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Long-term monitoring of Cuvier's beaked whale diving behavior in southern California using 3D tracking from fixed hydrophone arrays

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UNIVERSITY OF CALIFORNIA SAN DIEGO

Long-term monitoring of Cuvier's beaked whale diving behavior in southern California using 3D tracking from fixed hydrophone arrays

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Marine Biology

by

Lauren Michelle Baggett

Committee in charge:

Simone Baumann-Pickering, Chair  
Kaitlin Frasier  
John Hildebrand

2023

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The Thesis of Lauren Michelle Baggett is approved, and it is acceptable.  
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University of California San Diego

2023

## DEDICATION

I dedicate this thesis to my dad, mom, and sister: Steve, Amy, and Brooke. Thank you for encouraging me to follow my dreams, even though they led halfway across the country. Your unconditional love and support have made every achievement possible.

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## LIST OF ABBREVIATIONS

Zc	<i>Ziphius cavirostris</i> , Cuvier's beaked whale
De	Delphinid
TDOA	Time-difference of arrival
DOA	Direction of arrival
SCB	Southern California Bight
HARP	High-frequency acoustic recording package
AZ	Azimuth
EL	Elevation

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Baggett\_multipleWhales\_track\_video.mp4

Baggett\_initialDescent\_track\_video.mp4

Baggett\_initialDescent\_trackSpeed\_video.mp4

Baggett\_consistentTrajectory\_track\_video.mp4

Baggett\_consistentTrajectory\_trackSpeed\_video.mp4

Baggett\_variableTrajectory\_track\_video.mp4

Baggett\_variableTrajectory\_trackSpeed\_video.mp4

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## ABSTRACT OF THE THESIS

Long-term monitoring of Cuvier's beaked whale diving behavior in southern California using 3D tracking from fixed hydrophone arrays

by

Lauren Michelle Baggett

Master of Science in Marine Biology

University of California San Diego, 2023

Simone Baumann-Pickering, Chair

Cuvier's beaked whales are a deep-diving cetacean species known to forage in the submarine canyons of the Southern California Bight. Although this species is a top predator in deep-sea ecosystems, little is known about their social or foraging strategies because of their extreme diving behavior. In this analysis, time-difference-of-arrival (TDOA) localization is used

to track the position of Cuvier's beaked whales from echolocation clicks recorded on seafloor-mounted hydrophone arrays. This approach yielded 162 final tracks with estimated swim speeds of diving Cuvier's beaked whales at one acoustic monitoring site from July 2021 to October 2022. The number of individual whales captured on a single track ranged from 1 to 7, with a mean of 2.24. Tracks including four or more individuals were captured most often during the day, with notable peaks in July 2021, February 2022, and July 2022. Three distinct diving behaviors were observed, differentiated by minimum depth, change in depth, and lateral movement: initial descent dive segments ( $1.657 \pm 0.441$  m/s), consistent trajectory dive segments ( $0.913 \pm 0.596$  m/s), and variable trajectory segments ( $1.298 \pm 0.438$  m/s). This long-term monitoring effort and TDOA localization approach collected data from Cuvier's beaked whale foraging dives to reveal spatial use, group size, and diving behavior trends at our acoustic monitoring site. This extensive tracking dataset gives valuable insight into the social and foraging behavior at depth of Cuvier's beaked whales offshore Southern California.

## INTRODUCTION

*Ziphius cavirostris*, commonly known as Cuvier's beaked whales, are an odontocete species belonging to the beaked whale family *Ziphiidae* (Dalebout et al., 2004). Although this species is rarely sighted in many regions, stranding records indicate that they are distributed throughout global tropical and temperate oceans (Heyning & Mead, 2009). Beaked whales as a group are known for their extreme diving behavior (Tyack et al., 2006), with Cuvier's beaked whales holding both the current mammalian dive depth and dive duration records (Schorr et al., 2014; Quick et al., 2020).

Like other odontocete species, Cuvier's beaked whales are highly soniferous and produce echolocation clicks with species-specific characteristic to navigate and forage in the darkness of such extreme depths (Zimmer et al., 2005; Baumann-Pickering et al., 2013). Stomach content analyses from stranded individuals indicate their primary prey are deep sea cephalopods, with occasional mesopelagic fish and crustaceans (Santos et al., 2001; Kovačić et al., 2010; West et al., 2017). Because Cuvier's beaked whales are top predators in deep sea ecosystems, understanding and monitoring their social and foraging behavior at depth can give insights into overall ecosystem function and health. However, studying the behavior of such a deep-diving species *in situ* is no easy task.

Cetacean diving behavior has been studied using both tagging and acoustic methods. Early studies made use of suction-cup tags with only time and depth recording capabilities (Baird et al., 2006; Baird et al., 2008), or additionally fitted with hydrophones, accelerometers, and magnetometers (Tyack et al., 2006; DeRuiter et al., 2013). These efforts yielded valuable but short-term information since tags stayed attached for less than 48 hours each deployment. Long-duration barbed satellite tags have successfully remained attached to individual cetaceans for

weeks or months, but record and transmit data at a low temporal resolution (Andrews et al., 2008; Schorr et al., 2009; Schorr et al., 2014; Joyce et al., 2017; Shearer et al., 2019; Barlow et al., 2020). Medium-duration barbed tags have allowed for collection of high-resolution depth, triaxial acceleration, and acoustic data for up to a few weeks (Sweeney et al., 2022). This tag data gives insight into the full range of diving patterns of individual cetaceans but is difficult to collect from more than a few individuals in a population. Finding and successfully tagging a cetacean, particularly a deep-diving one, is a time-consuming and labor-intensive process. Passive acoustic methods provide an alternate approach to tracking cetacean diving behavior that may require less time in the field and is less invasive. Acoustic receiver arrays can be towed, drifting, or moored to the seafloor and use time-difference-of-arrival (TDOA) localization of vocalizations to track the position of nearby cetaceans (Tiemann et al., 2006; Nosal & Frazer, 2007; Gassman et al., 2013; Yack et al., 2013; Gassman et al., 2015; Barlow et al., 2018; Jang et al., 2023). Using passive acoustics, snapshots of cetacean diving behavior in a specific region can be collected from multiple individuals to monitor long-term trends.

Studies using these tag and acoustic methods have provided some insight into the normal diving patterns of Cuvier's beaked whales. Average swim speeds range from 1-3 m/s (Tyack et al., 2006; Baird et al., 2008; DeRuiter et al., 2013; Gassman et al., 2015; Barlow et al., 2020). They regularly perform deep foraging dives to depths greater than 1,000 meters, lasting about 1 hour (Tyack et al., 2006; Joyce et al., 2017; Shearer et al., 2019; Barlow et al., 2020). The time between these deep dives, the inter-deep dive interval, can last between 30 minutes and several hours (Shearer et al., 2019). During an inter-deep dive interval, Cuvier's beaked whales perform a series of shallow dives (depths less than 500 meters) (Tyack et al., 2006; Joyce et al., 2017; Shearer et al., 2019). Echolocation clicks are not usually produced during these shallow dives,

which may allow for physiological recovery while also avoiding near-surface predators like *Orcinus orca* (Tyack et al., 2006; Aguilar de Soto et al., 2020). More time is spent near the surface (above 50 meters) at night than during the day (Barlow et al., 2020), further suggesting predator avoidance behavior.

This avoidance behavior may extend to include anthropogenic sounds, as Cuvier's beaked whales have exhibited behavioral changes including stranding in association with naval mid-frequency active sonar (Tyack et al., 2011; DeRuiter et al., 2013; Moore & Barlow, 2013; Simonis et al., 2020). The exact mechanisms behind these behavioral changes remain unclear but have been the subject of much research (Filadelfo et al., 2009; Tyack et al., 2011; DeRuiter et al., 2013; Falcone et al., 2017; Simonis et al., 2020). Gathering long-term data from many individuals in a population to understand baseline diving behavior will inform effective population management strategies and anthropogenic noise risk assessment.

The Southern California Bight (SCB) includes the waters offshore southern California, between San Diego to the south and Pt. Conception to the north. This stretch of coastal ocean is of economic, military, and ecological interest: bisected by commercial shipping lanes, the SCB includes an offshore naval range and the Channel Islands National Marine Sanctuary. The SCB's complex bathymetric features including basins and submarine canyons are a known Cuvier's beaked whale habitat (Falcone et al., 2009). The region's relative accessibility and varied stakeholders make this Cuvier's beaked whale population of particular interest for monitoring.

In this study, I use time difference of arrival (TDOA) localization to track Cuvier's beaked whale deep foraging dives from echolocation clicks recorded on seafloor-mounted hydrophone arrays in the SCB. First, I identified Cuvier's beaked whale echolocation clicks in the acoustic recordings and calculated whale positions using TDOAs of clicks recorded on

multiple arrays. Next, I collected information about group size by recording the number of individual Cuvier's beaked whales tracked per encounter. Then, I distinguished three distinct diving behaviors common in these tracked deep foraging dives using whale initial depth, change in depth, and change in lateral position. Finally, I used these tracks to estimate whale swim speed for each tracked whale. By tracking Cuvier's beaked whales using acoustic techniques, diving behavior can be studied over long time periods and across many individuals. With a better understanding of normal diving behavior, we can monitor Cuvier's beaked whale populations and their ecosystems worldwide.

