Beaked Whale Passive Acoustic Tracking

Offshore of Cape Hatteras 2017

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MPL Technical Memorandum 631
October, 2018
June 3, 2020, smw updated with new link for mp4 movies page 18.

Suggested Citation:

Wiggins, S. M, Thayre, B. J., Trickey, J. S., Baumann-Pickering, S., Hildebrand. J. A. "Beaked Whale Passive Acoustic Tracking offshore of Cape Hatteras 2017," Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, MPL Technical Memorandum 631 October 2018. Submitted to Naval Facilities Engineering Command (NAVFAC) Atlantic, Norfolk, Virginia, under Contract No. N62470-15-D-8006 Subcontract #383-8476 (MSA2015-1176 Task Order 003) issued to HDR, Inc.

Additional information on previous HARP deployments and availability of all associated reports can be found on the project profile page of the U.S. Navy's Marine Species Monitoring Program web portal.

This project is funded by US Fleet Forces Command and managed by Naval Facilities Engineering Command Atlantic as part of the US Navy's Marine Species Monitoring Program.

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Executive Summary

An array of passive acoustic monitoring recorders was deployed during May 2017 in the US Navy's Virginia Capes Range Complex offshore of Cape Hatteras to track marine mammals. The tracking array was configured as a large aperture array with three recorders at triangle vertices approximately 700 m apart. Two recorders were each outfitted with four hydrophones arranged in tetrahedron volumetric arrays with ~1 m sensor spacing; whereas the third recorder used one hydrophone. The two 4-hydrophone small aperture arrays were used to track the focus species, beaked whales.

Acoustic-Global Positioning System surveys were conducted to resolve seafloor-mounted recorder positions to within several meters, and to provide known source locations for adjusting the tetrahedron array attitudes so that animal localizations could be spatially related and geo-referenced.

New software tools were developed to more easily identify periods of concurrent beaked whale encounters on the two tetrahedron array recorders, in addition to new tracking data processing tools for removing noise, identifying and sorting individual sources, estimating locations, assembly tracks from successive locations, providing three-dimensional view maps and time-lapse movies of tracks.

A Cuvier's beaked whale encounter spanning 30 minutes was processed and evaluated in which three animals were tracked independently and found to travel down slope and over a seafloor ridge for more than 1 km. The tracks show an initial dive near the seafloor with some additional up and down movements along the tracks, and while the general track directions are similar, the swimming behavior of the three animal tracks are not identical nor synchronized.

Project Background

The US Navy's Virginia Capes Range Complex is located in the coastal and offshore waters of the western North Atlantic Ocean, offshore of Delaware, Maryland, Virginia, and North Carolina. The seafloor features a broad continental shelf (<200 m deep), and an outer zone extending to depths >2000 m. A diverse assemblage of marine mammals is found in this region, including baleen and toothed whales.

In March 2012, a passive acoustic monitoring effort was initiated within the boundaries of the Virginia Capes Range Complex at HAT site A (Figure 1, orange circle) with support from US Fleet Forces under contract to HDR and Duke University with the goal of monitoring marine mammal vocalization in the area. From this effort several beaked whale species have been detected, including high numbers of Cuvier's (~25 hrs/week) and Gervais' (~5 hrs/week) beaked whales (Frasier *et al.*, 2017; Rafter *et al.*, 2018).

This report documents beaked whale tracking efforts at a new location HAT site B (Figure 1, yellow square) at ~1100 m depth where an array of passive acoustic monitoring instruments was deployed in May 2017.

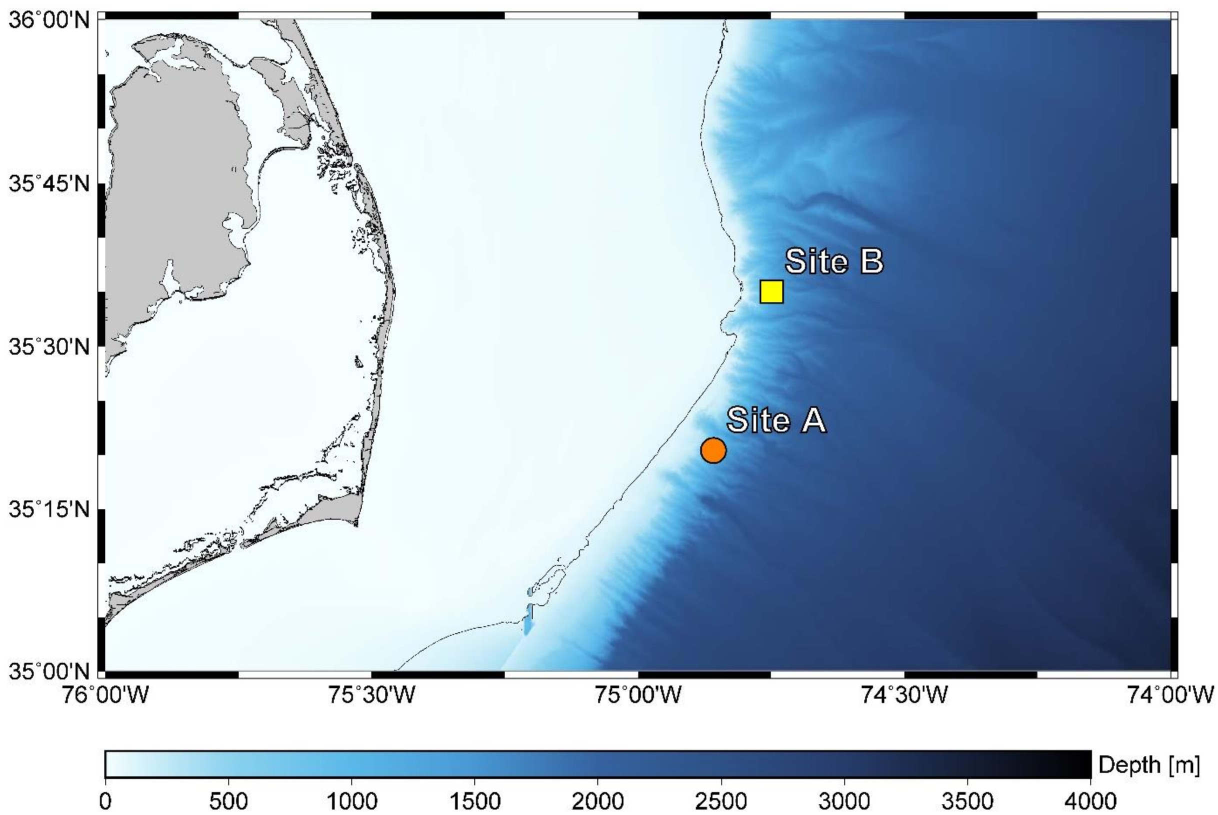


Figure 1. Regional map offshore of Cape Hatteras.
Sites HAT_A and HAT_B are designated by orange circle and yellow square, respectively. Thin black line is the 100 m depth contour, darker colors are deeper. Bathymetry data from Ryan et al. (2009).

Methods

Passive acoustic monitoring instruments and tracking arrays

On 9 May 2017, marine mammal passive acoustic monitoring and tracking was initiated at HAT site B (~35° 35'N, 74° 45'W), about 28 km northeast of HAT site A. Three High-frequency Acoustic Recording Packages (HARPs) were deployed for monitoring and tracking at site B, in two different configurations: one instrument as a single hydrophone sampling at 200 kHz (Figure 2 - left; Wiggins and Hildebrand, 2007), and the other two using four-hydrophones arranged in a small aperture (~1 m) array sampling at 100 kHz for each hydrophone (Figure 2 – right; Wiggins *et al.*, 2012). The three instruments were deployed to ~1100 m depth as a large aperture (~700 m) array (Figure 3) with the two four-hydrophone instruments recording continuously for 50 days each and the single-hydrophone instrument recording continuously for 169 days.

The large aperture array allows for tracking nearly omni-directional sounds such as baleen whale calls and dolphin whistles (e.g., Wiggins *et al.*, 2013; Varga *et al.*, 2018), and in some cases, intense directional signals, for instance, sperm whale and beaked whale echolocation clicks (e.g., Nosal and Frazer, 2007; Gassmann *et al.*, 2015). To localize sound sources in and around a large aperture array, the arrival time of the source signal is measured at each site hydrophone and differenced with each other site to provide site-pairs of Time Difference of Arrivals (TDOAs). The measured TDOAs are compared to modeled TDOAs at each location in a Cartesian gridded model to find the source location that produces the least amount of misfit between the measured and modeled TDOAs. Successive locations in near proximity are interpreted as tracks.

Sound source location precision is dependent on intra-instrument clock synchrony and site location precision. Immediately prior to deployment, each instrument clock was set with a high precision (100 ns) global positioning systems (GPS) reference clock, and upon recover, instrument clock drift was measured with the reference clock. Typical clock drifts are ~10^{-8} s/s.

