on the University of Washington's R/V *Thomas G. Thompson*. We want to thank everyone involved in this recovery, and especially the Principal Investigators of the project, Robert Stern and Ignacio Pujana, from the University of Texas at Dallas, for providing the shiptime. After the units were returned to Ithaca, New York, and the data was screened by the U.S. Navy (Navy), it was discovered that RH05 stopped recording prematurely on July 28, 2024, while RH10 continued recording data until September 12, 2024, when the unit ran out of battery.

Figure 4: Picture taken during the ROV *Jason* recovery of a lost Rockhopper off Guam.

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 (*Mesoplodon densirostris*), Indo-Pacific beaked whale (*Indopacetus pacificus*), Deraniyagala's beaked whale (*Mesoplodon hotaula*), Ginkgo-toothed beaked whale (*Mesoplodon ginkgodens*; BW43 call type), and the Cross Seamount beaked whale ('BWC') call type (species unknown). This post-processing results in 'binary files' (a proprietary PAMGuard file type) and a populated SQLite database, which is used to further analyze the data 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: 182–585 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 sec and dense-beaked = 0.28 sec)
- Presence of an upsweep on the Wigner-Ville transform (e.g., see **Figure 5**, right panel)

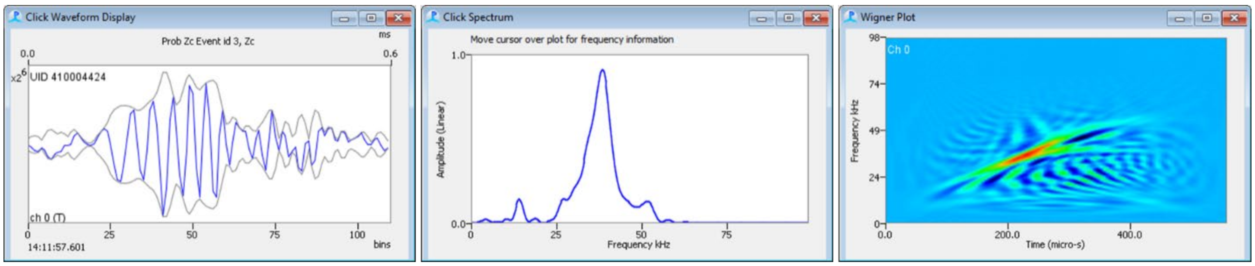


Figure 5: Graphical examples of important beaked whale echolocation click features.

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) provides a more detailed representation of time and frequency compared to a traditional spectrogram. It also 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 6**). Median values instead of means and percentiles instead of standard deviations were used because beaked whale click data typically exhibit 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). Additionally, occurrence patterns for each species and location were generated using a custom R script.

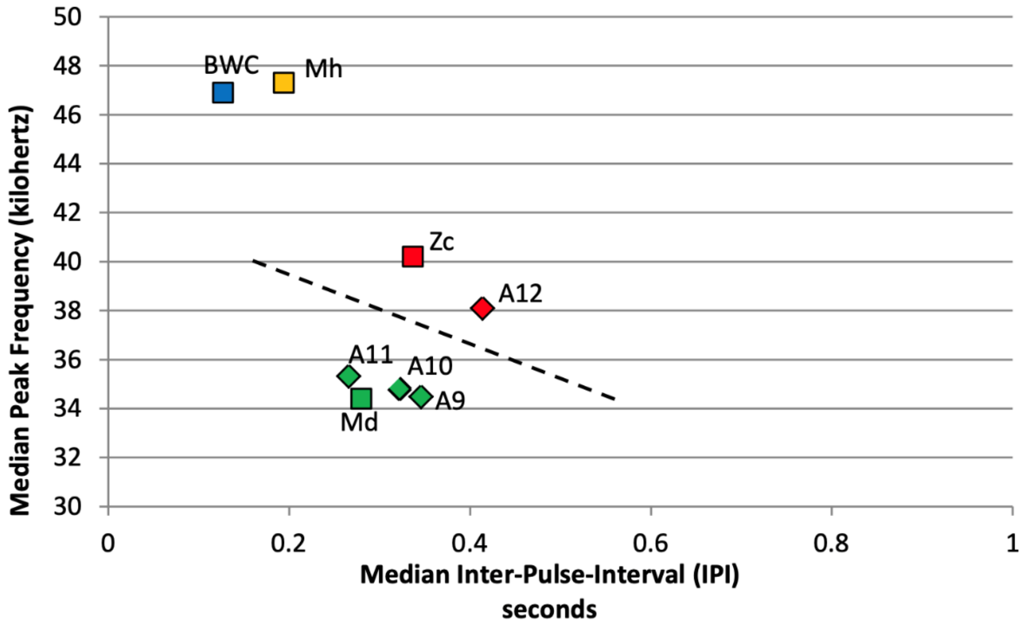


Figure 6: Beaked whale echolocation click median peak frequency vs. IPI for species identification.

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 whale (Zc), dense-beaked whale (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 SCR work described in **Section 3.2**. A regression analysis was employed to examine the spatial and temporal patterns of encounters at the two survey locations. A Generalized 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 among variables was performed using hypothesis tests (specifically F-tests) and associated p-values (at a significance 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 4.5.1 (R Core Team, 2025). The GAM was fitted using the mgcv package (version 1.9.3, Wood, 2017).

3.2. Beaked Whale Detection Function and Density Estimation

To estimate absolute animal abundance or density, a key required parameter is the probability of detection. This parameter accounts for missed detections during a survey, i.e., false negatives. Detection probabilities can be estimated by fitting a statistical model to survey data, often known as a "detection function". The primary method for estimating beaked whale detection functions in this analysis was acoustic SCR, as described by Stevenson *et al.* (2015). This method requires a record (known as a 'capture history') of which hydrophones the same beaked whale clicks were detected on. Initially, detections across all the instruments in the array were binned into 10-sec segments and used to create capture histories. Distance sampling was attempted in the previous deployment as an alternative method to estimate detection probabilities, but the results were likely biased due to several reasons (summarized in Klinck *et al.*, 2024). Therefore, only SCR was used in this analysis.

A detection function was fitted for each species, where sample size allowed. Further, if additional auxiliary information was available to parameterize Eqn. 1 for a given species, then beaked whale density was estimated around the array. Detection functions were fitted using the "ascr" R package vs. 2.2.4 (Stevenson, 2022). Due to near-continuous data collection by all instruments in the array, all array data were analyzed between March 7 and September 4, 2024. Using a buffer of 10 km and assuming homogenous density across space, a half-normal and a hazard rate detection function were fitted to the capture history data. Model selection was performed using Akaike's Information Criterion.

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

$\widehat{D}$ 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 sampling 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).

Density estimates were calculated for goose-beaked whales only, given the larger sample size and the availability of auxiliary information required for density estimation. While $\hat{c}$ and $\hat{v}$ could be estimated from the collected data, information about $\hat{s}$ was taken from the literature. The group size of goose-beaked whales was assumed to be 2.45 animals (coefficient of variation [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:

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

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 $\widehat{\lambda'}$ 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 and that they click constantly during their foraging dives.

3.3. MFAS Detection Analysis

The Navy sonar analysis was performed with a highly efficient detector developed by the Naval Information Warfare Center and the Naval Undersea Warfare Center 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 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 7**). An experienced analyst reviewed and verified the detections visually and aurally.

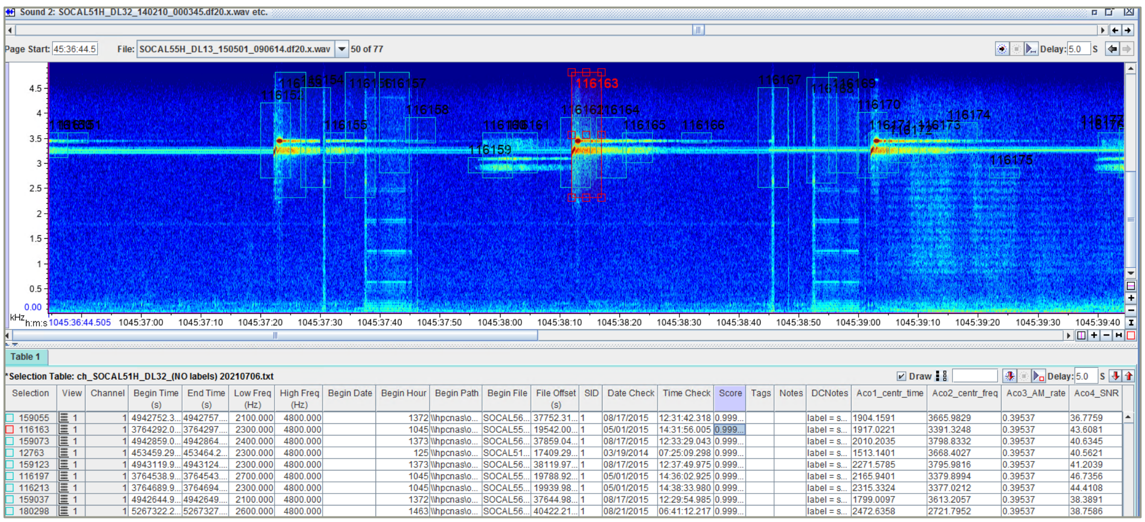


Figure 7: Screenshot of U.S. Navy mid-frequency active sonar detections (from a different dataset) generated with Raven-X and displayed in Raven Pro.