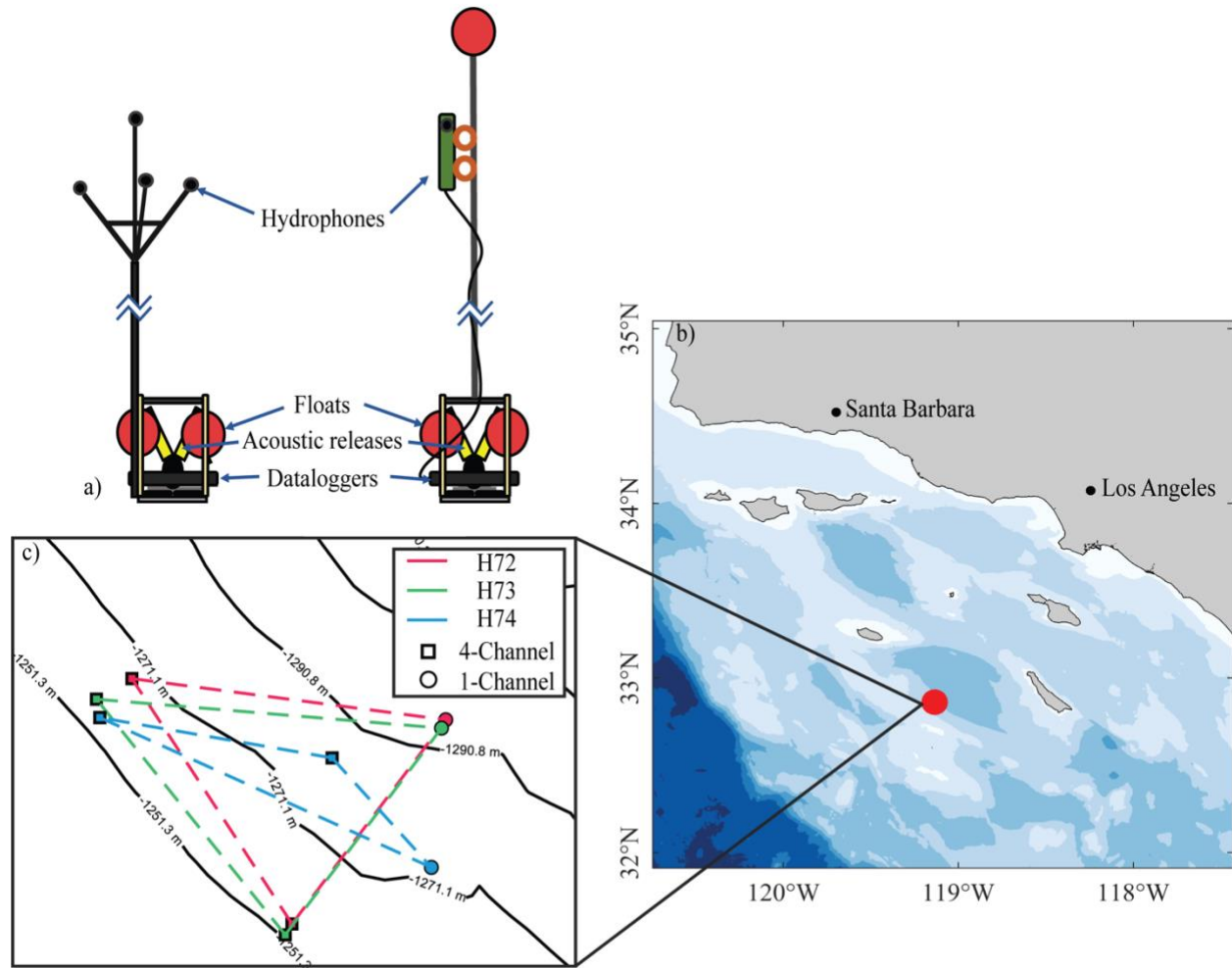
## METHODS

### *i. Acoustic data collection*

Acoustic data was collected offshore southern California at a site along the western edge of San Nicolas Basin, east of San Clemente Island (Figure 1b), referred to as SOCAL\_H. High-frequency Acoustic Recording Packages (HARPs) (Wiggins & Hildebrand, 2007; Wiggins et al., 2012) deployed at this site collected near continuous data from June 2021 to October 2022 (Table 1). Three HARPs at this site positioned approximately 1 kilometer apart collected data simultaneously across three deployments (Figure 1c). Two of these packages, “4-channel arrays,” were equipped with four hydrophones sampling continuously at 100 kHz. These four hydrophones were mounted tetrahedrally approximately 6 meters above the seafloor. Individual hydrophones were separated by 1 meter (Figure 1a). The third package, a “single channel receiver,” was equipped with a single hydrophone sampling continuously at 200 kHz. This hydrophone was part of a complex mooring ~1000 meters long. The hydrophone was attached near the bottom of this long mooring, sitting approximately 15 meters above the seafloor (Figure 1a).

Locations of the 4-channel and single-channel instruments were obtained through shipboard localization or trilateration using the two-way travel time of a ping transmitted from the surface to the instrument (Table 1). During localization, the ship followed a circular path with a radius of one water depth and then crossed over the drop location, sending many pings to the instrument to obtain a precise location. During trilateration, pings were sent to the instrument from three points in a triangular configuration to obtain a less precise location. The positions of the individual hydrophones within the four-channel arrays were calculated using the TDOAs of

the ship engine noise at a variety of known locations and inverting for the receiver positions that best minimized the error between expected and measured TDOAs (Snyder et al., in prep).



**Figure 1: (a) Diagram of acoustic instrumentation.** Renderings of a four-channel array and a single channel recorder (Snyder et al., in prep). **(b) Map of study site.** Acoustic data collection site offshore southern California, along the western edge of the San Nicolas Basin east of San Clemente Island. **(c) Instrument landing positions per deployment.** Instrument landing positions for each deployment in color. Square markers (□) represent 4-channel arrays, and circle markers (○) represent single channel recorders.

**Table 1: Recording times, positioning method, and landing position for each array per deployment.** Each deployment had three separate instruments: two 4-channels (“\_C4”) and one single-channel. Deployment names include the region (SOCAL), site (H), deployment number (72-74), and relative instrument position (E = east, W = west, S = south).

<b>Deployment Name</b>	<b>Start Date (UTC)</b>	<b>End Date (UTC)</b>	<b>Localization (L) or Trilateration (T)</b>	<b>Latitude (°N)</b>	<b>Longitude (°W)</b>	<b>Depth (m)</b>
SOCAL_H_72_HE	Jun 05, 2021	Dec 18, 2021	L	32° 51.670'	119° 8.214'	-1283
SOCAL_H_72_HS_C4	Jul 01, 2021	Dec 18, 2021	L	32° 51.391'	119° 8.328'	-1249
SOCAL_H_72_HW_C4	Jul 01, 2021	Oct 22, 2021	L	32° 51.727'	119° 8.555'	-1263
SOCAL_H_73_HE	Dec 21, 2021	May 22, 2022	L	32° 51.659'	119° 8.116'	-1268
SOCAL_H_73_HS_C4	Dec 20, 2021	May 22, 2022	L	32° 51.376'	119° 8.338'	-1246
SOCAL_H_73_HW_C4	Dec 20, 2021	May 22, 2022	L	32° 51.698'	119° 8.606'	-1253
SOCAL_H_74_HE	May 23, 2022	Oct 15, 2022	T	32° 51.470'	119° 8.130'	-1292
SOCAL_H_74_HS_C4	Jun 10, 2022	Oct 15, 2022	L	32° 51.618'	119° 8.271'	-1426
SOCAL_H_74_HW_C4	Jun 10, 2022	Oct 15, 2022	L	32° 51.673'	119° 8.601'	-1251

### *ii. Sound speed estimation*

At each deployment, a CTD cast was taken near the drop location. The Seasoft V2: SBE Data Processing software (Sea-Bird Scientific, 2017) was used to extract data from each cast and calculate profiles of sound speed (Chen & Millero, 1977). Sound speeds below 700 meters were averaged for each cast. Subsequent calculations used these average sound speeds obtained from the CTD cast taken at the beginning of that deployment (Table S1).

### *iii. Identification of Cuvier's beaked whale echolocation clicks*

A machine learning workflow for detecting and classifying odontocete echolocation clicks (Frasier et al 2017; Frasier 2021) was applied to the single channel data to identify Cuvier's beaked whale echolocation clicks. Single channel hydrophones were selected for this task because their faster sampling rate (200 kHz) can capture the higher frequencies in a Zc echolocation click, allowing for more confident identification.

Zc echolocation clicks were detected and classified using the MATLAB (Mathworks, Natick, MA)-based software *Triton* (Wiggins et al., 2010). A customized energy detector (Frasier 2021) applied a five-pole Butterworth bandpass filter with edges at 5 kHz and 95 kHz, and extracted signals with peak-to-peak received level  $\geq 118$  dB re 1  $\mu\text{Pa}^2$  and durations 30 to 1200  $\mu\text{s}$ . A two-phase unsupervised clustering algorithm identified and grouped recurring signals based on spectra and waveform (Frasier et al., 2017; Frasier 2021). These clusters were manually labeled and used to train a neural network (Frasier 2021). The neural network was trained to recognize biological signals (echolocation clicks from *Lagenorhynchus obliquidens*, *Grampus griseus*, *Ziphius cavirostris*, and presumed *Delphinus capensis* and *Delphinus delphis*) (Soldevilla et al., 2008; Zimmer et al., 2005; Zimmer et al., 2008) as well as anthropogenic

signals (boats, echosounders) common in data from this region. The neural network labels were manually verified in the MATLAB-based software *DetEdit* (Solsona-Berga et al., 2020).