To localize the seafloor instruments with a few meters of uncertainty, an acoustic-GPS survey was conducted from the instrument deployment and/or recovery vessels by concurrently collecting GPS positions and acoustic transponder ping two-way travel times between the ship and the seafloor instrument as the ship transited above the instrument. To provide good geometry for constraining instrument localization, the ship track was along an approximately circular path with a radius of about one water depth and crossed over the top of the instrument drop location. For each site survey, the acoustic ping two-way travel times, a sound speed of 1500 m s^{-1}, and GPS positions were used iteratively in an equal-weighted, least-squares inverse process to adjust the estimates of the seafloor instrument locations. Outlier two-way travel times from bad pings were removed via a two-step filtering process.

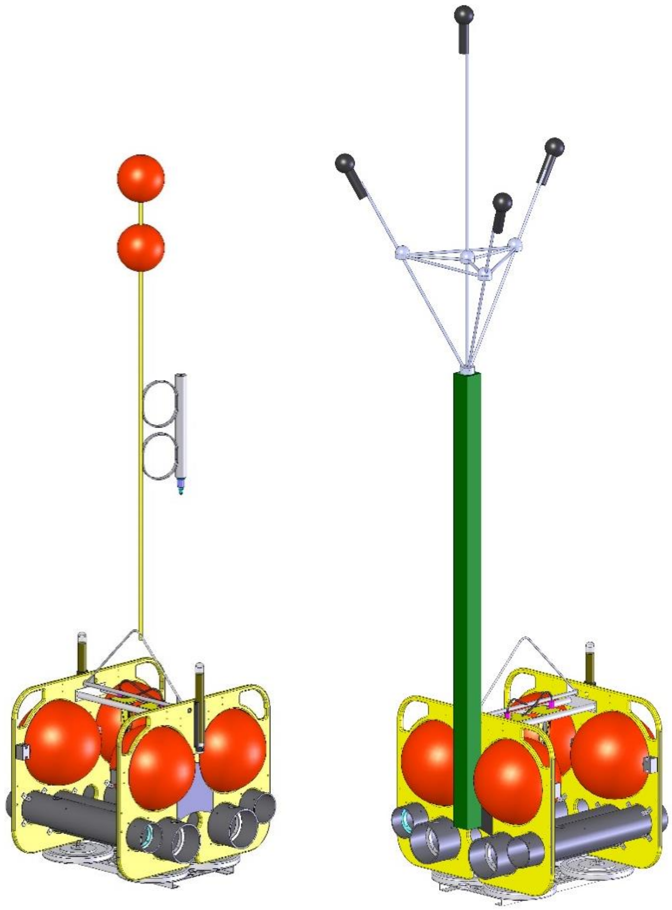


*Figure 2. High-frequency Acoustic Recording Package (HARP) configurations.
Orange spheres are flotation, black horizontal tubes are for data logger electronics and battery pressure housings, gray ballast weights are on the bottom of the yellow plastic frames, and hydrophones are above seafloor package. Standard seafloor-mounted HARP with one hydrophone tethered ~10 m above the seafloor (left), and Tracking HARP with four hydrophones arranged in a tetrahedron with ~1 m sensor spacing on a post ~5 m above the seafloor (right).*

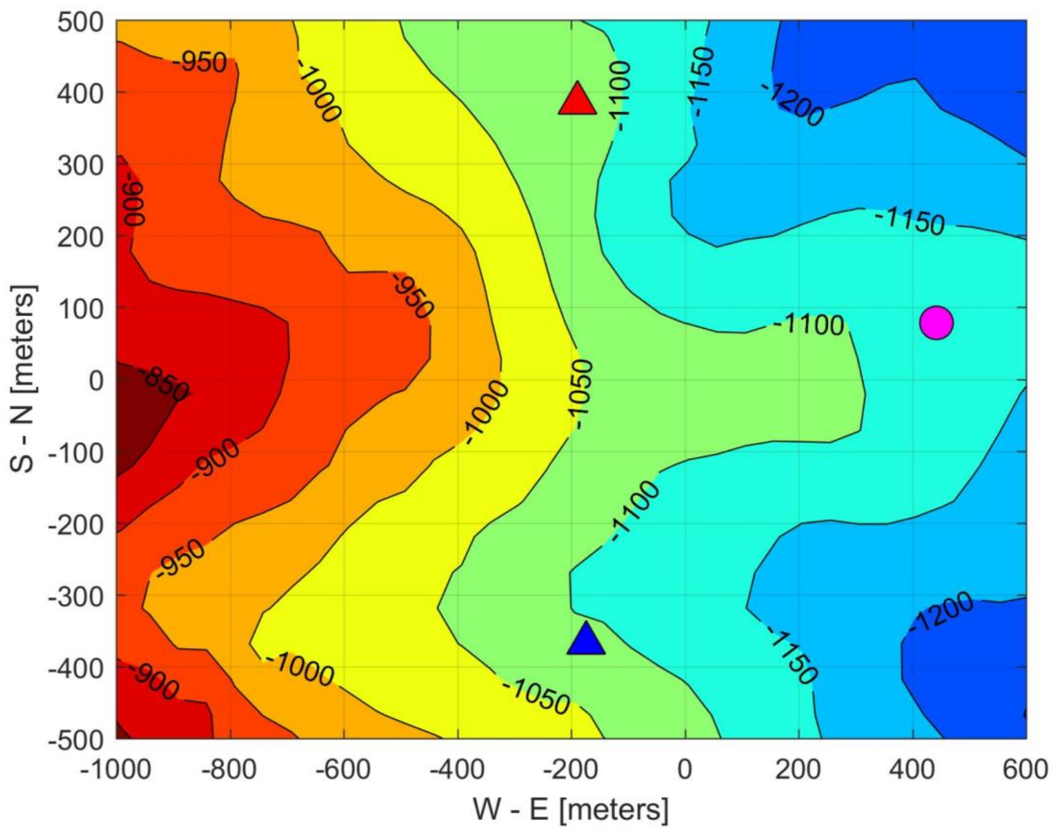


Figure 3. HAT site B_01 passive acoustic monitoring array map.
Instrument locations are from acoustic-GPS survey and local seafloor bathymetry map is from Ryan et al. (2009). Magenta circle on the east side of the large aperture array represents a single hydrophone instrument; whereas, the blue and red triangles on the west were 4-hydrophone small aperture array instruments. Contours are at 50 m increments, with cooler colors to the east deeper.

Small aperture tracking array

Similar to the large aperture array, signal TDOAs between hydrophone sensor pairs in the individual instrument small aperture arrays are measured and fitted to modeled TDOAs to provide information about a source location; however, the Cartesian coordinates xyz source location is not directly estimated, but rather the spherical coordinates azimuth and elevation angles (AZELs) to the distant source are estimated. Range to the sound source can be estimated by fixing the source depth or elevation above the seafloor, by cross-fixing with other AZELs from nearby small aperture arrays, or by combining small aperture array TDOAs with array-proportionate weighted large aperture array TDOAs during the least-squares fitting process. Other techniques, such as the use of Kalman filters or using known swimming behaviors, may provide additional constraints to estimate tracks.

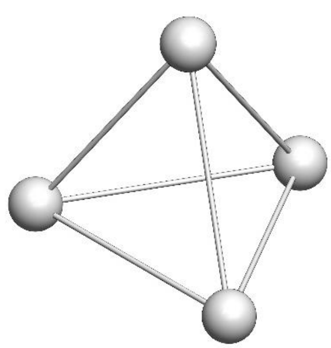
Also similar to the large aperture array, precise hydrophone location and synchronization of recorded hydrophone waveforms are also required for providing good estimates of sound source direction AZELs, although these parameters are much more easily determined with small aperture arrays where hydrophone pair distances are measured with a tape measure (± 0.01 m) and timing between sensors is at most one-half of a sample interval (5 µs for this array) because all four hydrophone signals are digitized by the same analog-to-digital converter (ADC).

Four hydrophones in an array provide six unique hydrophone pairs and TDOAs (2-1, 3-1, 4-1, 3-2, 4-2, and 4-3) each which were transformed by a direction cosine matrix using the order roll-pitch-yaw to the x-axis to estimate the sound source directional angle, γ, to the incoming plane wave which is related to the sensor spacing d, TDOA δT, and ocean sound speed v, by

$$\gamma = cos^{-1}\left(\frac{v * \ \delta T}{d}\right)$$

(Figure 4). Instead of using a Cartesian grid to model TDOAs, a unit sphere with grid points at one degree increments in azimuth and elevation was used (i.e., 360 x 180) where six TDOAs were calculated for each AZEL grid point using the direction cosine matrix. Sets of six measured TDOAs were differenced, summed and squared with calculated TDOAs at each sphere model grid point to provide a measure of fit with the minimum providing an estimate of the AZEL for each measured set of TDOAs (i.e., least-squares fit minimization).