3.4. MFAS Direction-of-Arrival Estimation

Verified detector outputs and the associated raw acoustic data were used for the sonar direction of arrival analysis described in the following section. For each of the two sonar events detected on the array, associated audio recordings were synchronized using the signals from the co-deployed pingers (see **Section 2.2**). This process involved downshifting audio by 33 kHz and stacking it into five-channel files to simplify analysis of high-frequency synchronization pings. For one hour in every two-week interval, all visible emitted pings and arrival times were manually logged. These times were used to determine precise empirical travel times between pairs of units, estimated sound speed, and relative drift throughout the deployment. A piecewise-linear correction was used to adjust all timestamps relative to the center unit, and cross-validation across measurements was used to confirm that this procedure would yield relative time alignment within 1 second across units. This precision was sufficient for spatial-capture recapture analysis, which considered beaked whale clicks within 10-sec windows. Low-frequency content was also stacked into five-channel files for sonar work, with a quieter section selected to identify clear sonar segments. As the sonar analysis required high temporal precision, multichannel sonar files were individually synchronized by manually logging emitted and received pings. A template MFAS ping was cross-correlated with the rest to detect peaks, aiming for 8–10 segments per hourly file. The results were then plotted for visual verification. After correcting for drift, sonar time-difference-of-arrival (TDoA) values were obtained, and direction-of-arrival (DoA) estimation was performed, selecting the segment with the highest likelihood for visualization. This process is repeated for all hours, with sonar detections over the two days.

4. Results

4.1. Beaked Whale Occurrence Patterns

Beaked whale occurrences are initially reported on an encounter basis (though the regression modeling 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 8**).

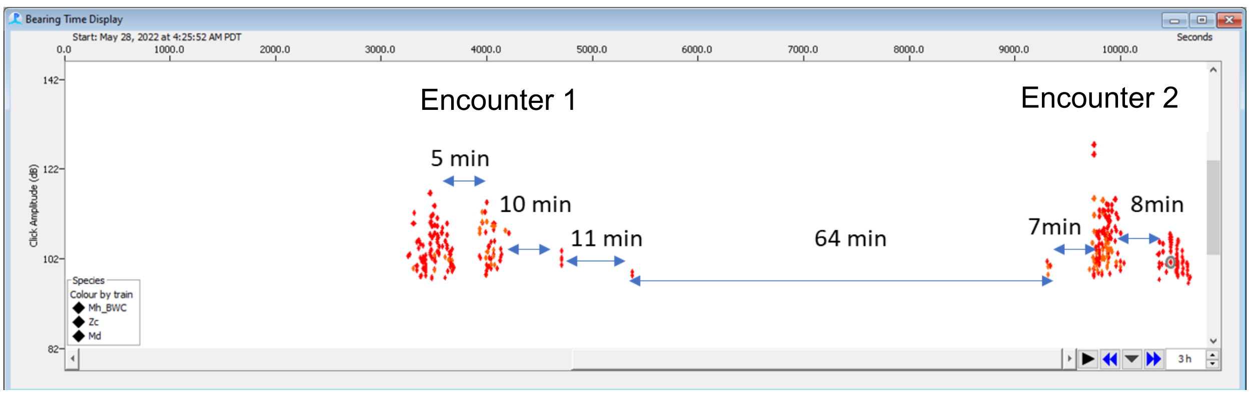
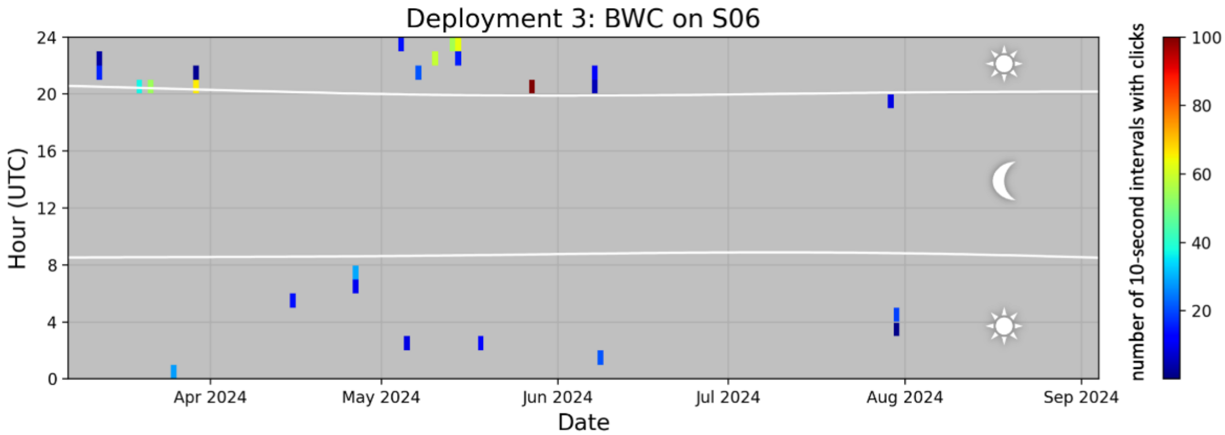
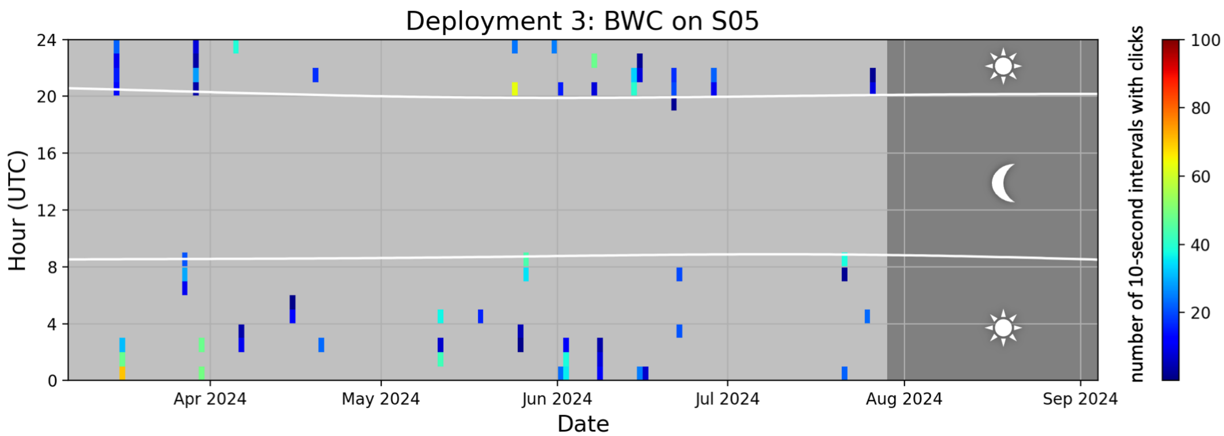
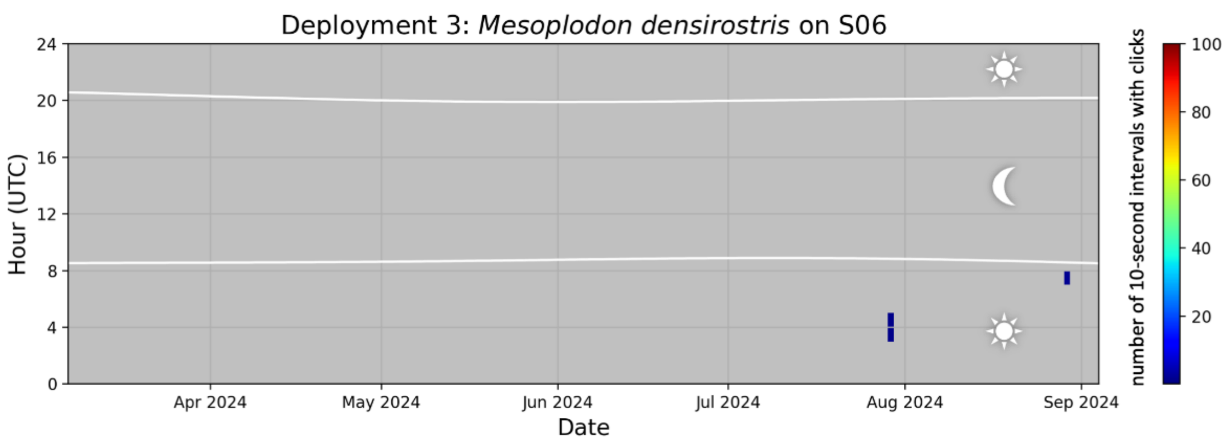


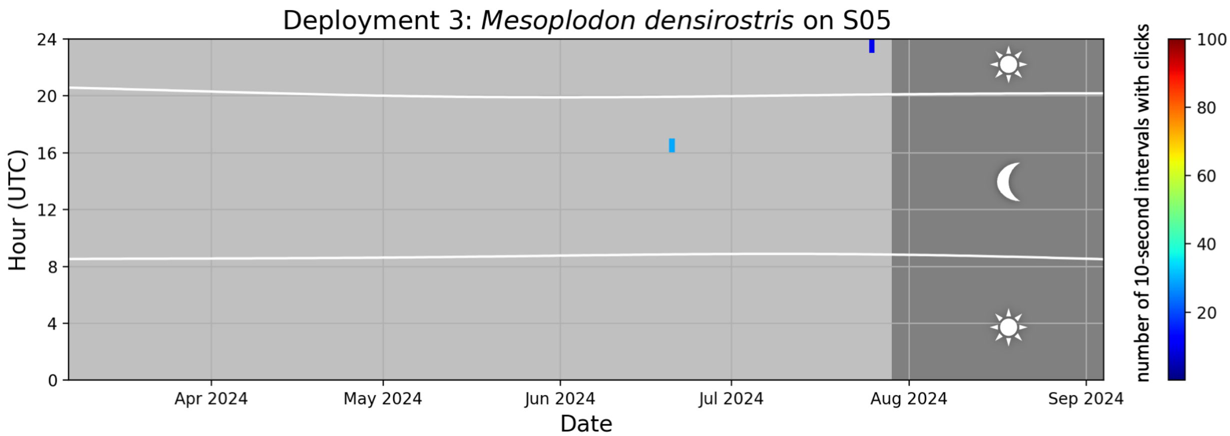
Figure 8: Two goose-beaked whale encounters displayed in PAMGuard.