This workflow culminated with the successful identification of times when *Zc* echolocation clicks were recorded on the single-channel system. To define time periods when those same encounters were likely recorded on the 4-channel systems, an hour buffer was added before and after the encounter detection times from the single channel.

#### *iv. Localization — Where's Whaledo*

The following steps were calculated using the MATLAB-based software package *Where's Whaledo* (Snyder et al., in prep).

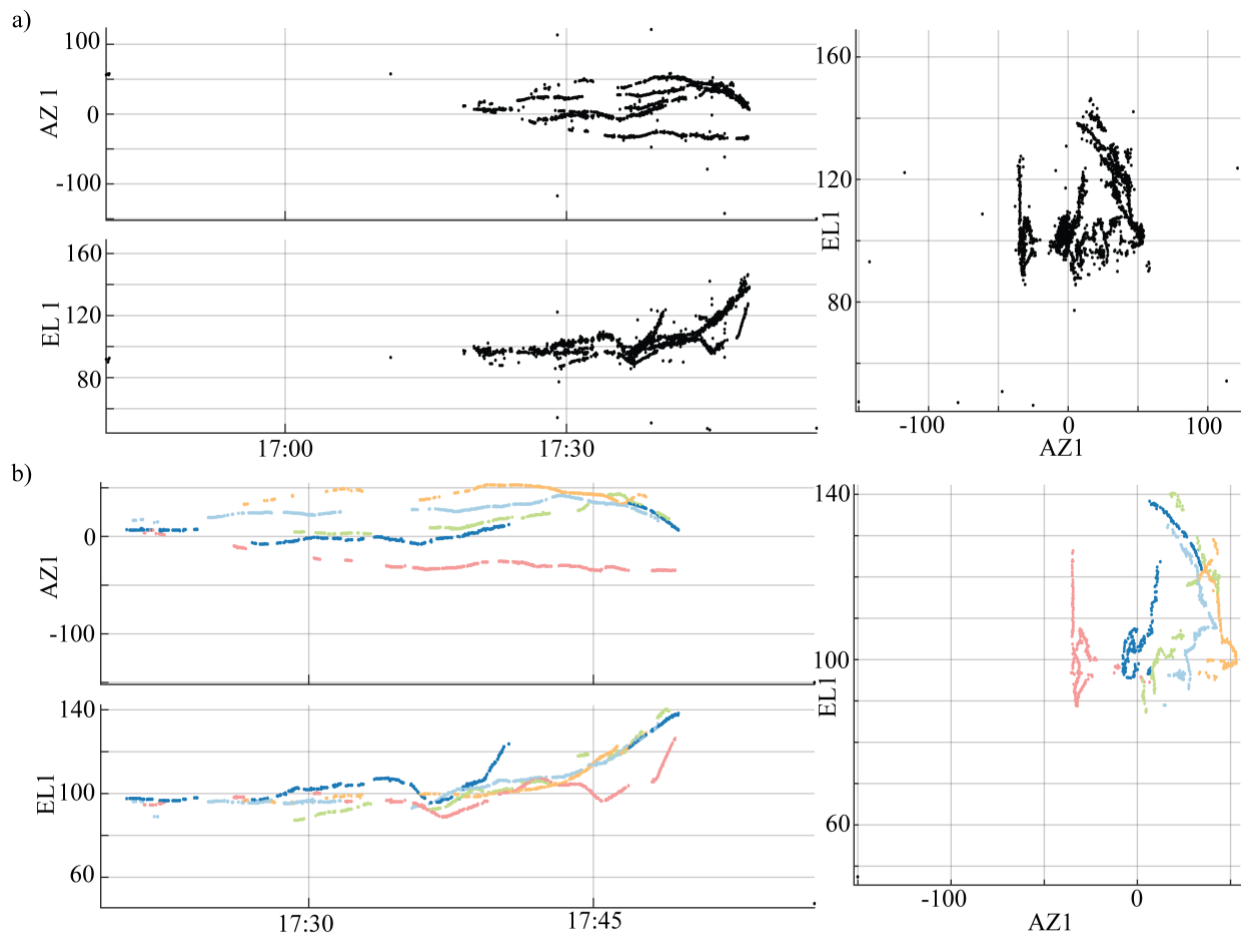
The 4-channel data, at only the buffered detection times from the single channel data, was run through a highpass filter with a cutoff frequency of 20 kHz. Acoustic data from each of the hydrophones on the 4-channel system was cross-correlated to calculate time-difference-of-arrivals (TDOAs). Because of the proximity of receivers on the 4 channel arrays, these TDOAs converged in a single direction. This gave a direction of arrival (DOA) of the click relative to each array. These DOAs were converted to azimuth and elevation values and plotted on the *brushDOA* interface (Snyder et al., in prep).

#### *v. Track cleaning — Where's Whaledo*

All tracks resulting from the *Where's Whaledo* localization step were manually inspected, sorted, and cleaned. Tracks with less than 10 minutes of continuous detections or fewer than 400 total detected clicks were discarded (Figure S1). Tracks where Delphinid detections obscured *Zc* clicks were also excluded from further analysis. Delphinid detections can be differentiated from *Zc* in the *brushDOA* interface by their variable elevation values or using their spectral

characteristics in Triton (Figure S2). Tracks with clear Zc detections were kept for further analysis and manually cleaned (Figure 2).

The *brushDOA* interface was used to manually clean tracks with visible Zc detections (Snyder et al., in prep). First, Delphinid detections were removed from the track. Next, detections far from clearly visible Zc detections were removed. Finally, Zc individuals from each track were manually assigned a unique color (Figure 2). Tracks labeled in color on one array were identified on the second array and labeled the same color using click-train correlation (Snyder et al., in prep).



**Figure 2: Before (a) and after (b) of a track that was manually cleaned using the brushDOA interface.** Azimuth and elevation values from one 4-channel array are plotted over time. Each point represents an acoustic signal, like an echolocation click, that has been localized. This track shows five distinct whales, labeled in color, clicking simultaneously.

#### *vi. Group size*

Group size was defined as the number of distinct individuals present in a single encounter. Encounters were determined as times where consecutive Cuvier's beaked whale echolocation clicks were recorded on the single-channel receiver less than 1800 seconds apart. Encounters also included the hour buffer before and after the timestamps of first and last recorded clicks. It is assumed that individuals captured in the same encounter are close enough temporally and spatially to be associated with one another. Group size values were obtained from encounters after the brushDOA cleaning step, so that whales picked up on one receiver but not the other were still included in the count.

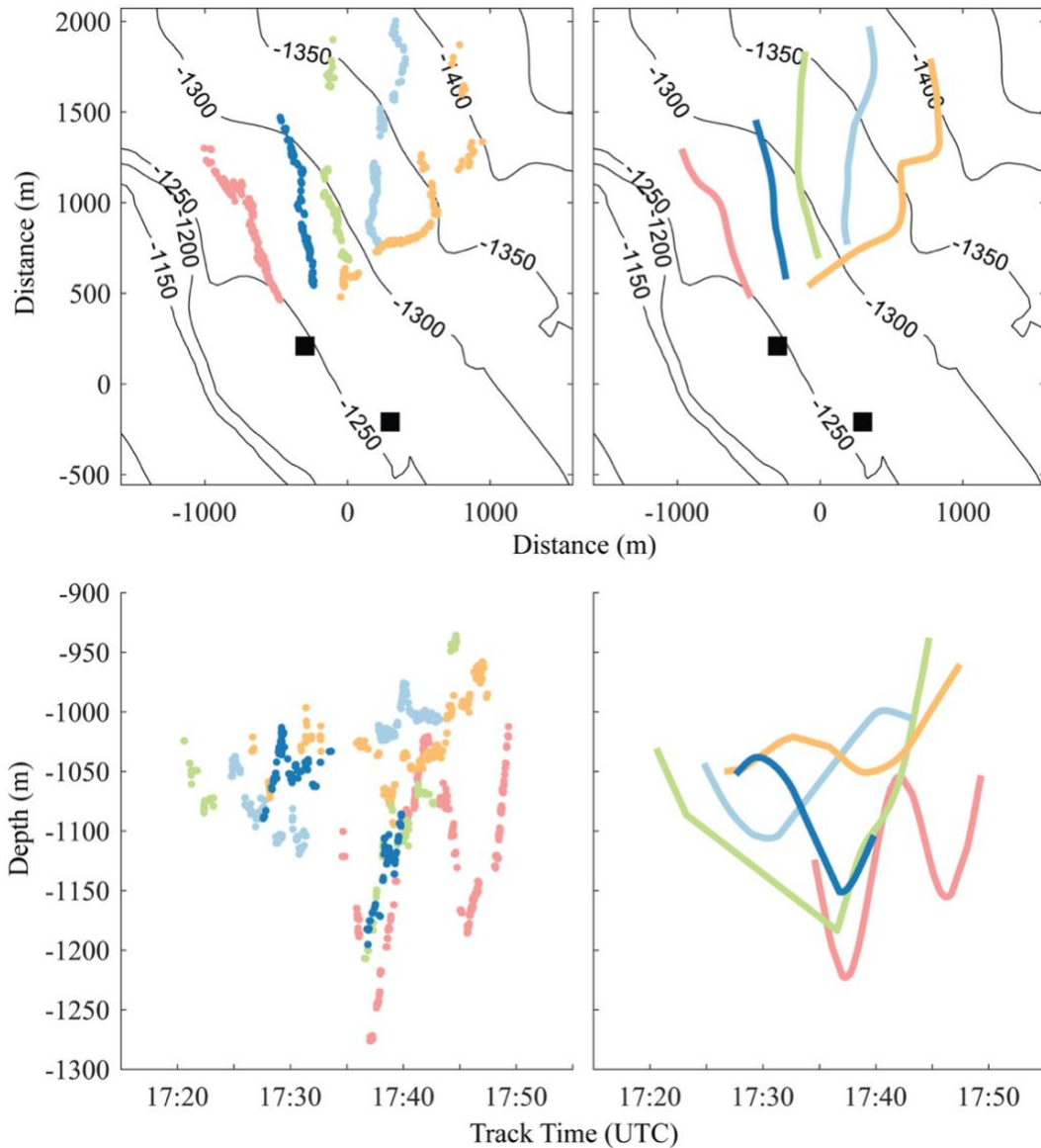
Normalized time of day was calculated by finding the number of minutes between the start of an encounter and sunset, and then dividing by the total number of minutes of daytime or nighttime on that day. Normalized encounter times recorded during the day were given a value between sunrise (-1) and sunset (0), and during the night were given a value between sunset (0) and the next sunrise (1). Sunrise and sunset times at the study site were obtained from the sunrise and sunset API (<https://sunrise-sunset.org/api>). Calculating normalized time of day removed seasonal changes in the length of day and night, allowing better comparison of diel trends in group size across the entire study period.