Measured TDOAs were estimated as the peak of the time-domain cross-correlation of hydrophone-pair recordings over specified periods. For short duration events, such as beaked whale pulses, a high-frequency pass filter and a simple energy detector were used to detect individual pulses on the highest hydrophone. For beaked whales, a 20 kHz high pass filter was used and 1 ms windows before and after the pulse were used to define the period for the cross-correlations. A 30 ms delay was used before allowing another pulse detection to reduce noise from reflected signals.



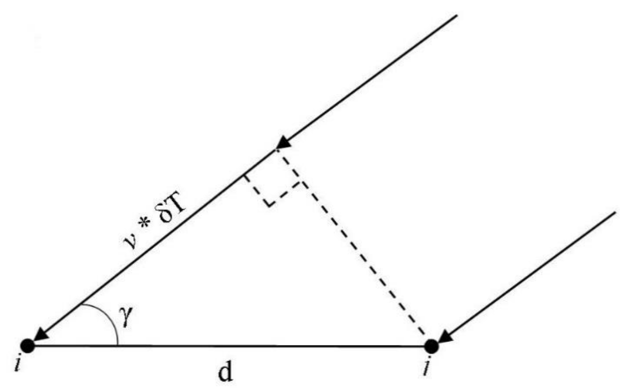


Figure 4. Small aperture hydrophone array geometry.
Tetrahedron with six unique hydrophone pairs (right). Each hydrophone pairs was transformed by a direction cosine matrix on to the x-axis (left) so that sets of six plane-wave time difference of arrivals (TDOAs) could be modeled to provide azimuthal and elevation angles to source locations.

Compass and tilt sensors were not attached to the four-hydrophone instruments, so the tetrahedron array attitude (roll, pitch, and yaw) of each instrument needed to be resolved before any resulting tracks could be mapped into real-world coordinates or combined with other instrument tracking data. The attitudes of the small aperture arrays were determined by using ship propulsion sounds recorded during the acoustic-GPS instrument localization surveys. Cross-correlation TDOAs were calculated from 1 s windows and 100 – 10,000 Hz bandpass filtered waveforms and were differenced and minimized with the TDOA sphere model to estimate AZELs. The measured TDOA time series were interpolated when gaps were present, and smoothed by applying a running average filter and by removing outliers. The resulting AZELs were compared to the azimuth and elevation angles calculated from the ship GPS locations and the array attitude was analyst-adjusted for a best-fit.

Two different synthetic ship tracks are provided to show how locations in the Cartesian coordinate system map into TDOA-space and the spherical coordinate angles, AZELs (Figs. 5 and 6). In both examples, the small aperture array is at 1000 m depth, the ship sound source is on the sea surface (i.e., 0 m depth), the ship transit time is 20 minutes, and the array attitude is 0° roll, 0° pitch, and 0° yaw. In the first example (Figure 5), the ship travels along a circle with a radius equal to the water depth such that the azimuth angle to the array changes at a constant rate from -180° to 180° and the elevation angle is constant. The TDOAs appear sinusoidal with the hydrophone pairs of the horizontal plane of the tetrahedron array having the greatest change; whereas, the TDOAs associated with the top vertex sensor have smaller changes. In the second example (Figure 6), the ship travels a straight path over the top of the array along the diagonal of the map and the azimuth is a step function from -135° to 45° and the elevation angle increases non-linearly from about 20° to 90° when directly overhead. The TDOAs appear less sinusoidal and flatter than the circle path example, except when the ship is passing overhead the array, where most of the TDOAs change sign. More complicated source paths typically result in more complicated TDOA and AZEL time series.

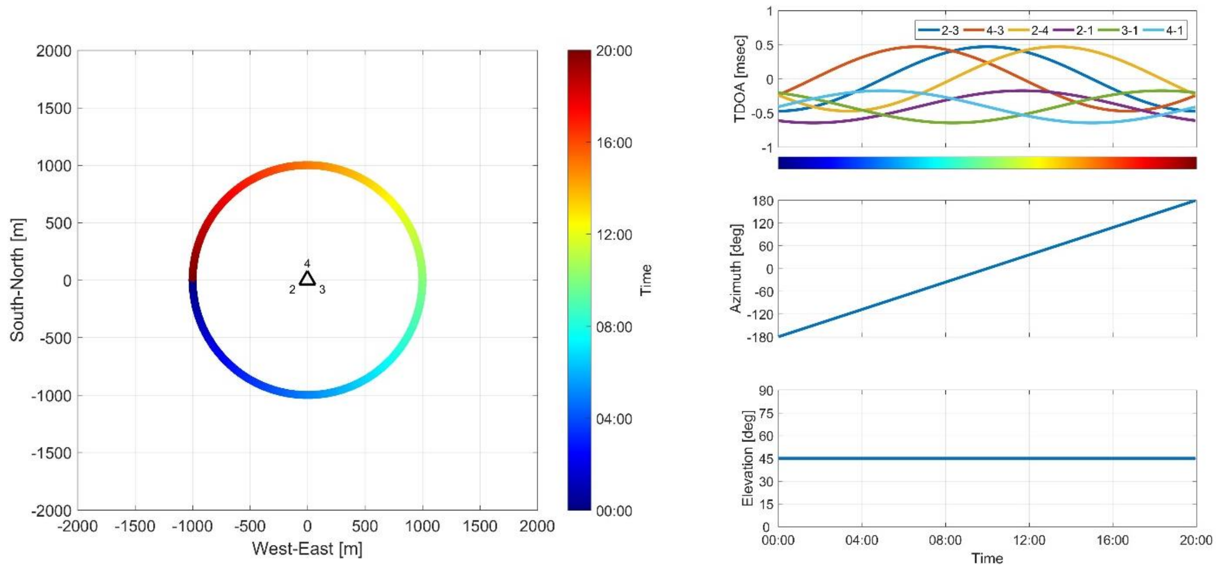


Figure 5. Map view of example circular source path.
Color path at sea surface corresponds to time colorbar with Tracking HARP at 1000 meter depth (right). Resulting TDOA, azimuthal and elevation time series (left).

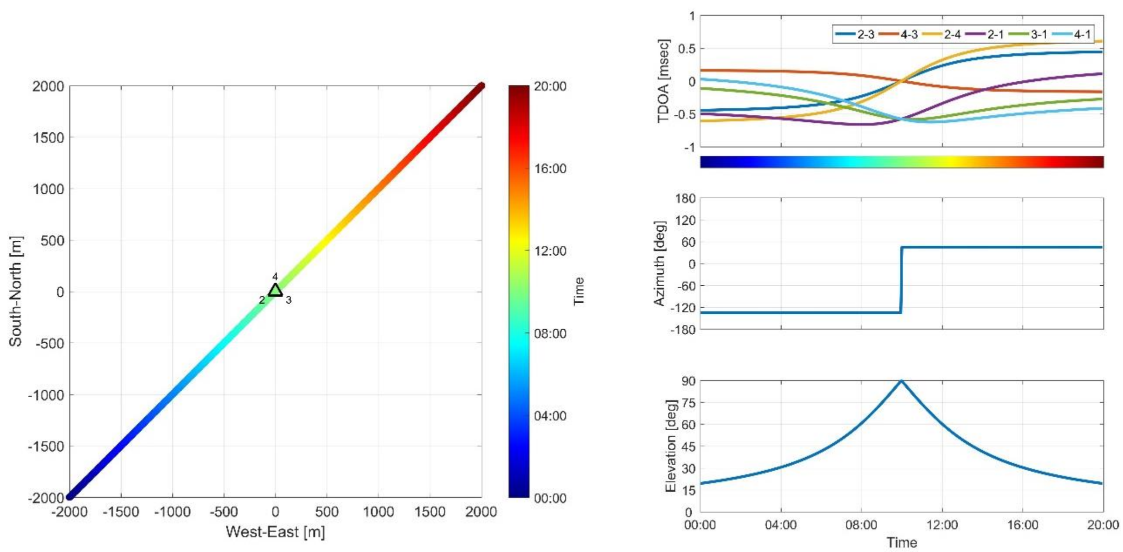


Figure 6. Map view of example linear source path.
Color path at sea surface corresponds to time colorbar with Tracking HARP at 1000 meter depth (right). Resulting TDOA, azimuthal and elevation time series (left).

Identifying periods for marine mammal tracking

The highest quality marine mammal acoustic localizations and tracks will be possible when each signal is received at all instruments in an array; however, this constraint is often difficult to meet with odontocete echolocation clicks because their signals' high directionality reduce the likelihood of individual signals being received at multiple instruments and their high frequencies attenuate rapidly with distance. For example, with beaked whales traveling near the seafloor, Gassmann et al. (2015) showed that the best tracks were from animals heading toward or within the single-hydrophone and four-hydrophone instrument array with ~700 m aperture.