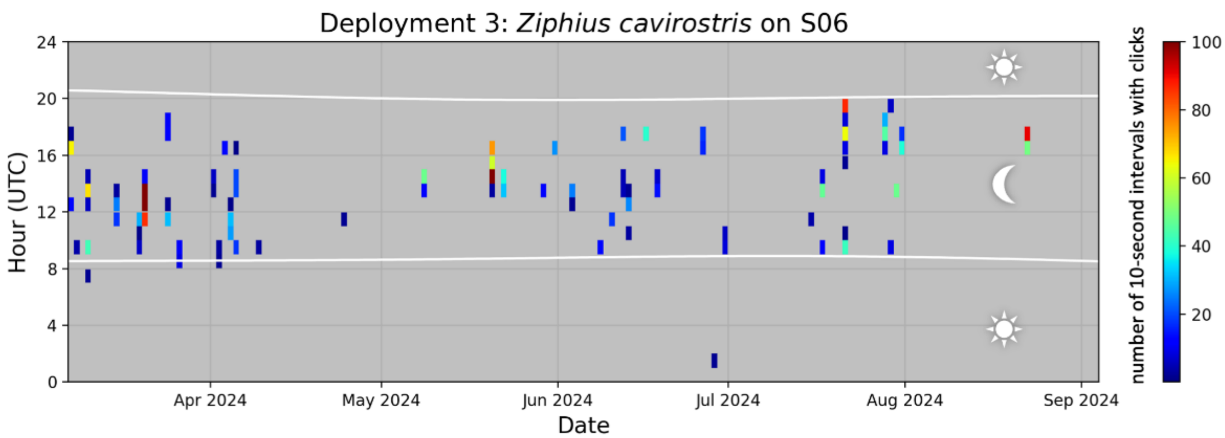
At the single-unit site (S05), a total of 113 encounters (60 goose-beaked whales, 50 BWC, 2 dense-beaked whales, and one unidentified beaked whale, respectively) were registered. At the array site (S06, center unit), the number of encounters was significantly lower (n = 79) but also primarily driven by occurrences of goose-beaked whales (n = 55), followed by BWC (n = 20), dense-beaked whales (n = 2), and two encounters of unidentified beaked whales. Details are presented in **Figure 9** below and in **Appendix A**, **Table A-1** and **Table A-2**.

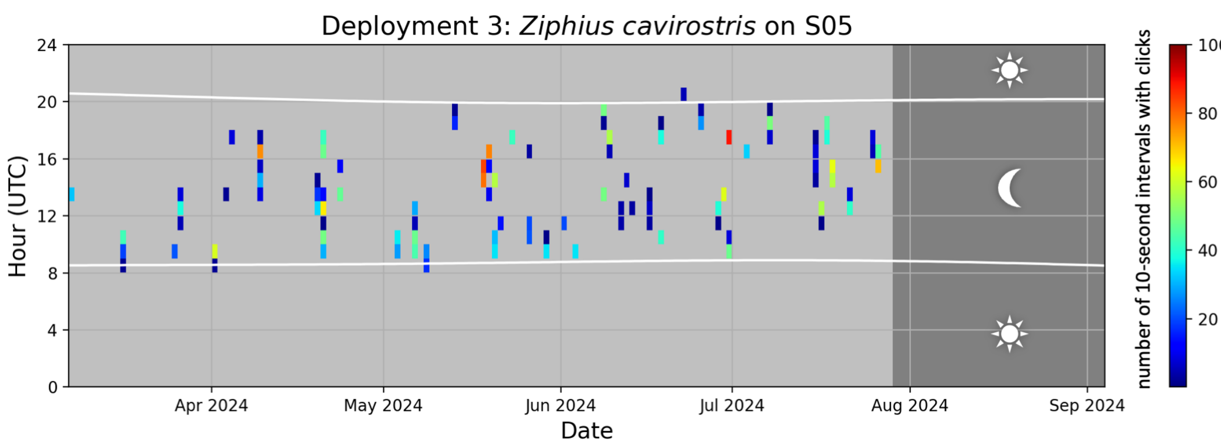

Deployment 3: BWC on S06
Hour (UTC)
Date
Apr 2024
May 2024
Jun 2024
Jul 2024
Aug 2024
Sep 2024
number of 10-second intervals with clicks


Deployment 3: BWC on S05
Hour (UTC)
Date
Apr 2024
May 2024
Jun 2024
Jul 2024
Aug 2024
Sep 2024
number of 10-second intervals with clicks


Deployment 3: *Mesoplodon densirostris* on S06
Hour (UTC)
Date
Apr 2024
May 2024
Jun 2024
Jul 2024
Aug 2024
Sep 2024
number of 10-second intervals with clicks


Deployment 3: *Mesoplodon densirostris* on S05
Hour (UTC)
0
4
8
12
16
20
24
Apr 2024
May 2024
Jun 2024
Jul 2024
Aug 2024
Sep 2024
Date
number of 10-second intervals with clicks
20
40
60
80
100


Deployment 3: *Ziphius cavirostris* on S06
Hour (UTC)
0
4
8
12
16
20
24
Apr 2024
May 2024
Jun 2024
Jul 2024
Aug 2024
Sep 2024
Date
number of 10-second intervals with clicks
20
40
60
80
100


Deployment 3: *Ziphius cavirostris* on S05
Hour (UTC)
0
4
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Jun 2024
Jul 2024
Aug 2024
Sep 2024
Date
number of 10-second intervals with clicks
20
40
60
80
100

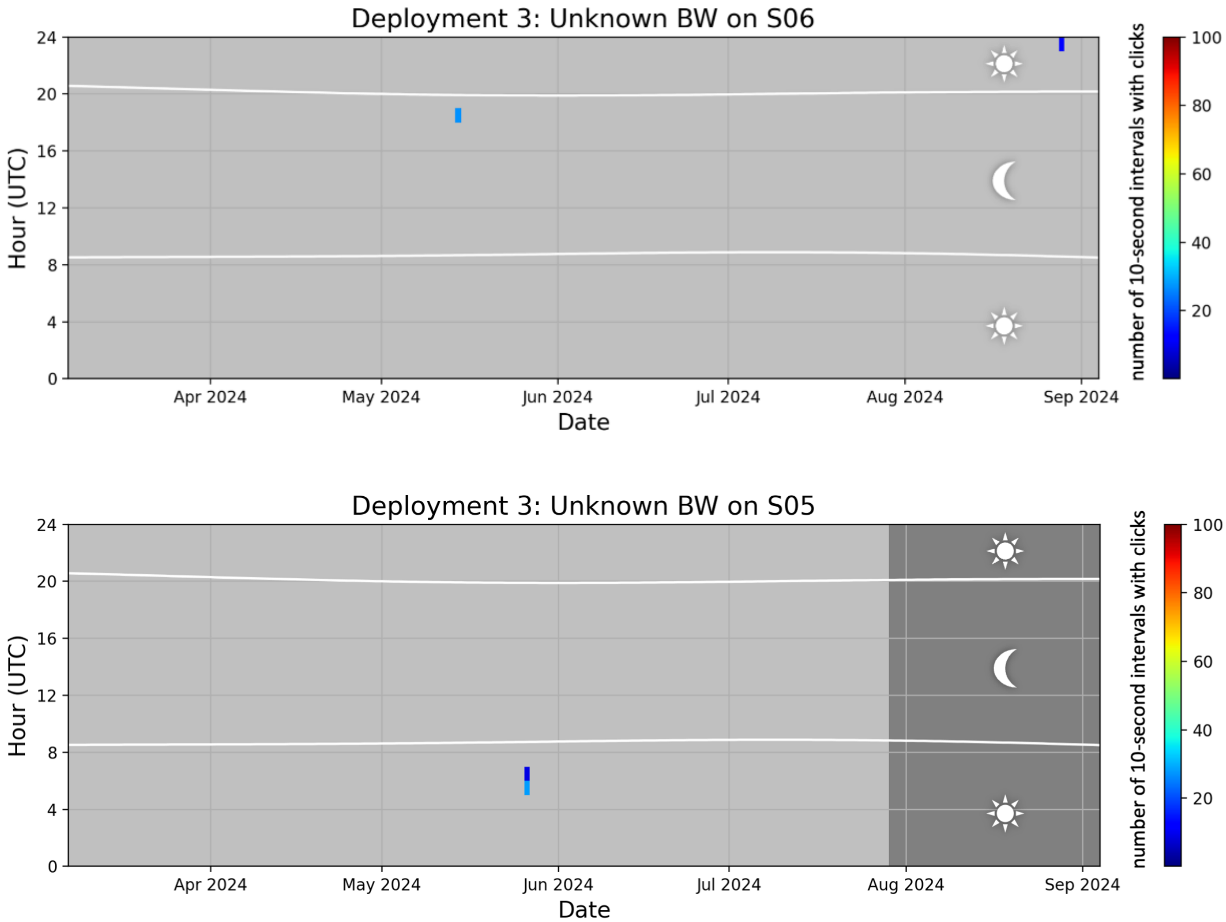

Figure 9: Beaked whale occurrence patterns for the array (S06) and the single unit (S05) by species. The dark gray area (S05 only) indicates a data gap.

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 were collected from March 7, 2024, through September 4, 2024, for S06 and from March 7, 2024, through July 28, 2024, for S05, with dark gray for non-recording periods.