#### *vii. 3D intersect — Where's Whaledo*

Three-dimensional whale positions relative to the receivers were calculated from the intersect of direction of arrival (DOA) values of cleaned detections recorded on both 4-channel arrays. Tracks which had many detections on one 4-channel array but few detections on the other 4-channel array were too sparse and subsequently removed from analysis. Error was estimated using jackknifing cross-validation (Tukey 1958; Miller 1974), iteratively removing a single

TDOA pair and recalculating position. A smoothing spline was then fit to the path of each whale in every track (Figure 3).

Bathymetric data used in plotting was obtained from the Global Multi-Resolution Topography Synthesis (GMRT) (Ryan et al., 2009).



**Figure 3: Before (left) and after (right) applying the smoothing spline fit to a track.** Top figures show XY whale position in meters from the midpoint of the two 4-channel arrays. Bottom figures show Z position (depth in meters) over time. 4-channel arrays are denoted by black squares (■). Colored points are localized echolocation clicks produced by distinct whales, and colored lines are splines fit to those localized points.

*viii. Dive segment classification*

During manual track review, three recurring diving patterns were observed (Figure 4). These recurring patterns, representing segments of deep foraging dives, were classified by their minimum depth, change in depth, and lateral movement (Table 2). Each diving pattern was assigned a descriptive name for ease of identification (Table 2).

**Table 2: Dive pattern descriptive names and classification parameters.** These classification parameters distinguish between recurring dive behaviors observed during manual track review. These recurring patterns represent different diving behaviors that Cuvier’s beaked whales exhibited during deep foraging dives.

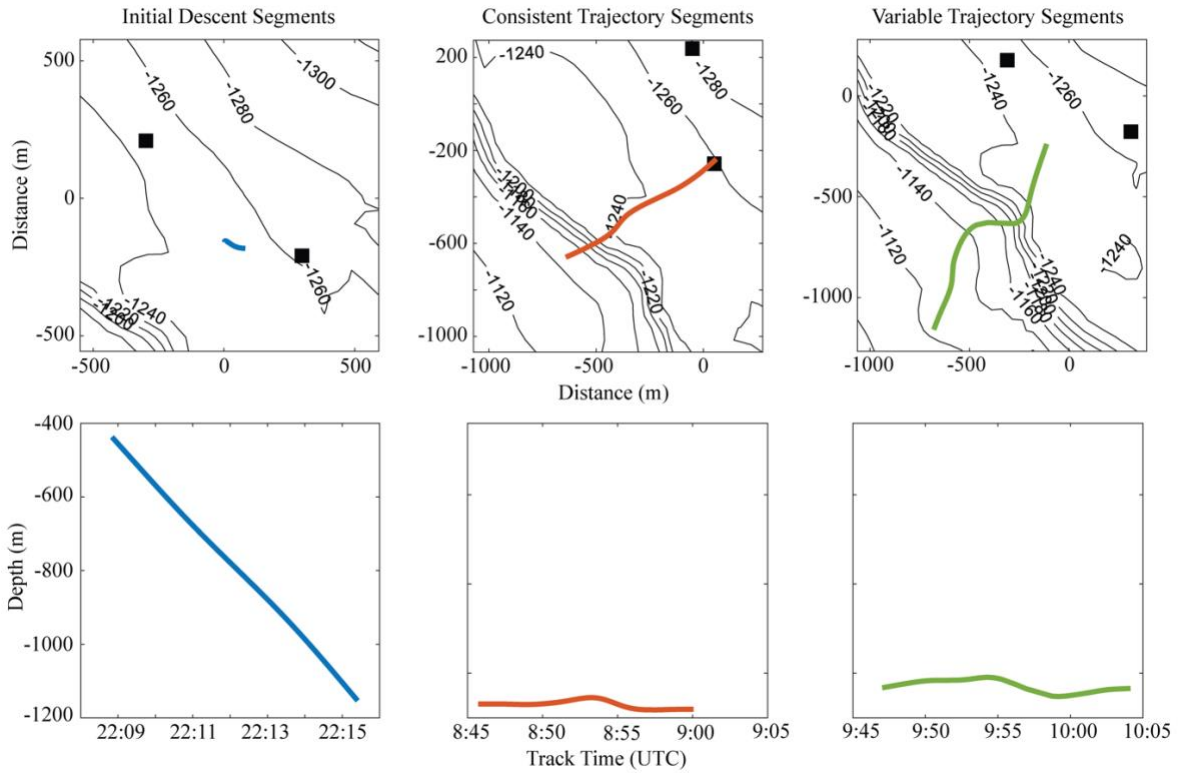
<b>Dive pattern name</b>	<b>Minimum depth (m)</b>	<b>Vertical movement (m)</b>		<b>Lateral movement (m)</b>
Initial descent	<800	>350		—
Consistent trajectory	>800	<100	&	<100
Variable trajectory	>800	100-350	or	>100

*ix. Swim speed and distance estimation*

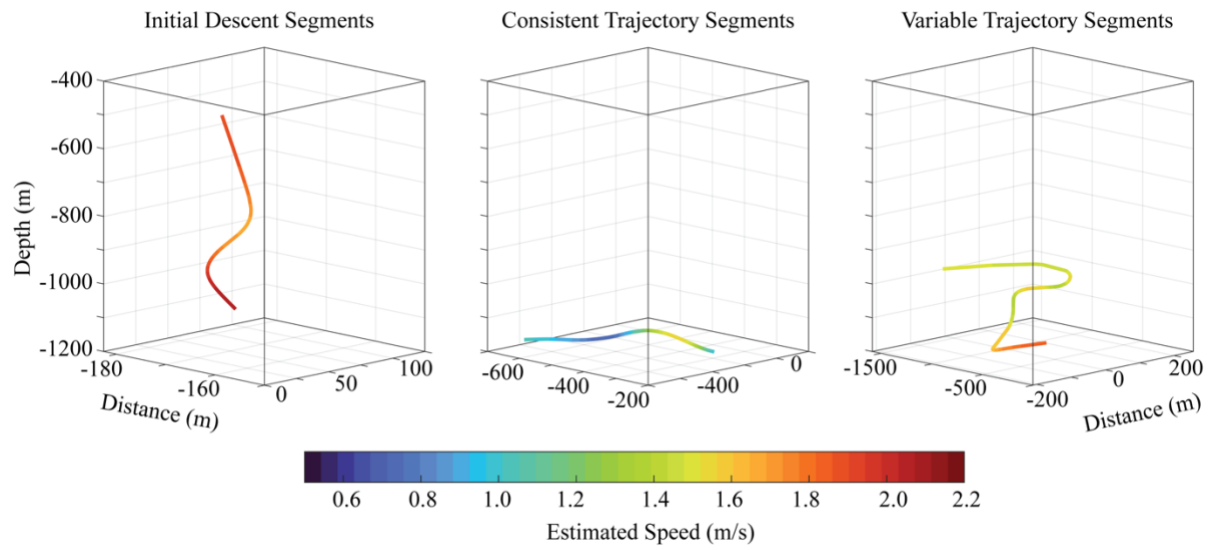
Swim speed was estimated for each whale in each track using the smoothed whale positions. Distance between three-dimensional smoothed points was calculated using the Euclidean distance formula, and then divided by time interval between those smoothed points to get an estimate of swim speed throughout the track (Figure 5). These speed values were averaged per track to give average track speed.

For each dive segment type, average swim speeds per track were averaged again. This estimated an average swim speed per dive segment type that weighted all tracks equally, regardless of their duration. Change in speed per track was calculated as the difference between

minimum and maximum estimated speeds. Distances between smoothed points throughout the track were summed to calculate total distance traveled.