To assist with identifying periods for potential marine mammal tracking, a new tool was developed to be used with the Triton software package (Wiggins and Hildebrand, 2007). Triton was developed for analyzing HARP single- and four-hydrophone recordings, but also works with standard wav format files from other devices. Recently, Triton has been enhanced to accept user-developed 'add-on' programs dubbed Remoras. A new Remora tool was developed to display and step through time synchronized long-term spectral averages (LTSAs) and TDOAs from two four-hydrophone recordings in the same window. This provides an ability to evaluate the spectral-temporal characteristics of a given period for a specific species identification along with the quality of automatic detection TDOAs, and whether temporal overlap is sufficient to attempt tracking.

As an example, Figure 7 shows LTSAs and TDOAs from a beaked whale encounter recorded on the two four-hydrophone instruments. While the encounter spans about 30 minutes for site 02, there was only about 10 minutes of concurrent overlap of beaked whale clicks with site 03. Also note that the number of individual clicking animals at different locations can be surmised from the number of concurrent same color TDOA tracks, which appear to be two or three for this example, allowing group size to be estimated, an important parameter for density estimation.

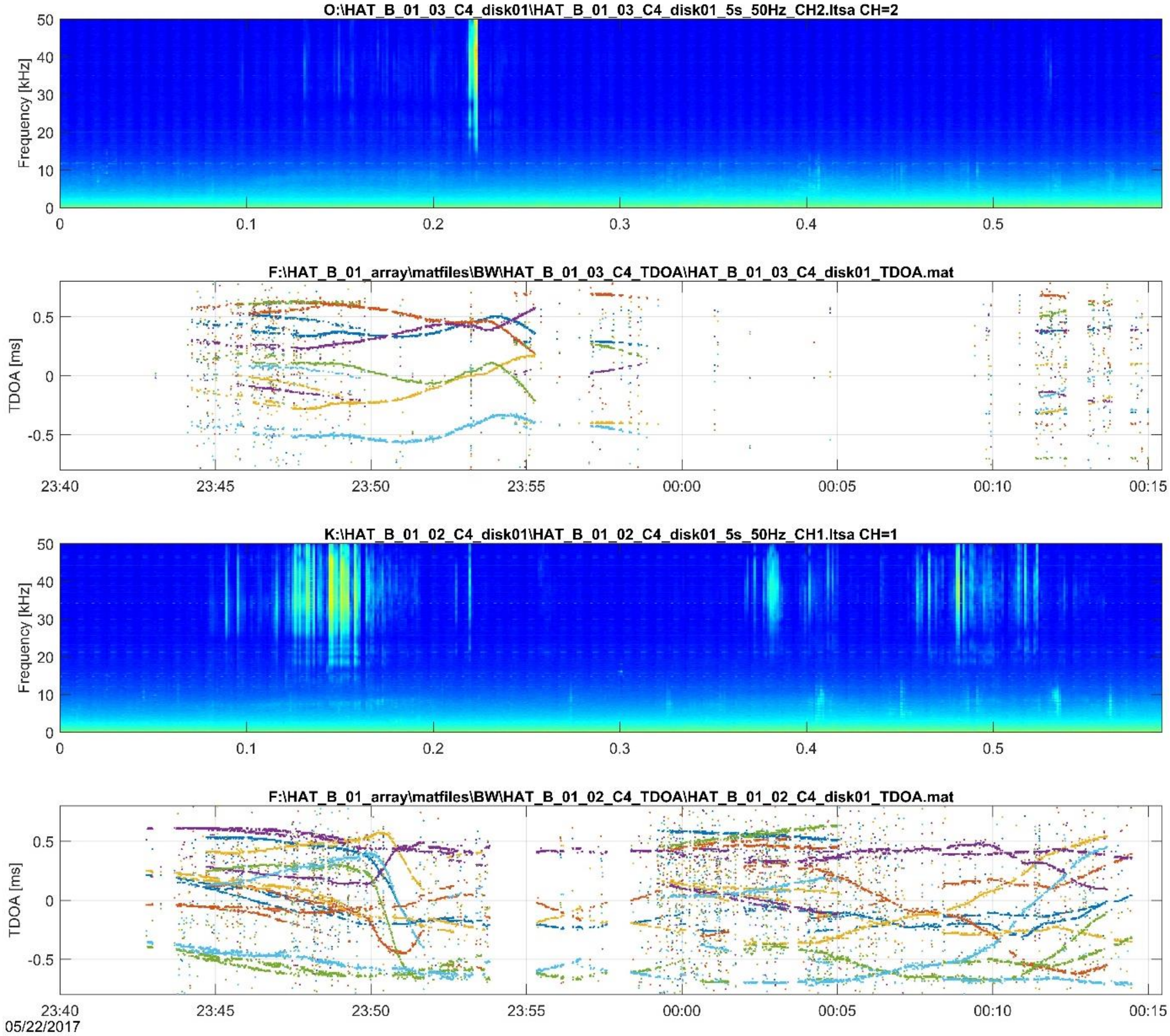


Figure 7. Example of two Tracking HARPs' synchronized LTSAs and TDOAs.
Plot window from the newly developed Triton Remora for identifying potential periods for tracking marine mammals. Long-term spectral averages (LTSAs) and time difference of arrivals (TDOAs) for the two four-hydrophone instruments at northern site 03 (top) and southern site 02 (bottom) from 22 May 2017 show a beaked whale encounter over a period of ~30 minutes. There are six TDOA colors for the six hydrophone pairs. Multiple concurrent TDOA tracks indicate individual animals at different locations.

Azimuth and elevation angles to xyz locations

Measured TDOAs transformed via the sphere model grid search minimization into AZELs typically have outliers and noise in addition to AZEL tracks from unsorted individual animals. An analyst graphical user interface (GUI) tool was developed to remove outliers and noise, and to identify and sort individual animal AZEL tracks by manually assigning different colors to noise and individual tracks in three plots: azimuth and elevation angle time series, and azimuth versus elevation angle. The spatial and temporal continuity of individual tracks in the three different plots for each recorder allows for easily identifying noise and sorting tracks to individuals.

After the AZEL tracks have been sorted, individual tracks were smoothed via a running average using windows of 15 samples and interpolated to a common time vector with steps of 1.0 s. The smoothing reduces track roughness associated with TDOA resolution restrictions and AZEL estimation uncertainty; whereas, the interpolation allows the different tracks from the different recorders to be synchronized and comparable at each discrete time step.

As shown in the previous section (Figure 7), beaked whale TDOA (and resulting AZEL) time series from two nearby small aperture tetrahedron arrays temporally overlap some of the time, but typically not all of the time. When an individual's track is concurrent between the two recorders, the two sets of measured AZELs can be "cross-fixed" to estimate xyz positions using a Cartesian xyz gridded model (5 m resolution) where two sets of modeled AZELs are calculated from each grid point to both recorder locations. The measured concurrent AZELs are compared to each model grid point AZEL set and minimized by least-squares to estimate a xyz position and successive positions form tracks.

To estimate xyz tracks for individuals when AZELs exist for only one recorder, the endpoints from the cross-fixed xyz tracks in the previous step are used as starting locations for a piecewise position estimation in which successive locations are constrained to be a specified horizontal distance from the previous location. Based on the cross-fixed tracks and previous beaked whale tracking work (Wiggins *et al.*, 2012), we chose a constant horizontal speed of 1.0 m/s to define a circle around a previous location which was intersected with the next position's azimuthal angle to estimate the next xy position. This xy position was used with the elevation angle to estimate depth (z). The process was repeated such that successive position estimates define a piecewise track, and individual animal cross-fixed tracks and piecewise tracks were combined to provide an overall track for each animal. Three-dimensional (3D view) plots and time-lapse movies of these tracks with site bathymetry provide insights to how these animals move through the study area.

Results

Large aperture array instrument localizations

Acoustic-GPS localization surveys were conducted for each of the three instruments shortly after deployment; however, the transponder two-way travel times did not provide sufficient geometric coverage to yield good localizations, so additional surveys were conducted just prior to instrument recovery which resulted in good localizations with location uncertainties between 7 and 17 m RMS (Figure 8 and Table 1). All three instruments moved similar distances northeast from their drop locations, consistent with the direction of ocean currents associated with the Gulf Stream offshore of Cape Hatteras. The two four-hydrophone instruments, sites 02 and 03, had lower location uncertainty than the single hydrophone instrument, site 01, because a different ship was used for site 01 survey which had a larger horizontal distance offset between the GPS antenna and acoustic transponder than for the other two surveys. However, the geometric coverage and the number of acoustic pings were higher for site 01 survey, and the similar shift of the instrument location from the drop location suggests the localized position is valid. Ship GPS positions logged during the deployment surveys were used for estimating the attitudes of the four-hydrophone small aperture arrays.