Beaked whales were detected every month at both sites, except at the single site, which stopped recording on July 28, 2024. Similar to the 2022 analysis (Klinck *et al.*, 2024), 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, employed a negative binomial distribution to account for overdispersion. The day of the year was collinear with the month, so it 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. Furthermore, evidence of temporal correlation (up to a lag of four days) led to the fitting of an AR1 correlation structure to the GAM. Model selection resulted in species, unit, and month being retained as predictor variables (**Figure 10, Table 3**).

Table 3: Results from the final GAM.

Predictor variable	Effective degrees of freedom	F value	p-value
Unit	5	2.40	0.035
Species	3	92.40	<0.0001
Month	2.56	6.95	0.0001

Goose-beaked whales had the highest daily number of 10-sec time segments with detections (**Table 4**). Dense-beaked whales had the lowest number of segments per day compared to the other species (**Table 8**) compared to the other species (**Table 6**). Detections appeared to be higher at the start of the deployment (**Figure 10**). Three of the array instruments had significantly lower numbers of 10-sec time segments than the single instrument (**Figure 10**). The final model explained 24.1 percent 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, because the source level (and duty cycle) of the pinger is relatively low, the range over which these signals are audible to whales is considerably shorter than the detection range for beaked whale calls. Moreover, the observed number of encounters at the single-unit site (without a pinger) closely resembles those at the array site (60 vs. 55 encounters) for the most commonly encountered species (goose-beaked whale), suggesting that the pinger likely did not have a substantial effect on encounter-based measures of beaked whale presence. In comparison, during our previous survey (Klinck *et al.*, 2024), we reported a slightly higher number of encounters for goose-beaked whale for the array site compared to the single unit site (62 vs. 60 encounters).

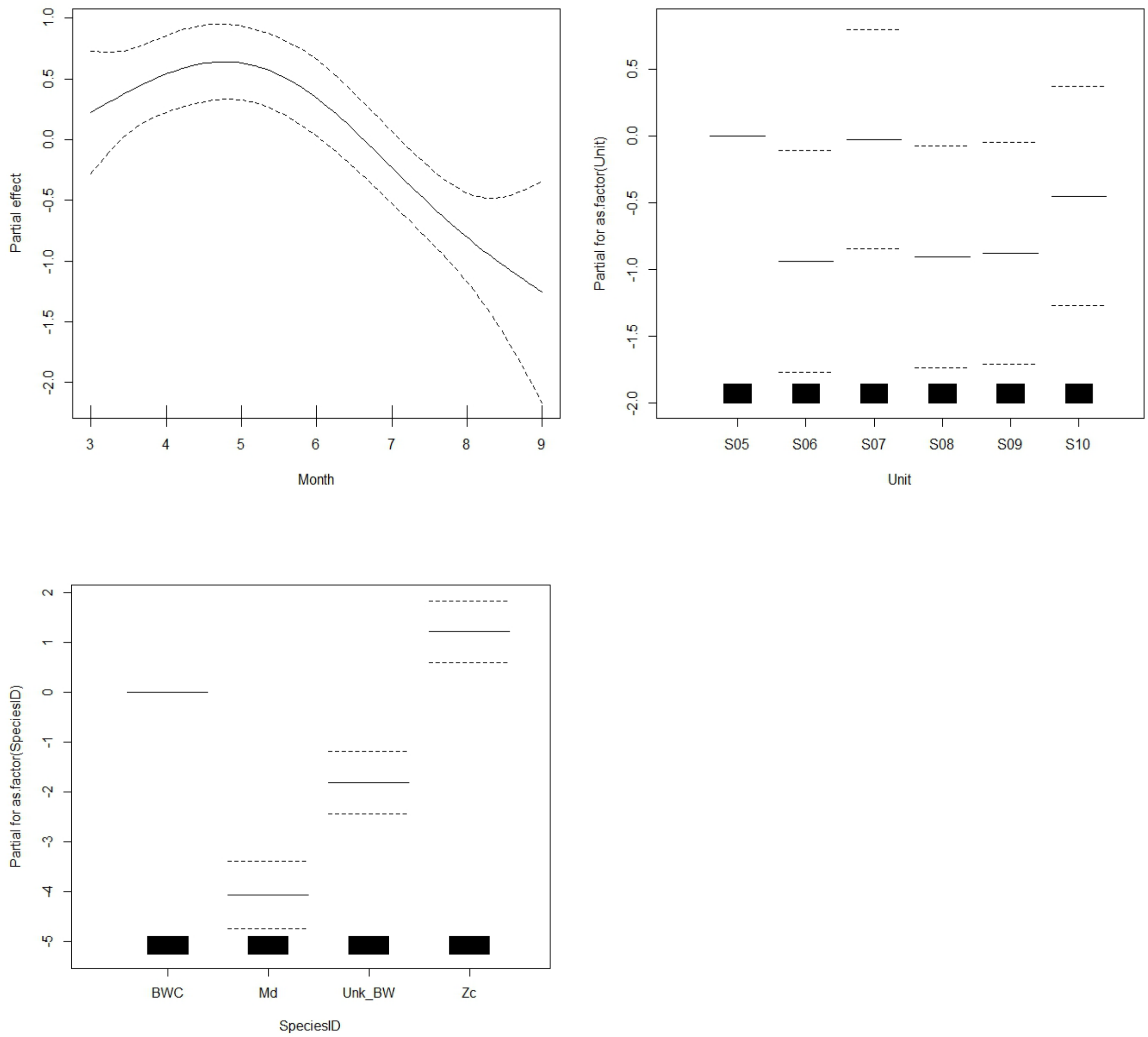

Figure 10: Results from the final GAM model showing relationships between the response variable and three predictor variables.

4.2. Beaked Whale Detection Function and Density Estimation

4.2.1 Goose-beaked Whales

A total of 5,797 unique 10-sec segments contained goose-beaked whale detections across the array (units S06–S10) during the entire deployment. The frequency of 10-sec segments detected on 1, 2, 3, 4, or 5 recording units 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 recording units within the array during the deployment.

Number of instruments	1	2	3	4	5
Number of unique 10-sec segments	3,343	1,397	700	269	88

Table 5: Number of unique 10-sec segments with goose-beaked whale detections in each month across the array (recording units S06–S10) during the deployment, with associated density estimation results.

Session	1	2	3	4	5	6	7
Dates	7–31 March	1–30 April	1–31 May	1–30 June	1–31 July	1–31 August	1–4 September
Number of unique 10-sec segments with detections	1,539	715	1,067	932	1,282	262	0
Total number of 10-sec segments with monitoring effort	181,080	259,200	216,000	224,640	250,560	241,920	25,920
Effective sampling area (km^2)	8.95	8.95	8.95	8.95	8.95	8.95	8.95
Density (animals per 1,000 km^2)	**11.64**	**3.78**	**6.76**	**5.68**	**7.00**	**1.48**	**N/A**
Density 95% CI (animals per 1,000 km^2)	10.14-13.34	3.26-4.38	5.87-7.79	4.92-6.55	6.10-8.05	1.24-1.77	N/A
CV Density (%)	7.01	7.52	7.21	7.30	7.10	8.99	N/A

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 1.40 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 possible convergence issues (**Figure 11**). The associated probability of a beaked whale group being detected at a horizontal distance of zero from an instrument in the array, known as *g(0),* was estimated to be 1 (CV: 1.13 x 10^{-3}), i.e., detection was certain. The resulting effective sampling area $\hat{v}$ was estimated to be 8.95 square kilometers (km^2, CV: 2.21 percent). From auxiliary data, the probability of a beaked whale group clicking in a 10-sec segment was estimated to be 0.20 (CV: 3.57 percent). Average densities per session ranged from 1.48 animals per 1,000 km^2 (CV: 8.99 percent) in August 2024 to 11.64 animals per 1,000 km^2 (CV: 7.01 percent) in March 2024.

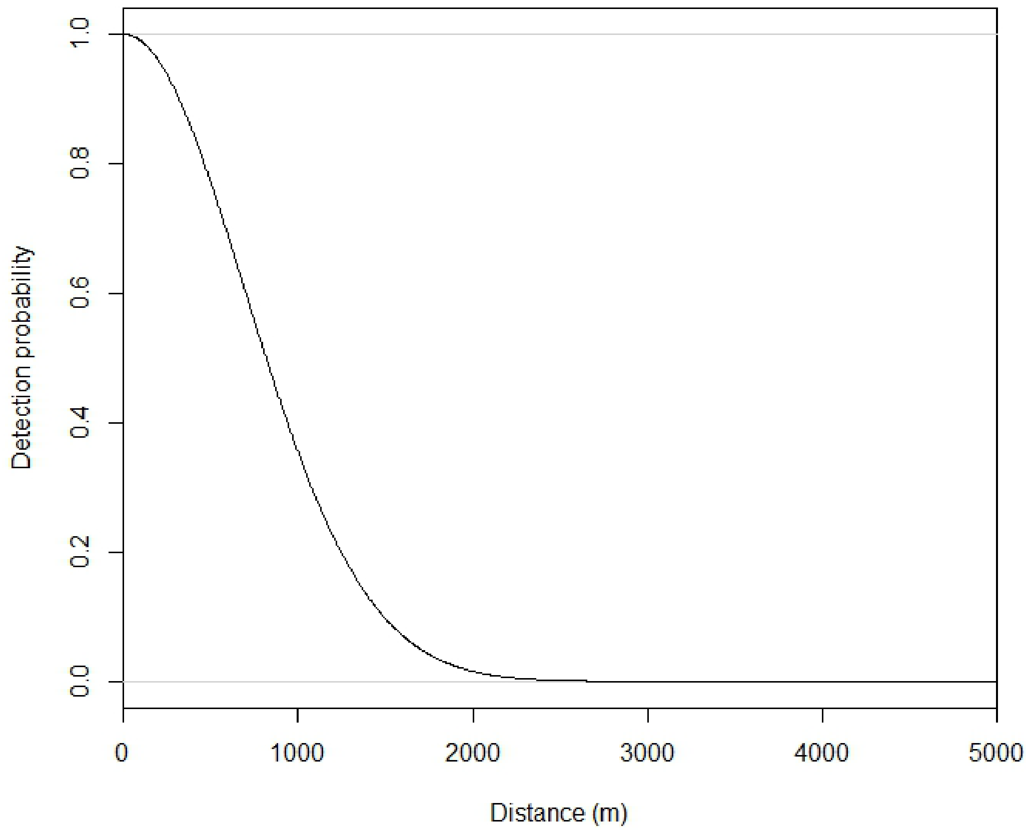

Figure 11: Estimated detection function for a single sensor from the SCR analysis for goose-beaked whales. A half-normal model was selected as the preferred model.