**Figure 4: Example dive patterns from localized Cuvier's beaked whale tracks.** Each example pattern is displayed in XY position (meters) from the midpoint of the two 4-channel arrays (top) and depth in meters over UTC time (bottom).

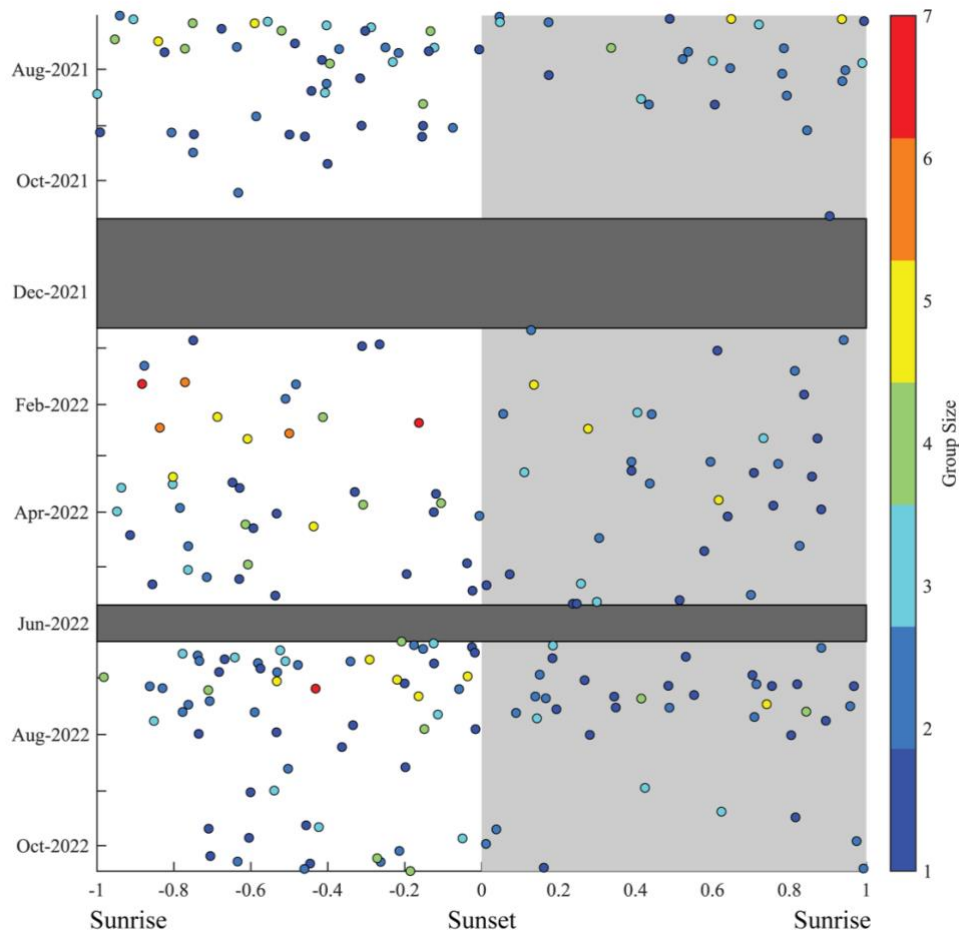


**Figure 5: 3D whale positions colored by speed, examples for each dive segment type.** XY distance is measured in meters from the center point of the two 4-channel receivers.

## RESULTS

### *i. Group size*

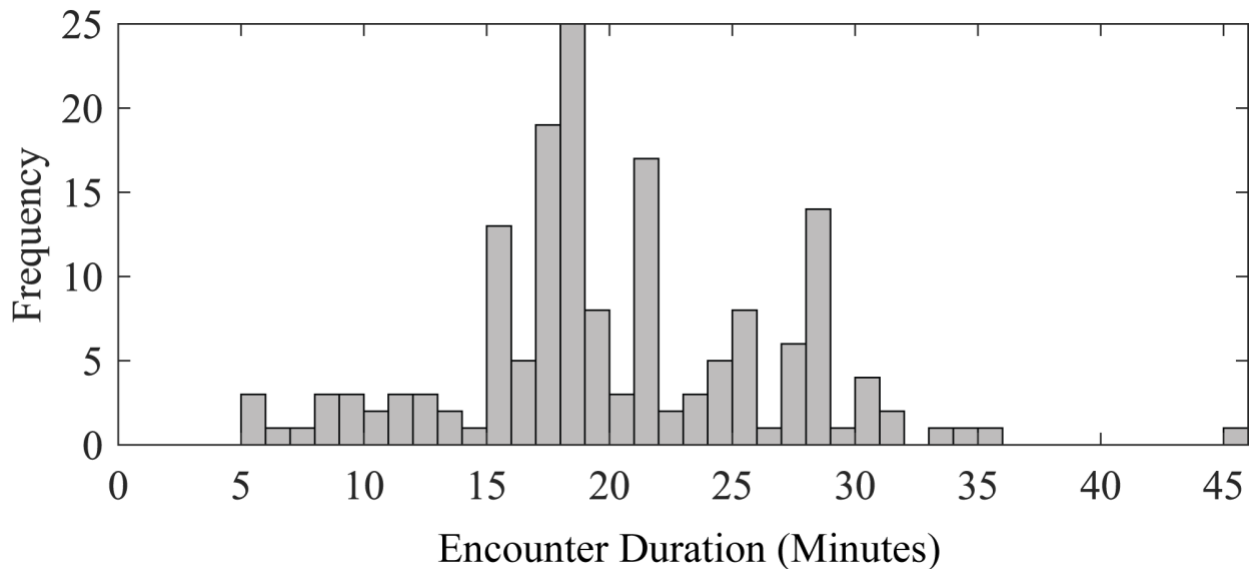
Group size information was obtained from 246 encounters. Larger group sizes were captured per encounter during the day ( $2.44 \pm 1.52$ ,  $N=148$ ) than at night ( $2.00 \pm 1.10$ ,  $N=98$ ) (Figure 6). Of the 44 tracks containing large groups (here classified as  $\geq 4$  whales per track), 35 were captured during the day and only 9 at night. These large groups were captured most often in July 2021, February-March 2022, and July 2022 (Figure 6).



**Figure 6: Number of whales per track throughout recording effort at normalized time of day.** Light gray shading denotes nighttime, while dark gray shading denotes time periods of no effort. Each point denotes one track, and color represents group size captured in that encounter.

### *ii. Cleaned Tracks*

Throughout the acoustic recording period 590 initial “raw encounters” were generated from the highpass filter and initial localization step, 162 of which were suitable for 3D localization (Table S2). Final track durations ranged from 5.5 - 45.2 minutes, with a mean of 20.2 minutes and median 18.5 minutes (Figure 7). Total duration of all recorded tracks was 54.5 hours.

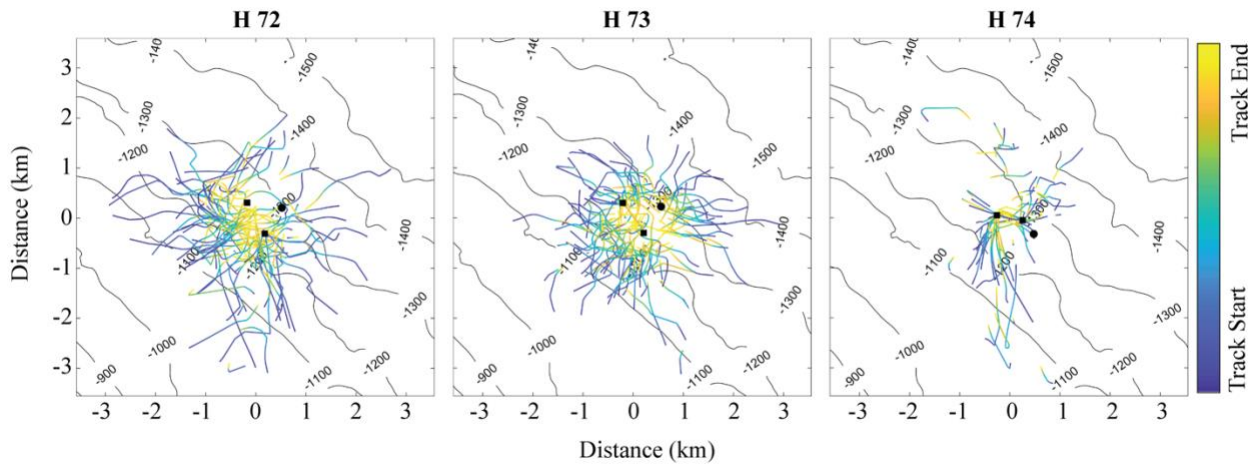


**Figure 7: Histogram of final cleaned encounter durations.**

### *iii. Track space use*

Instruments for each deployment landed in the same area, but the relative positions of each array differed more or less between deployments. Notably, the instruments at H\_74 landed almost linearly instead of the intended triangular configuration (Figure 1c). As a result, the space use of detected tracks was not the same between deployments. (Figure 8). Final tracks from all deployments show whales swimming from all directions toward the hydrophone arrays, with no apparent upslope or downslope trend for deployments H\_72 and H\_73; however, H\_74 showed a

different, more selective space use that may have originated from the modified positioning of the instruments (Figure 8). As the whales pass through the arrays, tracks end in the center. Likely the whales are continuing to echolocate, but because they are now facing away from the hydrophones the clicks are no longer received by the instruments.