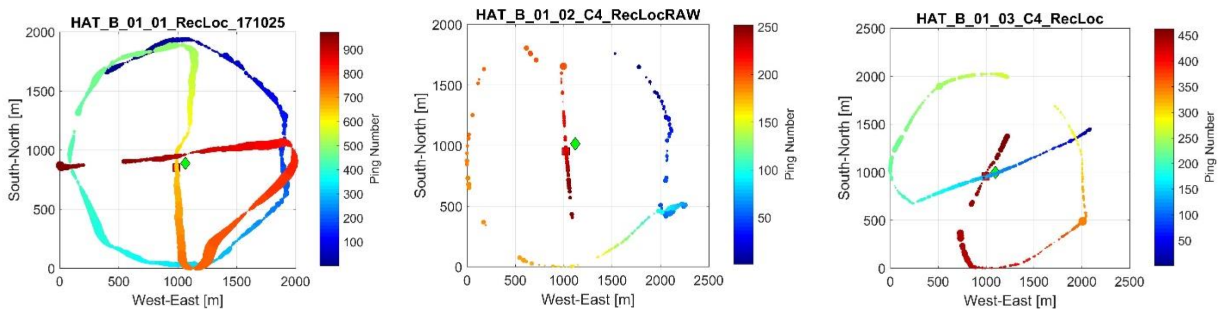


Figure 8. Acoustic-GPS survey ship paths and instrument localizations for HAT_B_01 array. Sites 01, 02, and 03 are left to right. Ship track color represents ping number of good two-way travel time and size is relative uncertainty. Red square is instrument drop location and green diamond is localized instrument location.

Table 1. HAT_B_01 HARP array locations.
Name, deployed (drop) location, acoustic transponder ping and GPS least-squares inverse localized location, deployment and localized location differences, and location uncertainty.

Site Name	Drop Location			Localized Location			Drop - Localized			Error
HAT_B	Lat N (deg)	Lon W (deg)	Depth (m)	Lat N (deg)	Lon W (deg)	Depth (m)	N (m)	W (m)	Depth (m)	RMS (m)
01_01	35.58333	74.75000	1106	35.58371	74.74912	1118	41	-80	12	17
01_02	35.57912	74.75698	1112	35.57969	74.75592	1112	62	-96	0	7
01_03	35.58610	74.75720	1075	35.58647	74.75608	1095	41	-102	21	7

Small aperture array attitude

Using ship propulsion sounds recorded shortly after deployment during acoustic-GPS instrument localization surveys, TDOAs time series were measured and smoothed (Figs. 9 and 10, top row).

The ship measured TDOAs were used with the unit-sphere model to estimate azimuth and elevation angles which were intersected with the sea surface to produce an estimate of the ship track. The estimated ship track was overlaid on the GPS ship track (Figs. 9 and 10, second row, left), and TDOA estimated azimuth and elevation angles were overlaid on ship GPS-derived azimuth and elevation angles (Figs. 9 and 10, bottom rows, left) to provide a basis upon which to adjust the tetrahedron array attitude for both four-hydrophone instruments. Array attitude adjustment was determined by an analyst (SMW) employing a trial-and-error method of changing one of the attitude parameters (roll, pitch, or yaw) at a time to minimize the misfit between GPS- and TDOA-based estimates of the track and azimuth and elevation angles. Yaw was the attitude parameter that needed the greatest change for both instruments, as expected for an upright instrument on the seafloor; whereas, roll and pitch were adjusted only a few degrees (Table 2).

Table 2. Small aperture array hydrophone-pair geometry.
Hydrophone pairs, direction cosine matrix transformations, and hydrophone pair distances. Determined array attitudes roll, pitch yaw (bottom).

	HAT_B_01_02		HAT_B_01_03	
Hydrophone Pair Number (pairs)	Transformation Angles [deg]	Distance [m]	Transformation Angles [deg]	Distance [m]
1 (2 – 3)	[0 0 0]	1.00	[0 0 0]	1.00
2 (4 – 3)	[0 0 60]	1.00	[0 0 60]	1.00
3 (2 – 4)	[0 0 -60]	1.00	[0 0 -60]	1.00
4 (2 – 1)	[0 -46 -30]	0.83	[0 -46 -30]	0.83
5 (3 – 1)	[0 -46 -150]	0.83	[0 -46 -150]	0.83
6 (4 – 1)	[0 -46 -270]	0.83	[0 -46 -270]	0.83
Roll [deg]	+5		-2	
Pitch [deg]	-5		-8	
Yaw [deg]	+147		+130	

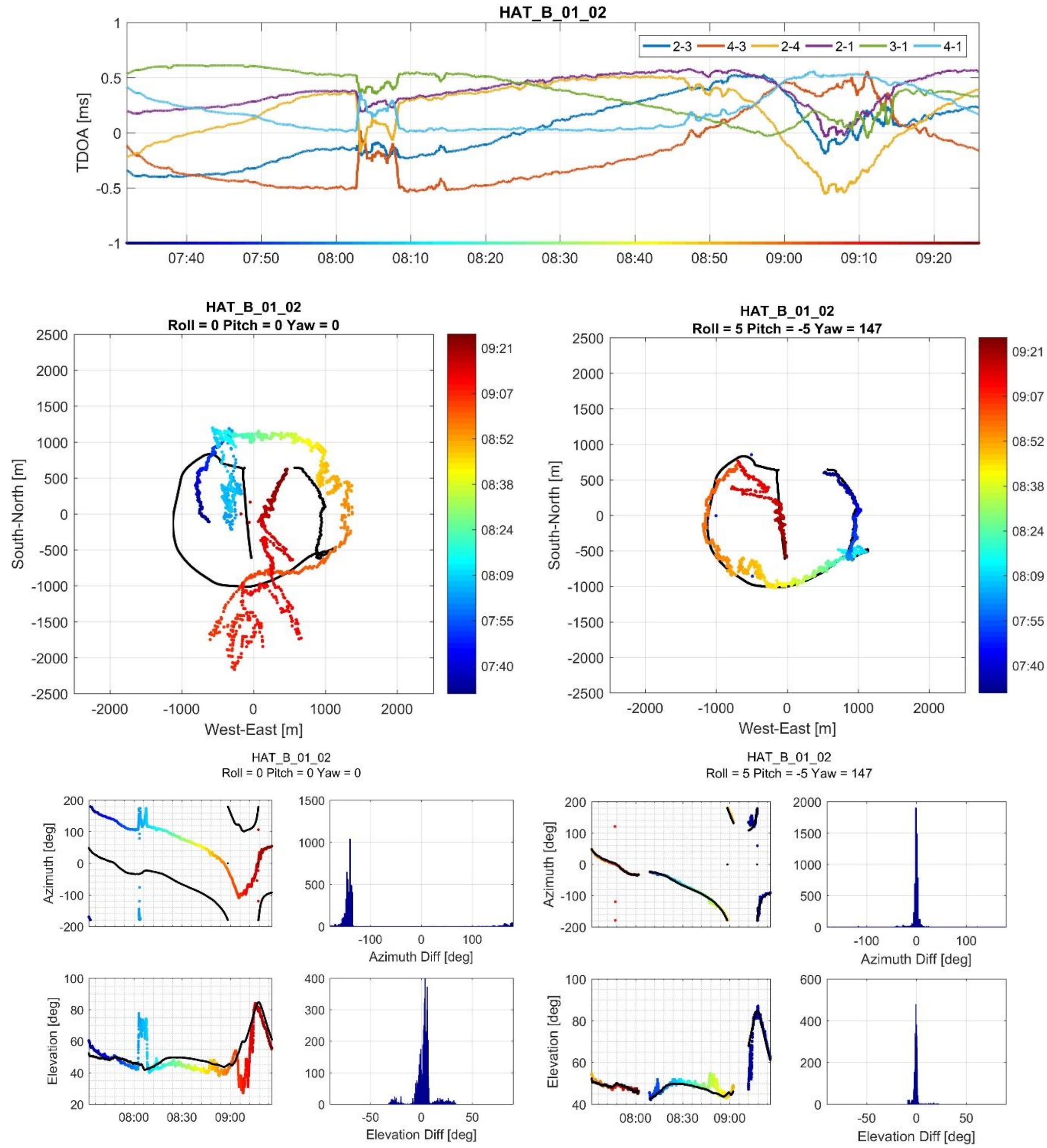


Figure 9. HAT_B_01_02 small aperture array attitude determination.
Tetrahedron attitude determined from ship propulsion sounds during deployment acoustic-GPS survey. Top: measured TDOA time series for six hydrophone pairs. Second Row: ship GPS track (black) overlaid with TDOA-derived positions (color=time) uncorrected (left), attitude-corrected (right). Bottom Rows show fit between GPS and TDOA-based azimuth and elevation angles before and after attitude correction.