4.2.2 Cross Seamount Beaked Whales (BWC)

A total of 2,182 unique 10-sec segments contained BWC detections across the array. The frequencies of 10-sec segments detected on 1, 2, 3, 4, or 5 instruments within the array are given in **Table A-1**. The number of detections in each month is given in **Table 7**. The total number of segments with monitoring effort for all species is the same as for goose-beaked whales (**Table 5**).

Table 6: Frequency of unique 10-sec segments with BWC detections detected on 1, 2, 3, 4, or 5 recording units within the array during the whole deployment.

Number of instruments	1	2	3	4	5
Number of unique 10-sec segments	1,256	555	236	72	63

Table 7: Number of unique 10-sec segments with BWC detections in each month across the array during the whole deployment, with the estimated effective sampling area.

Session	1	2	3	4	5	6	7
Dates	7–31 March	1–30 April	1–31 May	1–30 June	1–31 July	1–31 August	1–4 September
Number of unique 10-sec segments	525	248	1153	180	76	0	0
Effective sampling area (km^2)	10.82	10.82	10.82	10.82	10.82	10.82	10.82

The sample size was adequate to fit a detection function. The preferred detection function was the half-normal detection function (the hazard rate function had convergence issues; **Figure 12**). The effective sampling area, $\hat{v}$, was estimated to be 10.82 km^2 (CV: 4.86 percent), and *g(0)* was estimated to be 0.94 (CV: 2.81 percent).

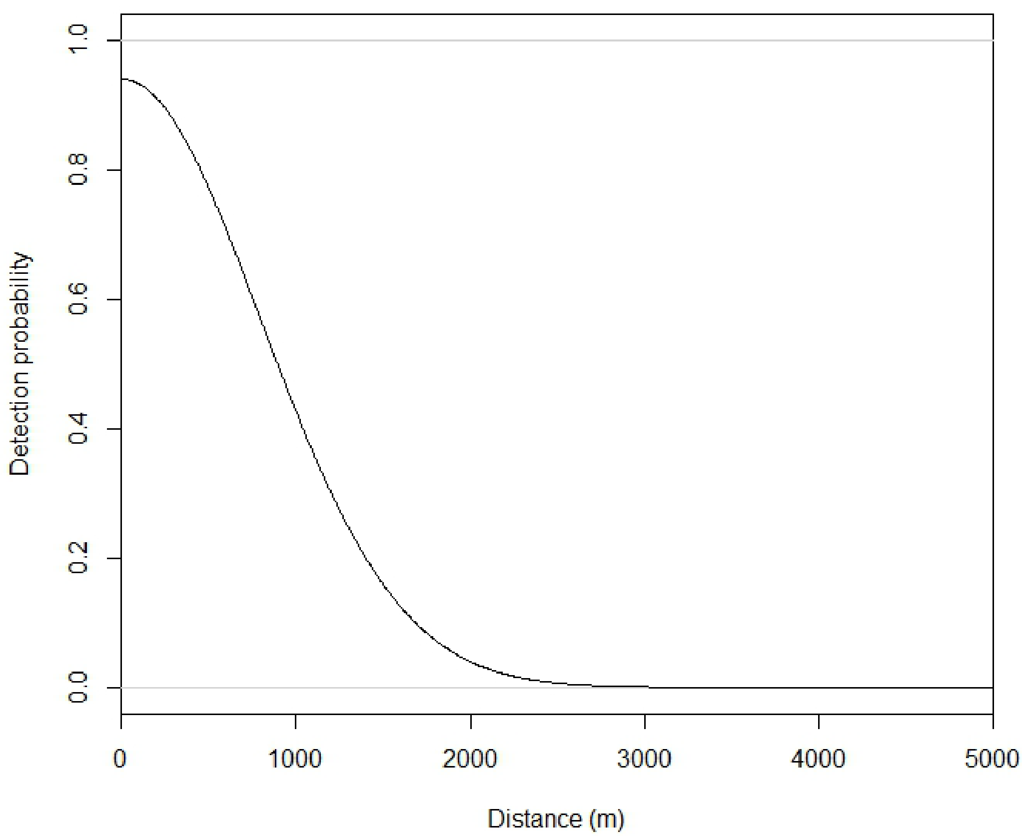

Figure 12: Estimated detection function for a single sensor from the SCR analysis for BWC detections. A half-normal model was selected as the preferred model.

4.2.3 Dense-beaked Whales and Unknown Beaked Whales

There were 36 and 457 unique 10-sec segments containing dense-beaked whales and unknown beaked whales, respectively (**Table 8**). These sample sizes were insufficient to fit the detection functions for either species category. The frequencies of 10-sec segments detected on 1, 2, 3, 4, or 5 instruments within the array for both species categories are given in **Table A-1**, and the number of detections in each month is given in **Table 9**.

Table 8: Frequency of unique 10-sec segments with dense-beaked whale (Md) and unknown beaked whale (Unk_BW) detections 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 - Md	34	2	0	0	0
Number of unique 10-sec segments – Unk_BW	213	141	103	0	0

Table 9: Number of unique 10-sec segments with dense-beaked whale (Md) and unknown beaked whale (Unk_BW) detections in each month across the array during the whole deployment.

Session	1	2	3	4	5	6	7
Dates	7–31 March	1–30 April	1–31 May	1–30 June	1–31 July	1–31 August	1–4 September
Number of unique 10-sec segments - Md	2	0	10	0	2	22	0
Number of unique 10-sec segments - Unk_BW	0	0	425	3	16	13	0

4.3. MFAS Occurrence Patterns

MFAS activity (two encounters total) was detected in the area in late August 2024 (see **Figure 13** and **Appendix B**). Note that at the time of the sonar encounters, the single unit (S05) had already stopped recording. Beaked whale detections did not occur during the periods when MFAS signals were detected. Beaked whales were detected throughout all hours, although, depending on the species, diel patterns were observed. Sonar detections, however, were limited to daytime hours. It is important to note that the detection ranges for these signals are significantly different. Beaked whales can generally be detected within a few km, while MFAS signals are typically detectable over many tens of km. Due to these vastly different spatial scales, no conclusions can be drawn about the potential impact of MFAS on beaked whales in the area.

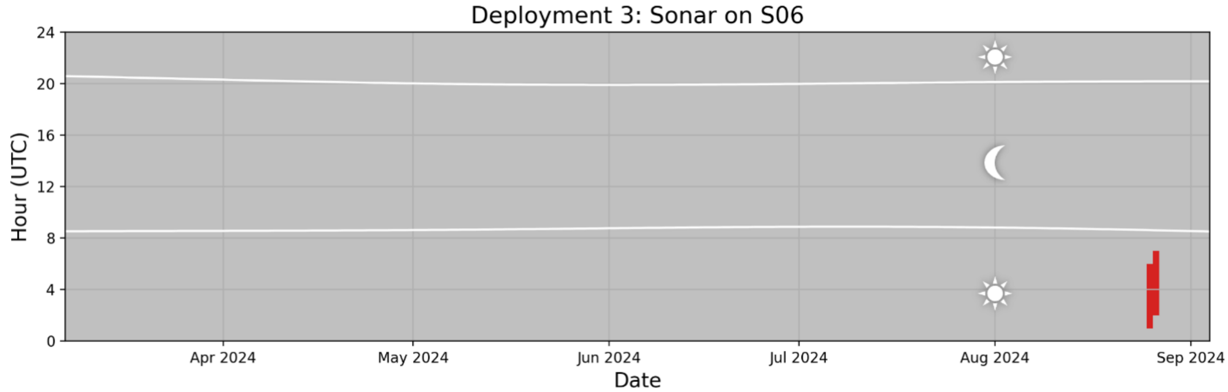

Figure 13: MFAS occurrences for the array site.

Notes: The x- and y-axes show the date and time of day, respectively, and the red grid cells indicate detected sonar. The acoustic data were collected from March 7, 2024, through September 4, 2024.

4.4. MFAS Direction-of-Arrival Estimations

Figure 14 displays polar plots of the DoA estimates for the two sonar events detected on the array on August 25 and 26, 2024. Each curve represents the highest-likelihood direction over an hour-long duration, with color indicating the time of day. Overall, the events predominantly originated west of the array.