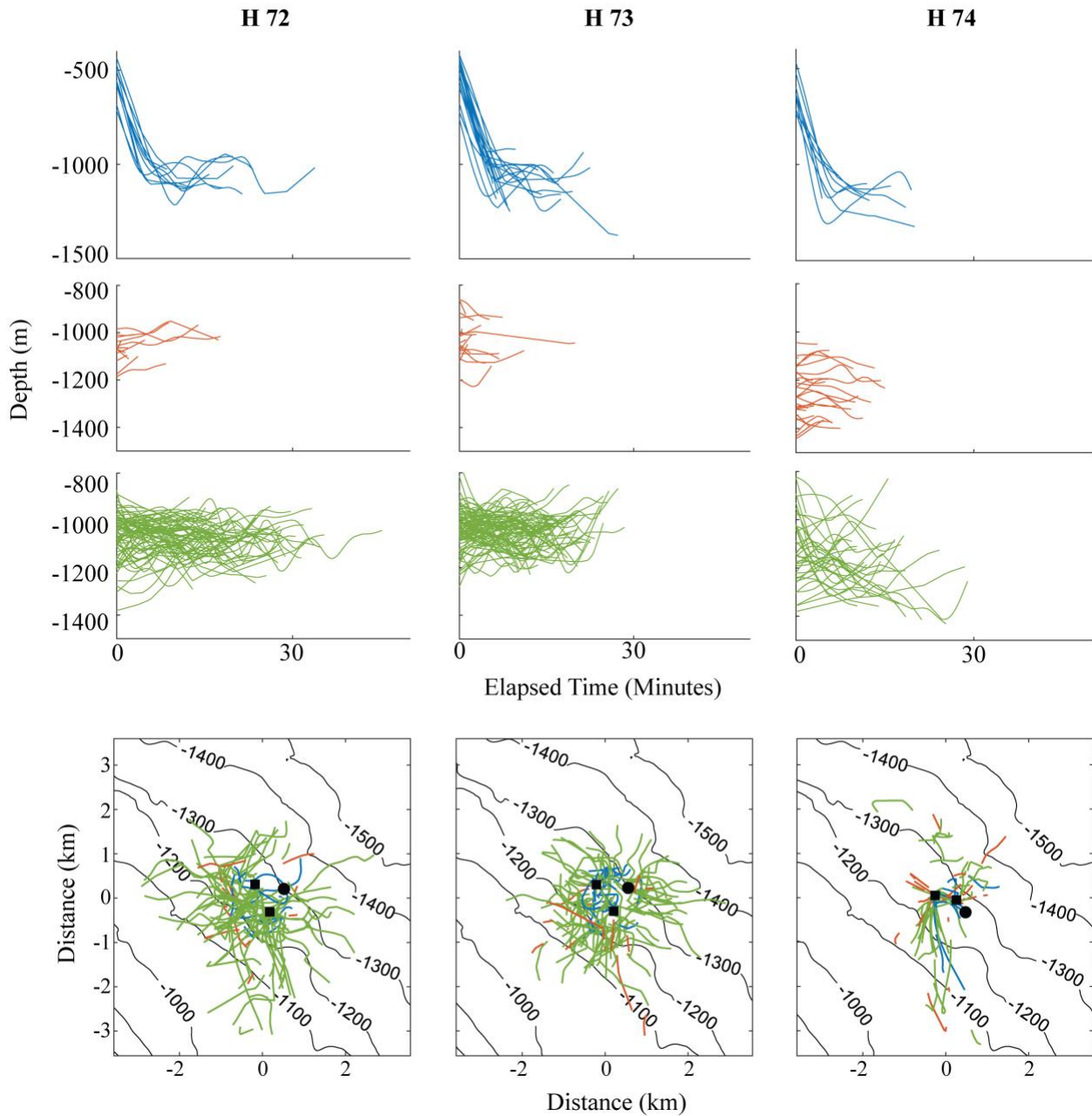
**Figure 8: Smoothed XY positions for all whales recorded throughout each deployment at SOCAL\_H.** Black square markers (■) denote positions of 4-channel arrays, and black circle markers (●) denote positions of single-channel arrays. Individual tracks are colored by normalized track time. Each deployment is shown situated within the same latitudinal and longitudinal boundaries.

#### *iv. Dive segment classifications*

Each whale within a final encounter received a dive classification. By far the most common classification was the variable trajectory segments (193 tracks), followed by consistent trajectory segments (57 tracks) and then initial descent segments (40 tracks) (Table S3). Two tracks did not fit within the classification parameters for these types and were excluded from further analysis.

The shallowest recorded dive began at 419 meters and the deepest recorded dive reached 1442 meters. Average depth was greatest for consistent trajectory segments at 1143 meters,

followed by variable trajectory segments at 1074 meters. There is no clear pattern between dive classification and XY detection area (Figure 9).



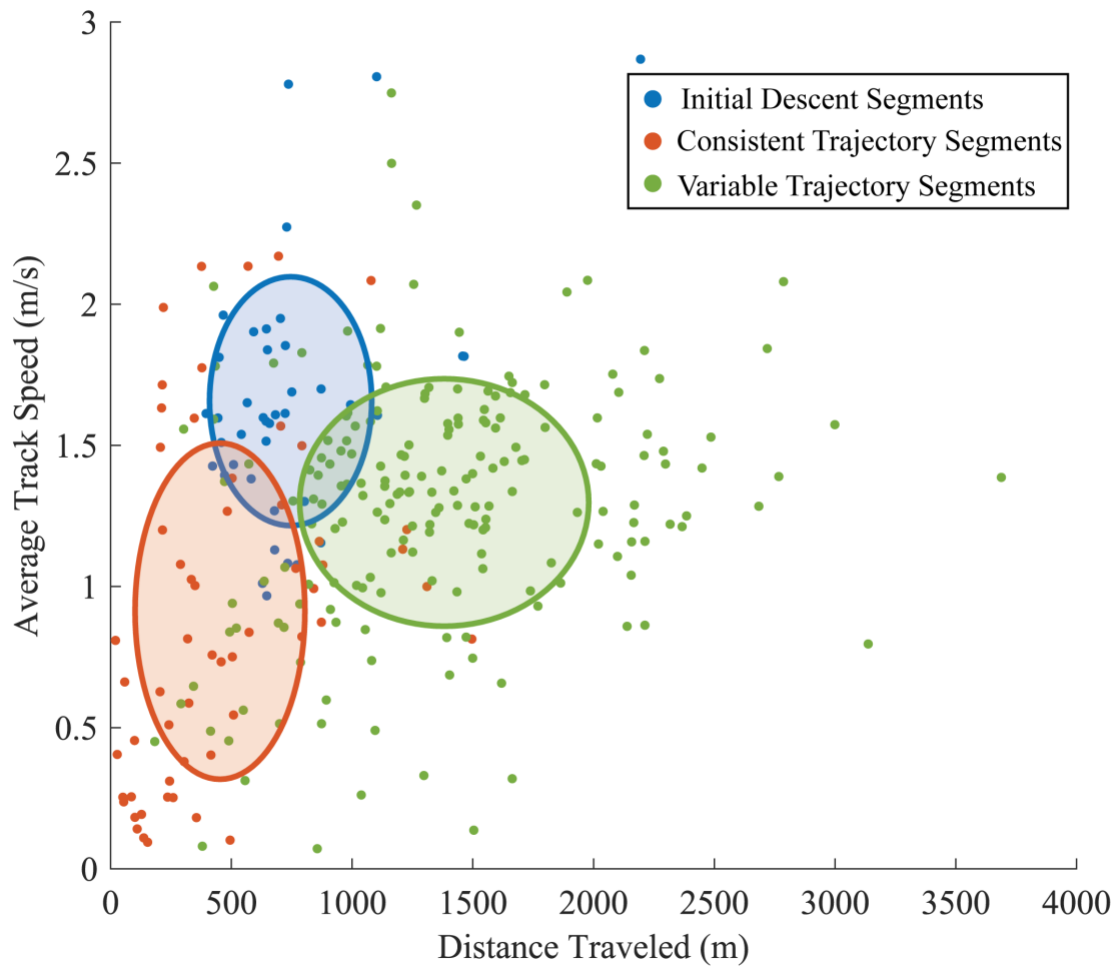
**Figure 9: Smoothed depth vs time (top) and XY positions (bottom) of all tracked whales per deployment.** Blue are initial descent segments, red are consistent trajectory segments, and green are variable trajectory segments. Black square markers (■) denote positions of 4-channel arrays, and black circle markers (●) denote positions of single-channel arrays.

*v. Swim speed and distance estimation*

Speed estimates, change in speed throughout track, and distance traveled were averaged per dive segment type. For initial descent segments, only the portion of the track where the whale was actively descending from the surface was included (Table 3). The fastest average dive speed was from initial descent segments, and the slowest from consistent trajectory segments. Variable trajectory segments had the largest change in speed throughout the track (Table 3). Variable trajectory segments traveled on average the furthest distance and were captured for the longest duration, and consistent trajectory segments traveled on average the shortest distance and were captured for a shorter duration (Table 3; Figure 10).