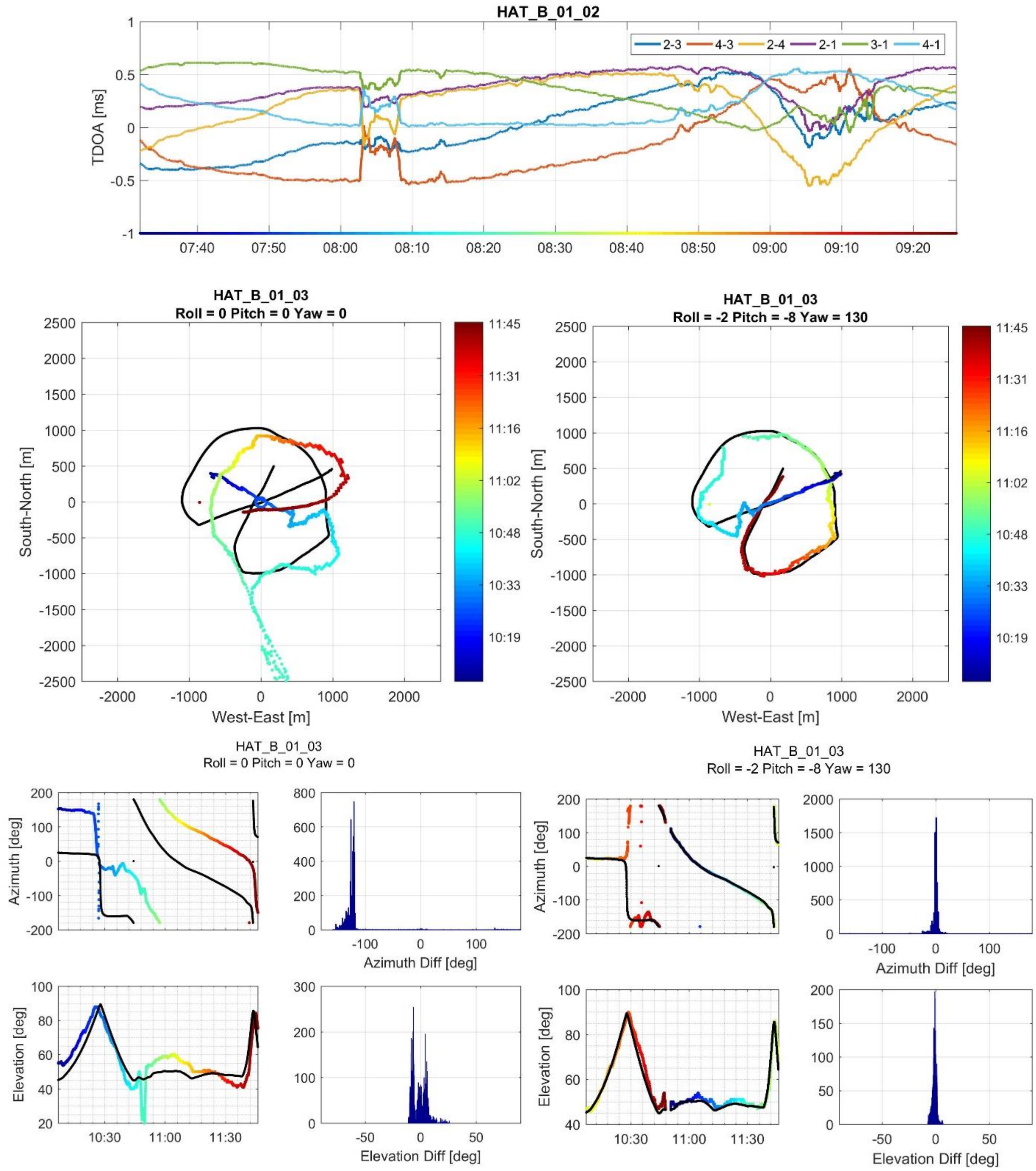


Figure 10. HAT_B_01_03 small aperture array attitude determination.
Tetrahedron attitude determined from ship propulsion sounds during deployment acoustic-GPS survey. Top: measured TDOA time series for six hydrophone pairs. Second Row: ship GPS track (black) overlaid with TDOA-derived positions (color=time) uncorrected (left), attitude-corrected (right). Bottom Rows show fit between GPS and TDOA-based azimuth and elevation angles before (left) and after (right) attitude correction.

Beaked whale tracks

Using the Triton LTSA/TDOA Remora, many periods of beaked whale encounters were found over the deployment period. An example encounter of Cuvier's beaked whales with good signal-to-noise (SNR) ratio and across-site concurrent detections was recorded on 10 May 2017 from approximately 12:15 – 12:45 (Figure 11). Multiple same-color TDOAs in each record suggest a group size of three animals. Beaked whale pulses were first detected at the northern site (HAT_B_01_03), and were last detected at the southern site (HAT_B_01_02), suggesting a north to south transit.

Measured TDOAs were used with the calculated TDOA sphere model and a least-squares fit minimization to provide estimates of azimuth and elevation angles (Figure 12). Estimates of beaked whale pulse received sound pressure level (RL) were made from the maximum peak-to-peak amplitude waveform and accounting for the hydrophone transfer function. Received levels often show increase and decrease over time related to the signals' directivity and animal heading.

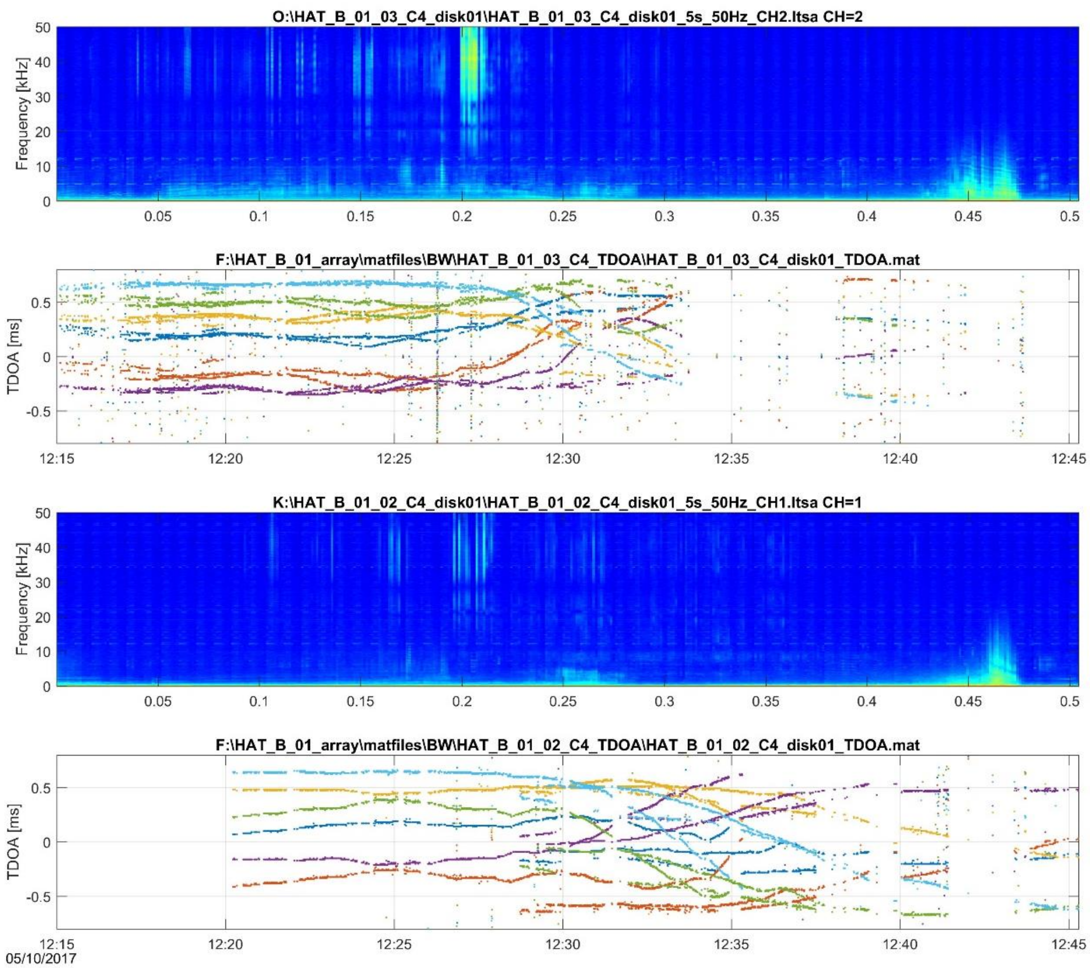


Figure 11. LTSAs and TDOAs for beaked whale bout.
HAT_B_01 northern site 03 (top panels) and southern site 02 (bottom panels) from 10 May 2017 over ~0.5 h. Close inspection of the TDOAs suggest there are three animals creating pulses.