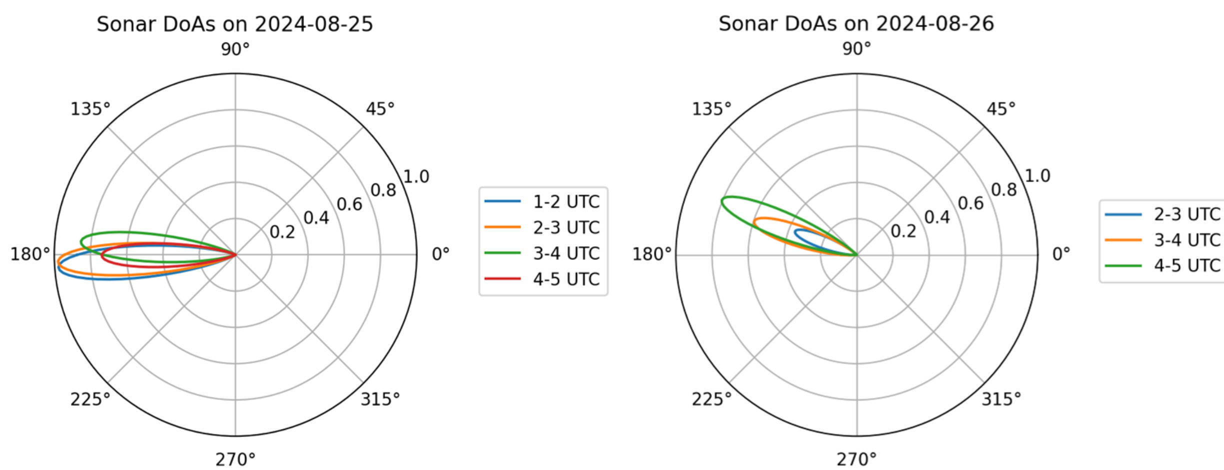

Figure 14: Direction-of-arrival estimates for the two sonar events detected on the array.

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

5. Discussion and Recommendations

Similar to the 2022 deployment, this deployment has yielded sufficient data to conduct a SCR analysis, estimating densities for goose-beaked whales. A detection function for the BWC beaked whale was also fitted, like the goose-beaked whale detection function, reaching a very low probability of detection beyond 2 km. The main difference between the two functions was that the probability of detecting a goose-beaked whale at zero distance from an instrument in the array was estimated to be 1, i.e., certain. However, the detection function for the Cross Seamount beaked whale estimated probability at zero distance to be lower (0.94), leading to a larger effective sampling area. Although the differences between the fitted detection functions are relatively small in this case, this does highlight the benefit of estimating species-specific detection functions. Density estimates for the BWC beaked whale were not estimated due to uncertainty about (1) which species this signal type represents and, therefore, (2) the lack of suitable auxiliary data for Eqn. 1 (e.g., group size). The number of detections was too low to fit detection functions for the dense-beaked whales and the unknown beaked whale category. Combining data from Deployment 1 would not have provided sufficient sample sizes to fit detection functions to these data. However, an extension of this analysis would be to try pooling data from multiple species into a single detection function model, using species category as a covariate. The model might provide a detection function for the dense-beaked whale, and auxiliary data from the literature could be used to estimate its density.

The 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, which investigated patterns in daily levels of beaked whale detections, measured as the number of 10-sec time segments with detections in a given day. The goose-beaked whale was the species with the highest daily levels of detection, with dense-beaked whales having the lowest detection levels (**Figure 10**). The single-unit site (S05) had a higher daily level of detection activity than all the array sites, though the detection levels were similar to some of the array instruments (**Figure 10**). Similar to the 2022 deployment, goose-beaked whale detections (at both sites) again occurred almost exclusively at night. Additionally, BWC detections occurred almost exclusively during the day, indicating niche partitioning between the two species. We hypothesize that the strong diel pattern we observed in these species is related to diel movement patterns that are potentially driven by prey availability 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 in daily detection levels relative to the predictor variables (e.g., month and site).

The densities of goose-beaked whales estimated through SCR analysis showed monthly variation and were similar to both (1) the estimates from the 2022 deployment (Klinck *et al.*, 2024, **Appendix C** for updated results) and (2) estimates by Badger et al. (2024). The monthly estimates indicated higher densities in spring, decreasing over summer into fall. This pattern was also observed in 2022, suggesting some consistency across years, though more data are needed to establish a longer-term trend. However, key assumptions and data analysis steps must be considered when interpreting these density estimates. First, consistent with the 2022 analysis, detections of beaked whales in 10-sec segments were matched across the array using PAMGuard detection times (synchronized when necessary), assuming that detections in the same 10-sec bin represented the same group of animals. Using data from the localization workflow in the 2022 analysis could improve the accuracy of matching detections across instruments, but this would require significant additional analysis and may only benefit some detections. Additionally, including TDoA and signal-strength data was considered to enhance the precision of detection function results (Stevenson *et al.*, 2015). However, applying TDoA and signal strength data to 10-sec snapshots with multiple clicks is complex and has not yet been implemented.

Second, auxiliary information on group size and probability of producing clicks within a 10-sec time segment was taken from the literature (Badger *et al.,* 2024; Baird, 2019; Barlow *et al.,* 2020, 2021; Yano *et al*., 2022). Although the studies used were goose-beaked whale studies from the Pacific, they were not all located near Guam, so it is possible that the assumed parameters are not appropriate for animals near Guam and could bias the results. The results should be updated with more regionally specific data, should such data become available. Further, two key assumptions relating to the auxiliary data were that (1) goose-beaked whale groups dived and clicked synchronously, and (2) once foraging, goose-beaked whales clicked almost continuously (in this study, every 10 sec or less, to match the snapshot length). Assuming animals click synchronously will underestimate a group's availability, and assuming that animals click almost constantly when foraging will overestimate a group's availability, if these assumptions are not met. Therefore, these assumptions have the potential to alter density estimates in either direction. Regarding the latter assumption, Barlow et al. (2021) provide additional methods for testing it. Such an investigation would be an important and natural next step in the analysis.

Finally, the 2022 and 2024 analyses have yielded similar detection function results for goose-beaked whales at two locations. For example, the effective sampling area (the estimation of which incorporates the detection probability) for goose-beaked whales in 2022 (when the whole array was operational) was 8.55 km^2, compared to 8.95 km^2 in the 2024 deployment. The 2024 analysis also showed differences in detection functions across species categories; the effective sampling area for BWC detections was larger (10.82 km2) than that for goose-beaked whales. Increasing the number of monitored sites would enable further exploration of any variability in detectability between species and/or sites. Initial survey design work has been completed to show a survey design south of Guam, though the parameters could be expanded/adjusted as required (Harris, 2024). A hybrid design could be implemented where an array is deployed at a subset of monitored sites, and single instruments are used at the other locations. Overall, the array configuration with a one km baseline worked well for the SCR density estimation task and would likely be maintained in future deployments.

6. Literature Cited

Badger, J., McCullough, J., Oleson, E., Barlow, J., Baird, R.W., and Sakai, T. (2024). Density and abundance of Cuvier's and Blainville's beaked whales in the Mariana Archipelago estimated using drifting acoustic recorders. Final Report to U.S. Navy Pacific Fleet, January 2024.

Baird, R.W. (2019). Behavior and ecology of not-so-social odontocetes: Cuvier's and Blainville's beaked whales. In B. Würsig (Eds.), *Ethology and Behavioral Ecology of Odontocetes* (pp. 305–329). Basel, CH: Springer Nature, doi: 10.1007/978-3-030-16663-2.

Barlow, J. (2016). Cetacean abundance in the California Current estimated from ship-based line-transect surveys in 1991-2014, in NOAA Southwest Fisheries Science Center Administrative Report LJ-16-01, Southwest Fisheries Science Center, La Jolla, CA.

Barlow J., Schorr G.S., Falcone E.A., and Moretti D. (2020). Variation in dive behavior of Cuvier's beaked whales with seafloor depth, time-of-day, and lunar illumination. *Marine Ecology Progress Series*, 644:199–214, doi: 10.3354/meps13350.

Barlow, J., Trickey, J.S., Schorr, G.S., Rankin, S., and Moore, J.E. (2021). Recommended snapshot length for acoustic point-transect surveys of intermittently available Cuvier's beaked whales. *The Journal of the Acoustical Society of America*, 149 (6):3830–3840, doi: 10.1121/10.0005108.

Baumann-Pickering, S., Roch, M.A., Brownell, R.L. Jr., Simonis, A.E., McDonald, M.A., Solsona-Berga, A., *et al.* (2014). Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific. *PLoS One*, 9:e86072, doi: 10.1371/journal.pone.0086072.

Baumann-Pickering, S., McDonald, M.A., Simonis, A.E., Solsona-Berga, A., Merkens, K.P.B., Oleson, E.M., Roch, M.A., *et al*. (2013). Species-specific beaked whale echolocation signals. *The Journal of the Acoustical Society of America*, 134:2293–2301.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L., and Thomas, L. (2001). Introduction to Distance Sampling. Oxford University Press, Oxford.

DON (Department of the Navy). 2020. Mariana Islands Training and Testing Activities Final Supplemental Environmental Impact Statement/Overseas Environmental Impact Statement. Naval Facilities Engineering Command, Pacific/EV21. Pearl Harbor, Hawaii. June 2020.

DON (Department of the Navy). 2014. Marine Mammal Marine Survey Report in Support of the Commonwealth of the Northern Mariana Islands Joint Military Training Environmental Impact Statement/Overseas Environmental Impact Statement. Pearl Harbor, HI: Naval Facilities Engineering Command, Pacific.

Dugan, P.J., Klinck, H., Zollweg, J.A., and Clark, C.W. (2015). Data Mining Sound Archives: A New Scalable Algorithm for Parallel-Distributing Processing. 2015 IEEE International Conference on Data Mining Workshop (ICDMW), 2015, pp. 768–772, doi: 10.1109/ICDMW.2015.235.

Gassmann, M., Wiggins, S.M., and Hildebrand, J. (2015). Three-dimensional tracking of Cuvier's beaked whales' echolocation sounds using nested hydrophone arrays. *The Journal of the Acoustical Society of America*, 138:2483–2494, doi: 10.1121/1.4927417.

Gillespie, D., Gordon, J., McHugh, R., McLaren, D., Mellinger, D.K., Redmond, P., Thode, A., Trindder, Pl., and Xiao, D. (2008). PAMGUARD: Semi-automated, open-source software for real-time acoustic detection and localization of cetaceans. *The Journal of the Acoustical Society of America*, 30:54–62.