**Table 3: Average and standard deviations of speed, change in speed, and distance per dive type.** For average track speed, individual tracks (regardless of duration) are weighted equally per segment type.

	<b>Initial Descent Segments</b>	<b>Consistent Trajectory Segments</b>	<b>Variable Trajectory Segments</b>
<b>Track Speed (m/s)</b>	1.7 ± 0.4	0.9 ± 0.6	1.3 ± 0.4
<b>Track Change in Speed (m/s)</b>	0.8 ± 0.5	0.6 ± 0.7	1.0 ± 0.6
<b>Track Distance (m)</b>	745.6 ± 335.8	453.1 ± 351.6	1381.5 ± 598.5
<b>Track Duration (minutes)</b>	5.3 ± 2.8	6.1 ± 4.7	17.1 ± 7.1



**Figure 10: Distance traveled vs track speed of all samples for each dive segment type.** Shaded ellipses for each dive segment type are centered at the average values and delineate one standard deviation in each dimension.

## DISCUSSION

### *i. Group size*

For this analysis, group size values were obtained by counting the number of individually labeled whales per encounter. Although whales captured in the same encounter were often clicking simultaneously, there were some occasions where individual whales were detected passing the arrays within three minutes of one another. It is impossible to know whether these individuals are truly affiliated with one another or happen to be conducting separate foraging dives in the same area close together in time. There is also the possibility that these detections are from the same whale circling back around, but this seemed less likely upon manual review due to the positions of the separately labeled detections. There were also many occasions where one or more whales in an encounter were only recorded on one of the four channel arrays, so a 3D position could not be obtained. In these cases, distances between individual whales could not be verified. In future analyses, only including whales that exhibited simultaneous temporal and spatial overlap would allow higher confidence that those whales were affiliated with one another. It is also possible that more whales may have been present that were not clicking or were oriented such that the clicks were not detected on either 4-channel array. This could lead to underestimates of group size.

Groups of four or more individuals were not uncommon in the data; this is consistent with sighting data from this same region (Falcone et al., 2009; Curtis et al., 2021) and indicates that the San Nicholas basin is an important habitat for Cuvier's beaked whales. Some individuals have been resighted in this basin for multiple years, while others are only sighted once (Falcone et al., 2009; Curtis et al., 2021). One hypothesis is that multiple Cuvier's beaked whale populations overlap in this region, perhaps a resident population there year-round and a transient

population that visits intermittently. This may explain the biannual group size peaks observed from these tracks if members of a transient population travel in larger groups than a resident population but is not testable using this dataset. Future research using methods like sighting photo-identification, tagging, and genetic sampling is necessary to determine if there are multiple Cuvier's beaked whale populations in this region.

Prey availability may also be driving the observed changes in group size. Perhaps higher abundances of prey can sustain higher numbers of whales foraging individually in the same region, or perhaps lower abundances of prey make collaborative foraging more advantageous. Both situations could lead to an increase in group size per encounter. To test these hypotheses, prey abundances could be estimated by modeling with oceanographic variables, or directly measured using frequent net tows or active acoustic data.

There is also a diel pattern in group size—of the tracks with four or more whales, by far the majority were recorded during the day. Previous research has shown that Cuvier's beaked whales spend less time at the surface and ascend slower during the day (Barlow et al., 2020) as a possible predator avoidance strategy (Aguilar de Soto et al., 2020). A possible explanation for the diel trend in group size is that forming larger groups during the day may provide safety from visual surface predators. *Orcinus orca* have occasionally been documented in the region (Simonis et al., 2012), but it is unknown whether any were present during this study period.

*Carcharodon carcharias*, white sharks, are known to occupy the coastal waters of the southern California Bight (Klimley 1985). Adult white sharks are predators of marine mammals including small cetaceans and have been documented to attack Cuvier's beaked whales (Long & Jones, 1996). The Channel Islands are known pinniped rookeries, and adult white sharks commonly prey on pinnipeds in the region (Weller 2009). Seasonal peaks observed in Cuvier's

beaked whale group size during this analysis coincide with pinniped pupping seasons in the Channel Islands: elephant seal pupping in February, harbor seal pupping in March, and California sea lion pupping in June and July (Odell 1971; Heath 1989). One hypothesis is that the high concentration of pinnipeds in the region attracts white sharks, who may also prey on Cuvier's beaked whales, and the behavioral response is to increase group size during the day at these times of years to protect against these visual predators. To test this hypothesis, more information is needed on adult white shark distribution and migration patterns in the region and on the relationship between white sharks and Cuvier's beaked whales.

## *ii. Cleaned tracks*

Most of the tracks in this analysis were too short to process to final tracks because the whales were too far from one or both 4-channel arrays to capture many echolocation clicks. This may be because Cuvier's beaked whale encounter times were determined using the single-channel array, which is about a kilometer away from the 4-channels. This is especially apparent in deployment H\_74, where the single-channel landed much closer to one 4-channel than the other. In future applications of this method, it might be better to detect beaked whales on the 4-channels directly. This would be an especially good approach if the 4-channels had a high enough sampling rate to capture the full frequency range of the Cuvier's beaked whale echolocation click.

Delphinid detections obscured beaked whale detections that otherwise may have been tracked. In future analyses where initial detection was performed on single-channel instrument data, a second neural network step could be added after running the detector on the 4-channel data to identify and remove dolphin clicks. This would allow only beaked whale

detections to be plotted during encounters that also captured dolphins, salvaging these encounters and making manual cleaning more straightforward.

### *iii. Dive segment classifications*

All tracks from this analysis represent segments of deep foraging dives. Although individual tracks were given specific classifications, it is likely that a single whale will exhibit multiple or all of these behaviors during a single deep foraging dive. Dive classifications in this analysis were determined through patterns noticed in manual track analysis, but in future research a clustering algorithm like that which has been applied to dolphin whistles (Frasier et al., 2016) could be applied to identify more specific patterns.

Tracks classified as initial descent segments likely represent the beginning of deep foraging dives because of the steep angle at which whales are diving from the surface. These dive segments capture whales swimming from 400 – 600 meters depth to 1000 meters or deeper. This is consistent with tag data showing Cuvier's beaked whales beginning echolocation at around 500 meters depth as they begin a deep foraging dive (Tyack et al., 2006).

Tracks classified as consistent trajectory segments were characterized by a lack of lateral or vertical movement at depth. One hypothesis is that the whales are transiting in search of a prey patch but not actively closing in on prey targets. This track segment type covered the shortest average distance, and a much shorter duration than variable trajectory segment types, so it is possible that these tracks did not capture as much data as others and are lacking behavioral context (Table 3).

Tracks classified as variable trajectory segments were characterized by large vertical or lateral movements at depth. Tag data indicates that vertical depth inflections during a deep

foraging dive at depth represent prey chases (Baird et al., 2006; Tyack et al., 2006). Other localization studies have reported similar vertical and lateral movements at depth (Barlow et al., 2018; Gassman et al., 2015; Jang et al., 2023). This dive classification is the most common and indicates that prey is plentiful in the region, explaining why there are high abundances of Cuvier's beaked whales and a possible resident population. To confirm that variable trajectory tracks capture prey chases, future analyses could search for buzzes. Cuvier's beaked whales are known to produce buzzes immediately before prey capture events (Tyack et al., 2006), so identifying them in these tracks would confirm that these dive segments capture prey chases.

It is important to note that this data was collected within the bounds of a naval range, and that the Cuvier's beaked whales were likely exposed to anthropogenic noise during the study period. This analysis did not explore if tracks were recorded during naval exercises, or if behaviors changed during or after exposure to anthropogenic noise. Future research using data from this site would benefit from exploring this possibility.

#### *iv. Swim speeds*

The swim speeds estimated from these tracks are consistent with previous estimates of Cuvier's beaked whale swim speeds (Tyack et al., 2006; Joyce et al., 2017; Shearer et al., 2019; Barlow et al., 2020).

It is important to note that swim speeds estimated in this analysis were obtained from smoothed whale positions which interpolated over detection gaps up to a few minutes in duration. The spline fit could have smoothed out small changes in direction, causing an underestimate in swim speed.

Initial dive segments were on average the fastest dive classification which is consistent with tagging data (Tyack et al., 2006; Baird et al., 2006). Consistent trajectory tracks were on average the slowest dive classification, while variable trajectory tracks had the largest average change in speed throughout the tracks. This is consistent with the hypothesis that variable trajectory tracks include prey chases, since quick changes in speed and direction are necessary for a successful prey capture.

## CONCLUSION

This approach yielded, to our knowledge, the longest continuous passive acoustic tracking dataset of Cuvier's beaked whales. Data on deep foraging dives was captured from many individuals, sometimes simultaneously, at a long-term acoustic monitoring site.

Diel and biannual increases in group size show that the intraspecies associations between individual Cuvier's beaked whales change regularly for unknown purposes. Future research using genetic, sighting, and tagging data is needed to confirm if these detections belong to whales from the same population. Information about prey availability using active acoustics or regular net tows, as well as information about predator distribution, might explain these group size trends. Continuing to track Cuvier's beaked whales using acoustic arrays in this region can confirm if these trends continue in future years.

This method collected information from Cuvier's beaked whale deep foraging dives and identified three distinct recurring behaviors using initial track depth, vertical movement, and lateral movement. We captured the initial descents of deep foraging dives, hypothesized transiting or prey searching behavior, and assumed prey chases. These tracks suggest that the San Nicholas basin is an important foraging spot for Cuvier's beaked whales in the region.