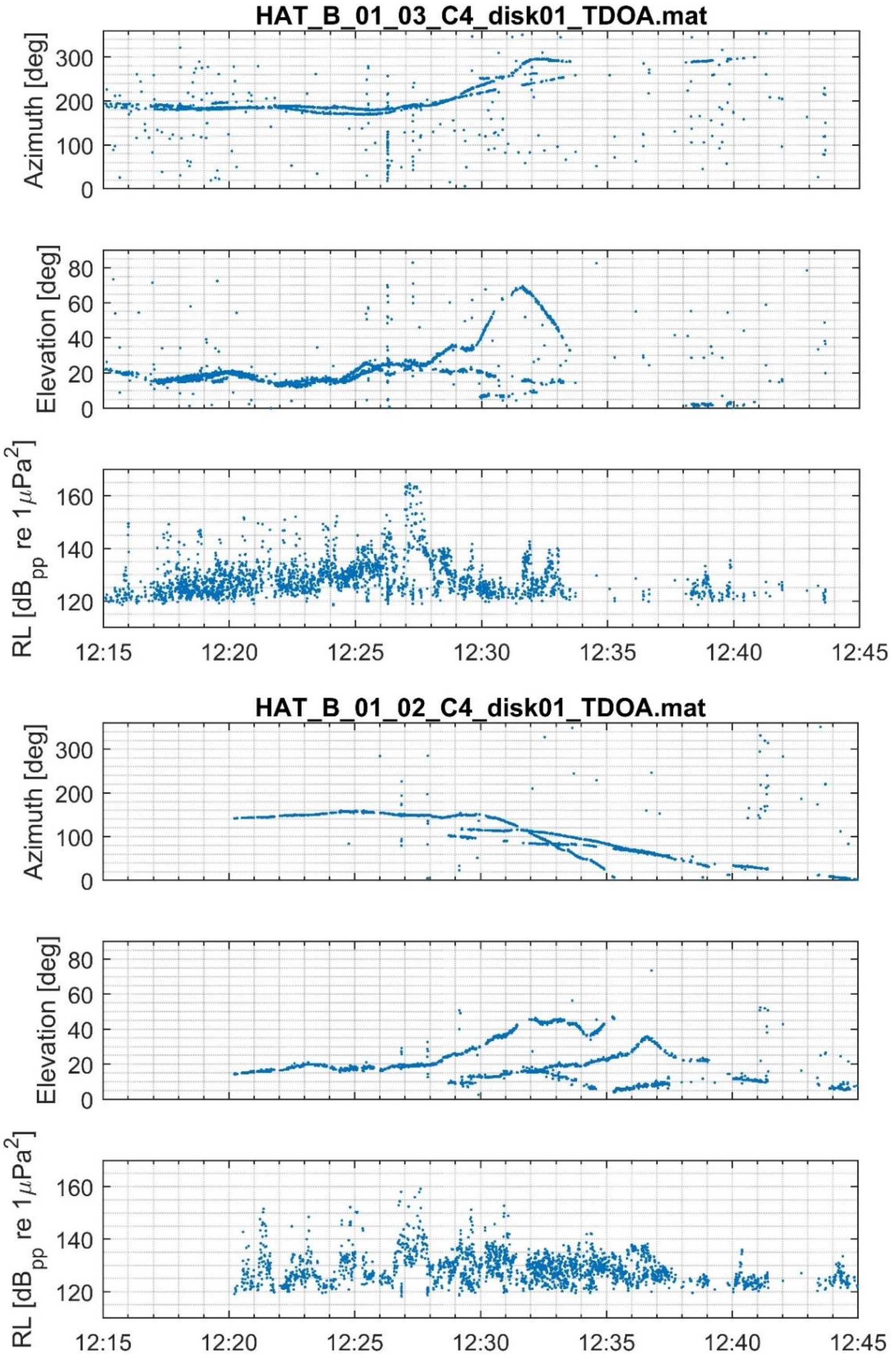


Figure 12. Beaked whale azimuth and elevation angles and received sound pressure levels. TDOA-derived AZELs and hydrophone transfer function corrected received level (RL) time series for sites 03 (top 3 panels) and 02 (bottom 3 panels).

A GUI tool was used to remove noise in the azimuth and elevation plots (Figure 12), in addition to color-code individual AZEL tracks from single animals based on track temporal and spatial continuity. AZEL tracks from three beaked whales were identified and colored black, green and blue (Figure 13). While temporal overlap in detected pulses at the two four-hydrophone sites spans about one-half of the 30 minute encounter and only a few minutes for individual AZELs on both instruments, smoothing and interpolation allowed concurrent cross-fixing AZELs for about 5 – 10 minutes of the encounter for each animal and provided starting locations for piecewise tracks.

Combining the cross-fixed tracks with the piecewise tracks for each animal produced three unique tracks traveling in the same general direction from the northwest to the southeast over a range >1 km (Figure 14). Initial track dives to near the seafloor (northwest) can be seen for the blue and black whale with overall-track depths (788 - 1063 m) generally followed the down slope bathymetry, but also varied up and down up to 100 m over individual tracks (Figure 15). While all tracks have a similar direction of travel, each have different in up and down variations, different paths, and are not synchronized (see website links to movies below).

All three tracks crossed over the ridge separating the two 4-hydrophone recorders, with black crossing first, green next, and blue last. Slight upward tracks can be seen at the end of each track in the southeast. Estimated swim speeds for the three beaked whales measured from the tracks is about 1 m s^{-1} (3.6 km hr^{-1} or 2 kts).

Additional effort on this dataset would yield more beaked whale tracks as well as tracks from other deep diving species such as pilot whales and sperm whales.

Website links to 3D view movies of three beaked whale tracks:

http://www.cetus.ucsd.edu/docs/reports/media/HAT_B_01_02&03_C4_170510_1215-1245_5m_10_30.mp4

http://www.cetus.ucsd.edu/docs/reports/media/HAT_B_01_02&03_C4_170510_1215-1245_5m_150_0.mp4

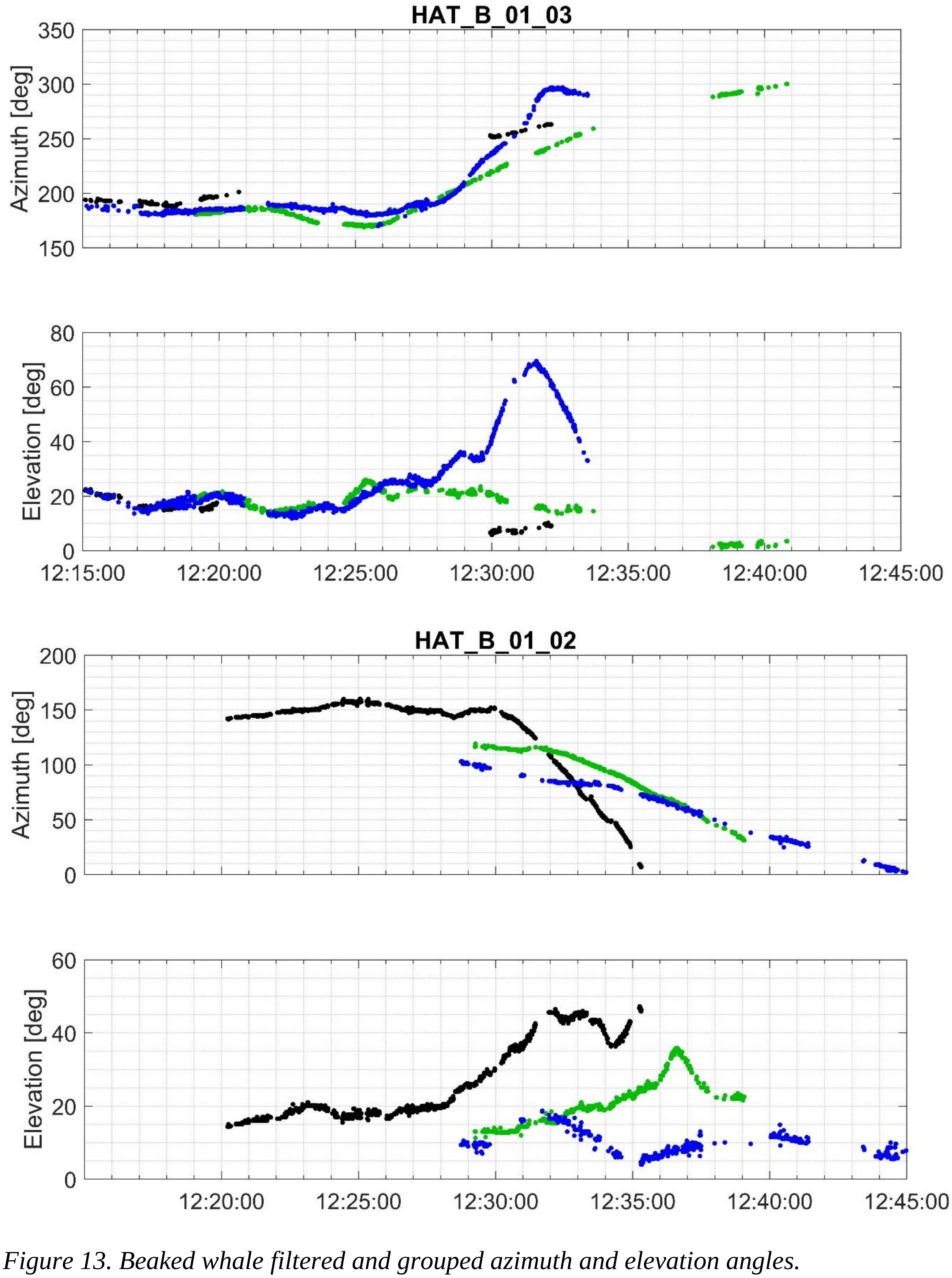


Figure 13. Beaked whale filtered and grouped azimuth and elevation angles.
Analyst-filtered TDOA-derived azimuth and elevation angles for a group of three beaked whales, separated by color.