Harris, D. (2024): Preliminary survey design of wider passive acoustic monitoring in the Mariana Islands. Submitted to Naval Facilities Engineering Command Pacific, Pearl Harbor, Hawaii, under Contract No. N62470-20-D-0016, Task Order No. 21F0194, issued to HDR Inc., Honolulu, Hawaii. October 2024.

Hill, M.C., Oleson, E.M., Bradford, A.L., Martien, K.K., Steel, D., and Baker, C.S. (2020). Assessing Cetacean Populations in the Mariana Archipelago: A Summary of Data and Analyses Arising from the Pacific Islands Fisheries Science Center Surveys from 2010 to 2019. NOAA Technical Memorandum NMFS-PIFSC-108, doi: 10.25923/wrye-6h14.

Klinck, H., Winiarski, D., Mack, R.C., Tessaglia-Hymes, C.T., Ponirakis, D.W., Dugan, P.J., Jones, C., and Matsumoto, H. (2020). The Rockhopper: a compact and extensible marine autonomous passive acoustic recording system. Global Oceans 2020: Singapore – U.S. Gulf Coast, 2020, pp. 1–7, doi: 10.1109/IEEECONF38699.2020.9388970.

Klinck, H., Yack, T., Tolkova, I., Salisbury, D.P., and Harris, D. (2024). Passive Acoustic Monitoring in the Mariana Islands: Density Estimation of Beaked Whales along the West Coast of Guam. Final

Report. Prepared for Commander, U.S. Pacific Fleet. Submitted to Naval Facilities Engineering Systems Command Pacific, Pearl Harbor, Hawaii, under Contract No. N62470-20-D-0016, Task Order No. 21F0194, issued to HDR Inc., Honolulu, Hawaii. October 2024.

Madsen, P.T., de Soto, N.A., Arranz, P., *et al.* (2013). Echolocation in Blainville's beaked whales (*Mesoplodon densirostris*). *The Journal of Comparative Physiology A,* 199:451-469, doi: 10.1007/s00359-013-0824-8.

Manzano-Roth, R., Henderson, E.E., Alongi, G.C., Martin, C.R., Martin, S.W., & Matsuyama, B. (2023). Dive characteristics of Cross Seamount beaked whales from long-term passive acoustic monitoring at the Pacific Missile Range Facility, Kaua'i. *Marine Mammal Science*, 39(1):22–41, doi: https://doi.org/10.1111/mms.12959.

Marques, T.A., Thomas, L., Martin, S.W., Mellinger, D.K., Ward, J.A., Moretti, D.J., Harris, D., and Tyack, P.L. (2013). Estimating animal population density using passive acoustics. *Biological Reviews*, 88(2):287–309.

McCullough, J.L., Wren, J.L., Oleson, E.M., Allen, A.N., Siders, Z.A., and Norris, E.S. (2021). An acoustic survey of beaked whales and Kogia spp. in the Mariana Archipelago using drifting recorders. *Frontiers in Marine Science*, 8:761.

Morrissey, R.P., Ward, J., DiMarzio, N., Jarvis, S., and Moretti, D.J. (2006). Passive acoustic detection and localization of sperm whales (*Physeter macrocephalus*) in the tongue of the ocean. *Applied Acoustics*, 67(11–12):1091–1105, doi: 10.1016/j.apacoust.2006.05.014.

Nosal, E. M. (2013). Methods for tracking multiple marine mammals with wide-baseline passive acoustic arrays. *The Journal of the Acoustical Society of America*, 134(3):2383–2392, doi: 10.1121/1.4816549.

Oedekoven, C.S., Marques, T.A., Harris, D., Thomas, L., Thode, A.M., Blackwell, S.B., Conrad, A.S., and Kim, K.H. (2021). A comparison of three methods for estimating call densities of migrating bowhead whales using passive acoustic monitoring. *Environmental and Ecological Statistics*. https://doi.org/10.1007/s10651-021-00506-3.

Oswald, J.N., and Yack, T.M. (2015). Development of Automated Whistle and Click Classifiers for Odontocete Species in the Western Atlantic Ocean and the Waters Surrounding the Hawaiian Islands. Report to ONR: Bio-Waves, Inc., Encinitas, CA.

Pacini, A.F., Nachtigall, P.E., Quintos, C.T., Schofield, T.D., Look, D.A., Levine, G.A., and Turner, J.P. (2011). Audiogram of a stranded Blainville's beaked whale (*Mesoplodon densirostris*) measured using auditory evoked potentials. *Journal of Experimental Biology*, 214:2409–1245, doi: 10.1242/jeb.054338. PMID: 21697433.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

R Core Team (2023). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

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

Russel, J.B., Eilon, Z., and Mosher, S.G. (2019). OBSrange: A New Tool for the Precise Remote Location of Ocean-Bottom Seismometers. *Seismological Research Letters*, 90:1627–1641.

Seber, G.A.F. (1982). The Estimation of Animal Abundance, 2nd Ed. Griffin, London.

Simonis, A.E., Brownell, R.L., Thayre, B.J., Trickey, J.S., Oleson, E.M., Huntington, R., and Baumann-Pickering, S. (2020). Co-occurrence of beaked whale strandings and naval sonar in the Mariana Islands, Western Pacific. *Proceedings of the Royal Society B: Biological Sciences*, 287:20200070, doi: 10.1098/rspb.2020.0070.

Stevenson, B.C., Borchers, D.L., Altwegg, R., Swift, R.J., Gillespie, D.M., and Measey, G.J. (2015). A general framework for animal density estimation from acoustic detections across a fixed microphone array. *Methods in Ecology and Evolution*, 6:38–48. https://doi.org/10.1111/2041-210X.12291

Stevenson, B.C. (2022). ascr: Acoustic Spatial Capture-Recapture. URL: https://github.com/b-steve/ascr.

Wood, S.N. (2017). Generalized Additive Models: An introduction with R (2nd edition), CRC.

Yack, T.M., Barlow, J., Calambokidis, J., Southall, B., and Coates, S. (2013). Identification of previously unknown beaked whale habitat in the Southern California Bight using a towed hydrophone array. *The Journal of the Acoustical Society of America*, 134:2589–2595.

Yano, K.M., Hill, M.C., Oleson, E.M., McCullough, J.L.K., and Henry, A.E. (2022). Cetacean and Seabird Data Collected During the Mariana Archipelago Cetacean Survey (MACS), May–July 2021. NOAA Technical Memorandum NMFS-PIFSC-128, doi: 10.25923/7pbh-zq68.

Zimmer, W.M., Johnson, M.P., Madsen, P.T., and Tyack, P.L. (2005). Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*). *The Journal of the Acoustical Society of America*, 117:3919–3927.

Appendix A. Summary of Beaked Whale Encounters

Table A-1: Detected beaked whale event times for the array site (S06).

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration (min)	Species
2024-03-07	12:28:09	25.25	Zc
2024-03-07	16:23:23	38.94	Zc
2024-03-08	09:08:52	8.69	Zc
2024-03-10	07:42:10	3.78	Zc
2024-03-10	09:26:52	26.99	Zc
2024-03-10	12:58:33	73.3	Zc
2024-03-12	21:00:35	6.32	BWC
2024-03-12	21:53:25	16.56	BWC
2024-03-15	11:44:58	79.97	Zc
2024-03-19	09:09:21	2.51	Zc
2024-03-19	10:54:26	44.27	Zc
2024-03-19	20:40:37	11.04	BWC
2024-03-20	11:11:29	195.26	Zc
2024-03-21	20:33:37	21.41	BWC
2024-03-24	11:23:21	44.42	Zc
2024-03-24	17:00:28	14.57	Zc
2024-03-24	18:22:38	12.81	Zc
2024-03-25	00:32:21	24.66	BWC
2024-03-26	08:50:04	16.84	Zc
2024-03-29	20:47:53	13.09	BWC
2024-04-01	13:56:08	12.81	Zc
2024-04-02	08:59:39	1.28	Zc
2024-04-03	16:06:26	4.92	Zc
2024-04-04	10:21:57	23.57	Zc
2024-04-04	11:37:07	24.76	Zc
2024-04-05	09:13:18	22.96	Zc
2024-04-05	13:43:06	43.08	Zc
2024-04-05	16:37:51	0.14	Zc
2024-04-09	09:00:33	1.52	Zc
2024-04-15	05:25:16	5.98	BWC
2024-04-24	11:40:50	1.63	Zc
2024-04-26	06:57:52	8.66	BWC
2024-05-04	23:40:01	2.58	BWC
2024-05-05	02:03:45	3.21	BWC
2024-05-07	21:51:42	5.82	BWC
2024-05-08	13:44:58	48.15	Zc
2024-05-10	22:15:40	18.12	BWC
2024-05-13	23:10:17	11.54	BWC
2024-05-14	18:47:10	5.18	UNK
2024-05-14	22:56:42	15.2	BWC

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration (min)	Species
2024-05-18	02:14:30	7.46	BWC
2024-05-20	13:57:38	154.99	Zc
2024-05-22	13:01:49	98.34	Zc
2024-05-27	20:02:26	32.34	BWC
2024-05-29	13:08:00	14.27	Zc
2024-05-31	16:22:29	31.92	Zc
2024-06-03	12:51:16	27.54	Zc
2024-06-07	20:57:35	5.41	BWC
2024-06-08	01:37:04	4.21	BWC
2024-06-08	09:18:18	4.48	Zc
2024-06-10	11:20:36	24.03	Zc
2024-06-12	13:49:49	24.9	Zc
2024-06-12	17:33:58	24.59	Zc
2024-06-13	10:13:27	12.69	Zc
2024-06-13	12:07:04	63.22	Zc
2024-06-16	17:26:30	25.6	Zc
2024-06-18	13:43:35	23.98	Zc
2024-06-26	16:24:12	43.42	Zc
2024-06-28	01:39:35	0.6	Zc
2024-06-30	09:48:10	26.97	Zc
2024-07-15	11:12:43	10.54	Zc
2024-07-17	09:20:32	4.9	Zc
2024-07-17	13:23:08	48.43	Zc
2024-07-21	09:24:07	40.41	Zc
2024-07-21	15:53:38	1.34	Zc
2024-07-21	16:55:54	71.43	Zc
2024-07-21	19:00:38	47.75	Zc
2024-07-28	16:15:50	24.88	Zc
2024-07-28	17:22:16	77.85	Zc
2024-07-29	03:47:41	28.41	Md
2024-07-29	09:32:00	22.83	Zc
2024-07-29	19:09:52	26.68	Zc
2024-07-29	19:48:44	2.78	BWC
2024-07-30	03:59:08	11.99	BWC
2024-07-30	13:19:47	26.14	Zc
2024-07-31	16:36:36	49.23	Zc
2024-08-22	16:29:00	62.96	Zc
2024-08-28	23:33:03	5.07	UNK
2024-08-29	07:23:34	3.4	Md

Key: BWC = Cross Seamount beaked whale; Md = dense-beaked whale; UNK = unknown beaked whale; Zc = goose-beaked whale.