This study uniquely monitored deep foraging dive behavior from many individual Cuvier's beaked whales in the Southern California Bight for over a year. This approach requires less fieldwork, is less invasive, and yields data from more individuals than traditional tagging methods. The information gained from this study is key to understanding the social and foraging behavior of Cuvier's beaked whales in the region and gives new insight into the deep-sea ecosystems that they belong to.

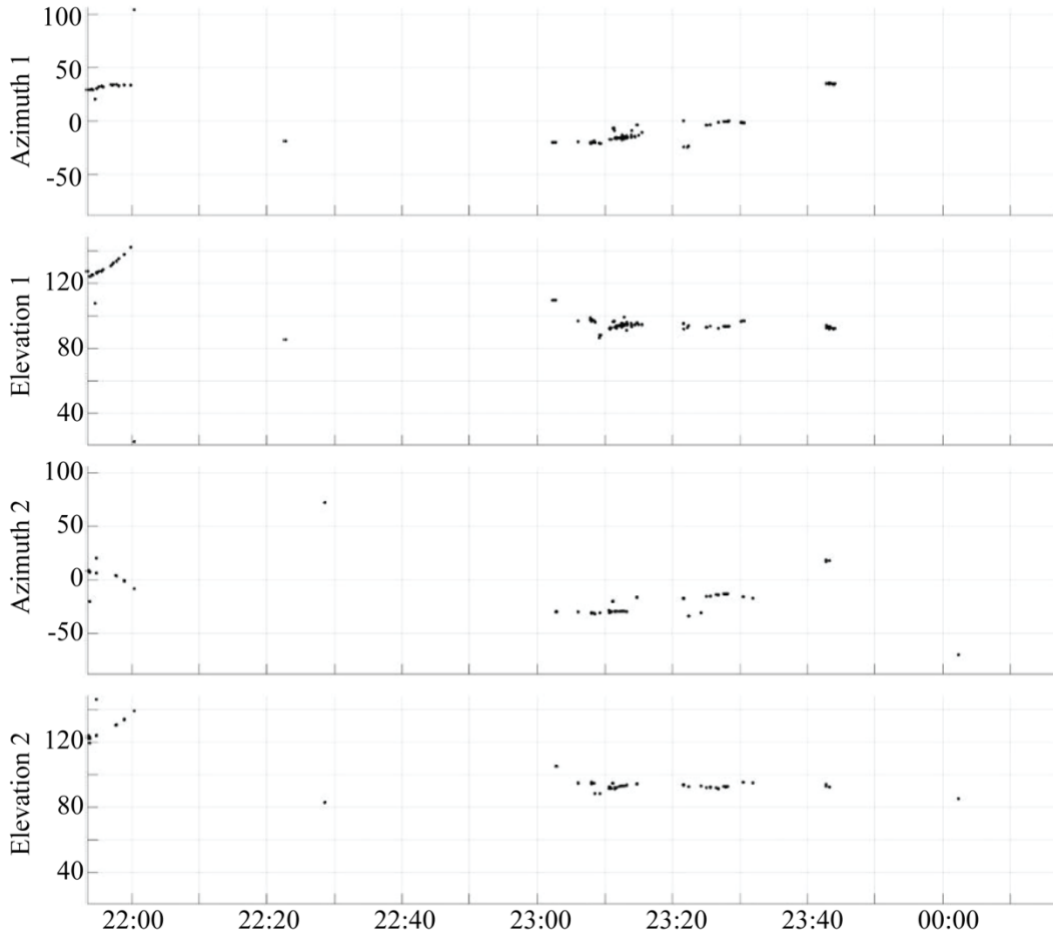
## ACKNOWLEDGEMENTS

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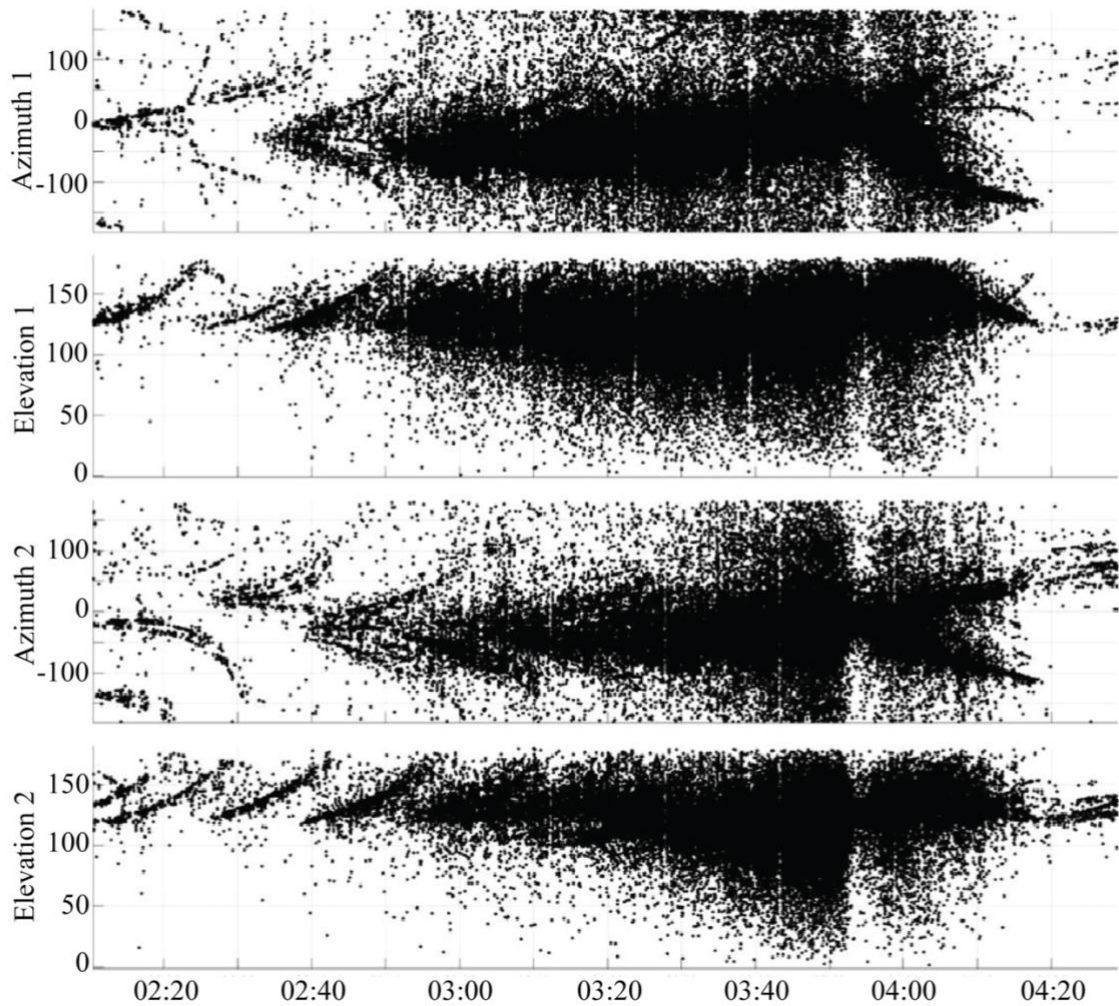
APPENDIX

**Table S1: Sound speeds calculated from CTD casts per deployment.** Average sound speed (m/s) below 700 meters and standard deviation.

Date of CTD cast	Corresponding Deployment	Sound speed (m/s)
July 29, 2021	SOCAL_H_72	1483.6 ± 0.2
December 19, 2021	SOCAL_H_73	1484.7 ± 1.7
October 15, 2022	SOCAL_H_74	1482.8 ± 1.3



**Figure S1: Example of a short track on the brushDOA interface.** The top figures show azimuth and elevation from the first 4-channel system over time, and the bottom figures show azimuth and elevation from the second 4-channel system over time. This track was classified as too short because it contained less than 400 detections.



**Figure S2: Example of an encounter with many Delphinid detections.** The top figures show azimuth and elevation from the first 4-channel system, and the bottom figures show azimuth and elevation from the second 4-channel system. This encounter is crowded with dolphin vocalizations that obscure any beaked whale detections. The detections are identifiable as dolphins because of the wide spread in azimuth and elevation values, indicating a large number of individuals spread out over a broad area.

**Table S2: Final encounter classifications.** Raw encounters are the initial encounters straight from the detector, short encounters have <400 clicks or are <10 minutes, and Delphinid encounters have Delphinid detections obscuring Zc clicks. Final encounters were successfully cleaned and localized in 3D.

<b>Deployment</b>	<b># Raw Encounters</b>	<b># Short Encounters</b>	<b># Delphinid Encounters</b>	<b># Final Encounters</b>
SOCAL_H_72	189	95	38	56
SOCAL_H_73	202	127	18	57
SOCAL_H_74	199	120	30	49
Total	590	342	86	162

**Table S3: Number of tracked whales assigned to each dive segment type, per deployment.**

<b>Deployment</b>	<b>Segment Type 1</b>	<b>Segment Type 2</b>	<b>Segment Type 3</b>
SOCAL_H_72	11	13	74
SOCAL_H_73	20	17	84
SOCAL_H_74	9	27	35
Total	40	57	193

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