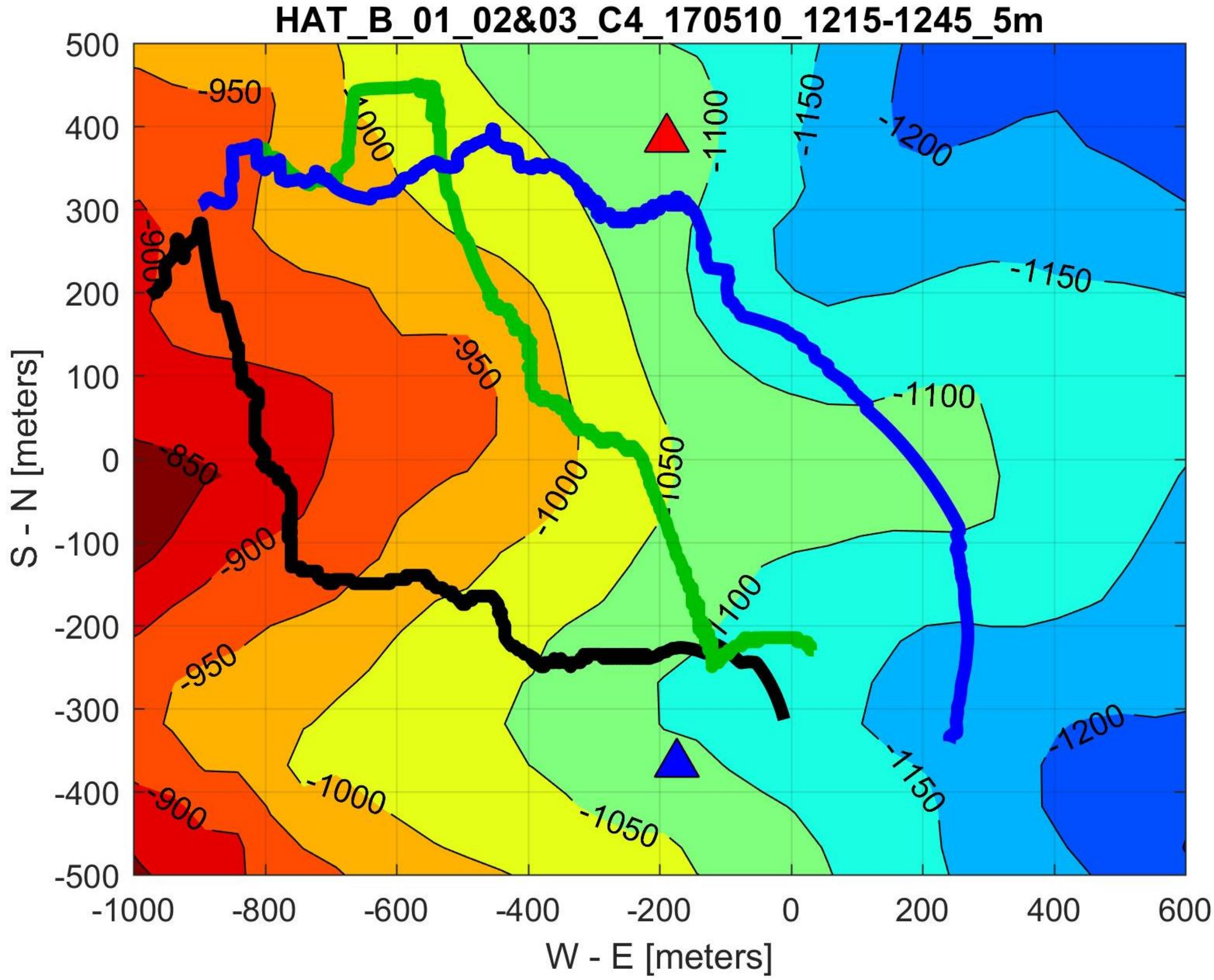


Figure 14. Map view of beaked whale tracks.
Beaked whale tracks transit from the northwest to the southeast and track colors are for individual animals. The two triangles depict the locations of the four-hydrophone tracking HARPs (blue = site 02, red = site 03). Bathymetry colors transition from shallow warm to deep cool with contours every 50 m.

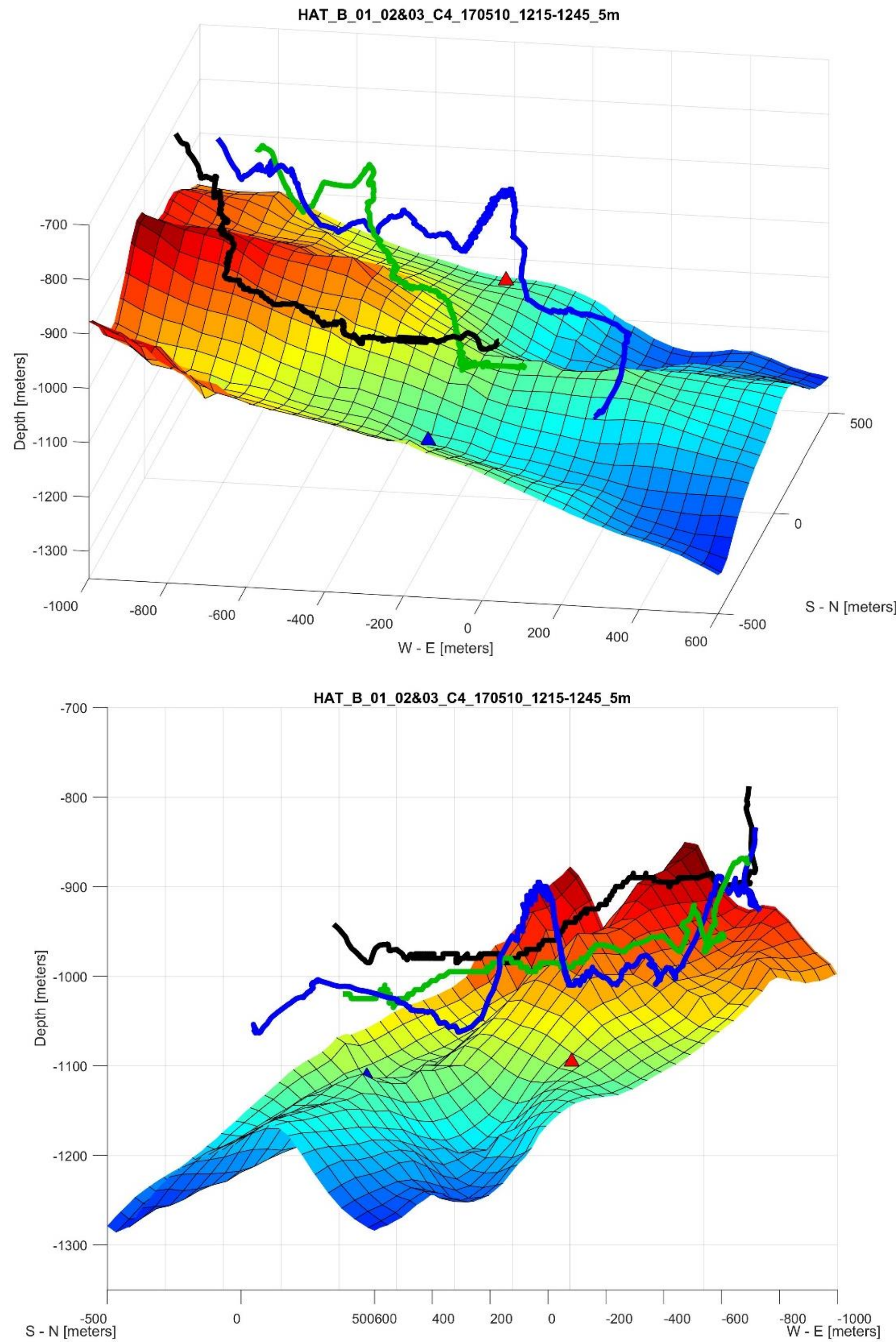


Figure 15. 3D views of three beaked whale tracks.
Two views (azimuth, elevation rotation angles): top (10, 30) and bottom (150, 0) show individual beaked whale paths (black, green, and blue lines) start in the northwest and travel southeast over a ridge between sites 02 (blue triangle) and 03 (red triangle). Bathymetry cooler colors to the east are deeper.

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