Table A-2: Detected beaked whale event times for the single-unit site (S05).

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration (min)	Species
2024-03-07	13:06:24	22.89	Zc
2024-03-15	20:41:13	2.55	BWC
2024-03-15	21:47:24	28.49	BWC
2024-03-15	23:24:16	47.25	BWC
2024-03-16	00:47:52	20.06	BWC
2024-03-16	02:01:36	8.57	BWC
2024-03-16	08:47:20	35.93	Zc
2024-03-16	10:28:25	23.19	Zc
2024-03-25	09:04:08	35.68	Zc
2024-03-26	11:55:53	93.34	Zc
2024-03-27	06:05:39	0.31	BWC
2024-03-27	06:46:44	24.13	BWC
2024-03-27	08:09:17	7.95	BWC
2024-03-29	20:59:11	7.13	BWC
2024-03-29	22:09:50	5.77	BWC
2024-03-29	23:00:29	5.81	BWC
2024-03-30	00:16:53	33.84	BWC
2024-03-30	02:25:50	13.17	BWC
2024-04-01	08:59:41	17.86	Zc
2024-04-03	13:53:13	0.22	Zc
2024-04-04	17:00:20	14.97	Zc
2024-04-05	23:23:03	8.3	BWC
2024-04-06	02:01:04	32.9	BWC
2024-04-06	03:10:27	1.1	BWC
2024-04-09	13:31:54	50.97	Zc
2024-04-09	15:40:37	86.45	Zc
2024-04-15	04:47:30	12.77	BWC
2024-04-19	12:28:58	51.25	Zc
2024-04-19	14:03:19	14.26	Zc
2024-04-19	21:33:27	5.78	BWC
2024-04-20	02:34:05	9.15	BWC
2024-04-20	09:44:28	47.76	Zc
2024-04-20	11:12:45	<0.1	Zc
2024-04-20	12:32:35	68.65	Zc
2024-04-20	16:17:54	72.02	Zc
2024-04-23	13:18:54	33.74	Zc
2024-04-23	15:29:23	3.05	Zc
2024-05-03	09:23:40	94.78	Zc

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration (min)	Species
2024-05-06	09:39:15	45.69	Zc
2024-05-06	11:39:42	63.58	Zc
2024-05-08	08:56:11	16.21	Zc
2024-05-11	01:05:19	33.13	BWC
2024-05-11	02:24:52	17.02	BWC
2024-05-11	04:19:55	9.0	BWC
2024-05-13	18:11:48	52.27	Zc
2024-05-18	04:48:39	3.22	BWC
2024-05-18	14:01:24	110.2	Zc
2024-05-19	13:27:02	9.95	Zc
2024-05-19	15:52:58	49.72	Zc
2024-05-20	09:47:46	34.55	Zc
2024-05-20	14:24:43	31.93	Zc
2024-05-21	11:07:42	3.45	Zc
2024-05-23	17:17:41	26.84	Zc
2024-05-24	20:24:52	33.43	BWC
2024-05-24	23:01:14	32.34	BWC
2024-05-25	02:59:06	2.18	BWC
2024-05-26	05:50:59	10.55	UNK
2024-05-26	07:06:09	9.47	BWC
2024-05-26	07:58:12	34.81	BWC
2024-05-26	10:38:59	57.08	Zc
2024-05-26	16:22:01	23.5	Zc
2024-05-29	09:30:49	32.98	Zc
2024-05-31	23:51:18	10.55	BWC
2024-06-01	00:54:25	3.63	BWC
2024-06-01	11:36:30	17.07	Zc
2024-06-01	20:04:52	31.87	BWC
2024-06-02	00:52:36	16.91	BWC
2024-06-02	02:23:07	2.31	BWC
2024-06-03	09:16:00	30.97	Zc
2024-06-07	20:39:16	2.91	BWC
2024-06-07	22:06:24	34.07	BWC
2024-06-08	00:07:48	2.9	BWC
2024-06-08	01:27:55	62.61	BWC
2024-06-08	13:03:42	29.13	Zc
2024-06-08	18:53:21	64.27	Zc
2024-06-09	16:51:28	41.17	Zc
2024-06-11	11:22:13	42.56	Zc

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration (min)	Species
2024-06-12	14:45:02	3.35	Zc
2024-06-13	12:04:22	3.54	Zc
2024-06-14	20:33:34	14.65	BWC
2024-06-14	21:24:26	10.6	BWC
2024-06-15	00:14:59	10.15	BWC
2024-06-15	21:38:27	23.27	BWC
2024-06-16	00:48:27	2.15	BWC
2024-06-16	11:27:43	16.59	Zc
2024-06-16	12:48:22	13.8	Zc
2024-06-18	10:03:55	37.8	Zc
2024-06-18	17:24:05	38.43	Zc
2024-06-20	16:09:13	15.82	Md
2024-06-21	19:57:33	104.23	BWC
2024-06-22	03:23:15	36.23	BWC
2024-06-22	07:06:57	4.03	BWC
2024-06-22	20:24:22	4.79	Zc
2024-06-25	18:33:34	44.63	Zc
2024-06-28	11:59:58	48.12	Zc
2024-06-28	20:31:33	56.23	BWC
2024-06-29	13:09:39	37.12	Zc
2024-06-30	09:34:52	29.56	Zc
2024-06-30	17:01:50	51.36	Zc
2024-07-03	16:26:20	14.94	Zc
2024-07-07	17:54:13	75.07	Zc
2024-07-15	14:42:47	147.31	Zc
2024-07-16	11:59:18	51.7	Zc
2024-07-17	17:00:22	89.81	Zc
2024-07-18	14:01:58	95.71	Zc
2024-07-21	00:23:14	4.02	BWC
2024-07-21	07:50:16	22.05	BWC
2024-07-21	12:25:09	42.39	Zc
2024-07-25	04:01:24	44.35	BWC
2024-07-25	16:51:11	38.2	Zc
2024-07-25	23:07:22	4.65	Md
2024-07-26	15:15:23	61.23	Zc
2024-07-26	20:39:03	51.3	BWC

Key: BWC = Cross Seamount beaked whale; Md = dense-beaked whale; UNK = unknown beaked whale; Zc = goose-beaked whale.

Appendix B. Summary of MFAS Encounters

Table B-1: Detected MFAS event times for the array site (S06).

Date (YYYY-MM-DD)	Start Time (HH:MM:SS UTC)	Duration (min)	Sonar Type
2024-08-25	01:46:26	231.1	MFAS
2024-08-26	02:59:37	188.0	MFAS

Appendix C. Corrections to Previous Beaked Whale Density Estimates

Table C-1: Updated results from Deployment 1 in 2022. Number of unique 10-second 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 Sept	28 Sept–18 Oct	19 Oct–22 Nov
Number of unique 10-second segments with detections	380	1930	841	328	225	896	952
Total number of 10-second segments with monitoring effort	51,480	258,840	266,760	267,480	231,840	181,080	293,760
Effective survey area (km^2)	8.56	8.56	8.56	8.56	8.56	7.44	6.27
Density (animals per 1,000 km^2)	**10.57**	**10.68**	**4.52**	**1.76**	**1.39**	**8.15**	**6.34**
Density 95% CI (animals per 1,000 km^2)	8.93 - 12.52	9.25 - 12.32	3.88 - 5.25	1.48 - 2.09	1.15 - 1.68	7.00 - 9.49	5.44 - 7.38
CV Density (%)	8.62	7.30	7.74	8.86	9.62	7.75	7.76

Small adjustments to the analysis code in the second round of analysis led to updates being provided for the Deployment 1 results (Klinck *et al.*, 2024). For the SCR analysis for goose-beaked whales, average densities per session ranged from 1.39 animals per 1,000 km^2 (CV: 9.62 percent) in September 2022 to 10.68 animals per 1,000 km^2 (CV: 7.30 percent) in June 2022 (**Table C-1**).

We also provide updated results for the distance sampling analysis from Deployment 1 (though these results have not been repeated in Deployment 2). The number of detections used for the distance sampling analysis, n, was 48 (after truncation), and k was 1,099,080 to represent the number of 10-second time periods between May and September 2022 (when localization was performed). The estimated effective detection area remained at 4.21 km^2, and the resulting density estimate (averaged over May–September) was 0.13 animals per 1,000 km^2 (95 percent CI: 0.09 - 0.19 animals per 1,000 km^2, percentage CV: 20.56 percent).