Beaked whale and dolphin tracking using a multichannel autonomous acoustic recorder

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To track highly directional echolocation clicks from odontocetes, passive hydrophone arrays with small apertures can be used to receive the same high frequency click on each sensor. A four-hydrophone small-aperture array was coupled to an autonomous acoustic recorder and used for long-term tracking of high-frequency odontocete sounds. The instrument was deployed in the spring of 2009 offshore of southern California in a known beaked whale and dolphin habitat at about 1000 m depth. The array was configured as a tetrahedron with approximately 0.5 m sensor spacing. Time difference of arrival measurements between the six sensor-pairs were used to estimate three-dimensional bearings to sources. Both near-seafloor beaked whales and near-sea surface dolphins were tracked. The tracks observed using this technique provide swimming and diving behavioral information for free-ranging animals using a single instrument. Furthermore, animal detection ranges were derived, allowing for estimation of detection probability functions.
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I. INTRODUCTION

Tracking marine mammals can provide a wide range of information on their behavior including migration, swimming, and diving dynamics. One method for tracking marine mammals is to attach satellite tags to individual animals. These devices relay their position when the animal surfaces to breathe, as long as favorable satellite transmission conditions exist (e.g., Mate *et al.*, 2007). For cetaceans, satellite tags are usually attached with barbed darts and remain attached for weeks or months providing long-term, large-scale positions and travel dynamics (e.g., Andrews *et al.*, 2008). Archival tags are similar devices, but need to be recovered to acquire the recorded data. These are attached with suction cups and stay on the animal only for a few hours to days, but typically have high data rate recorders allowing for a multitude of sensors including depth, compass heading, multi-axis acceleration, and sound (e.g., Johnson and Tyack, 2003; Schmit *et al.*, 2010). However, with either method, tag attachment may alter behavior and is often difficult, limiting the number of species and individual animals that have been tracked using tags.

Another approach to monitoring cetacean movements is to track the sounds they produce for communication and sensing their environment. For example, blue whale (*Balaenoptera musculus*) migrations offshore of western North America have been tracked using the U.S. Navy's Sound Surveillance System (SOSUS) stations spaced hundreds of kilometers apart (Stafford *et al.*, 1998; Burtenshaw *et al.*, 2004). Using smaller, km-scale hydrophone arrays, detailed tracks of individual animals have been made for large whales including blue, fin (*Balaenoptera physalus*), and sperm (*Physeter macrocephalus*) whales (e.g., McDonald *et al.*, 1995; Nosal and Frazer, 2007). These arrays consist of either cabled-hydrophones that are permanently fixed, limiting the number of species and areas that can be studied, or autonomous hydrophone recorders which are portable and used worldwide, but also requiring precise time synchronization between recordings for tracking. In either case, because of their large aperture, km-scaled arrays are not well suited to track high-frequency, narrow-beam sounds such as echolocation clicks from dolphins and beaked whales, since multiple widely separated sensors do not simultaneously fall within the on-axis beam of an echolocating animal and because signal attenuation is high (10–40 dB/km @ 40–100 kHz) for click frequencies.

Passive acoustic monitoring of marine mammals using autonomous recorders has become more prevalent over the past decade owing to advancements in computer and electronic technology. These monitoring efforts primarily use recorders as independent stations because of the added complexity and cost of array configurations, and to allow for the widest regional coverage by a limited number of recorders (e.g., Sirovic *et al.*, 2004; Oleson *et al.*, 2007; Soldevilla *et al.*, 2010). Typically, these independent stations consist of a single hydrophone allowing temporal patterns to be investigated for each site and gross spatial patterns to be compared between sites.

One way to track high-frequency cetacean sounds from a single recorder is to use a small-aperture array. If sensor

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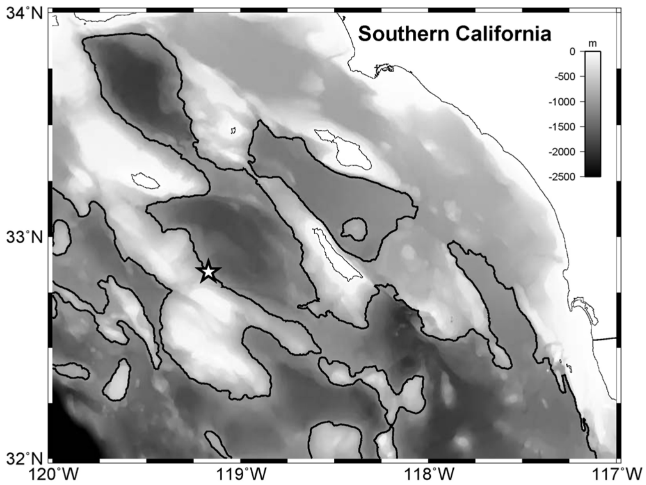

FIG. 1. Tracking HARP location (star) on the west side of the San Nicolas Basin, west of San Clemente Island in the Southern California Bight. Contours are 1000 m.

spacing is at least a few wavelengths, then standard time difference of arrival methods can be used to estimate three-dimensional bearings to the sound source, and these bearings can be tracked over time. With high frequency, short wavelength sounds, such as odontocete clicks, sensor separation can be less than 1 m, allowing for deployment of compact arrays. If two small-aperture arrays are used and separated by relatively large distances (e.g., ∼1 km), then the three-dimensional (3D) bearings can be cross fixed to provide 3D locations and tracks (Hirotsu *et al.*, 2010).

We developed a high-frequency, small-aperture array for use with an autonomous passive acoustic recorder to track echolocating odontocetes over long periods. This system was deployed offshore of southern California (Fig. 1) and tracked foraging deep-diving beaked whales and near-surface echolocating dolphins. In this paper, we describe the instrument, its initial deployment, our data analysis approach, and show tracks from beaked whales and dolphins as examples of this technique. In both cases, detailed movements are revealed by the array, providing insight on odontocete behavior.

II. METHODS

A. Small-aperture array

A single hydrophone pair can constrain the direction of an incoming plane wave, using the time difference of arrival (TDOA). If the hydrophone separation distance, or aperture, is similar to the range to the source, then the TDOA can be used to estimate a hyperboloid of possible locations for the source. However, for small aperture arrays with source ranges much greater than sensor spacing, the source lies along the surface of a cone (asymptote of a hyperboloid) providing a directional angle, γ, to the incoming plane wave [Fig. 2(A)], related to the sensor spacing d, TDOA δT, and ocean sound speed v, by

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

While it is possible to calculate the 3D direction of a sound source from three sensor pairs, we used four hydrophone sensors arranged at the vertices of a tetrahedron to provide six sensor pairs [Fig. 2(B)]. The additional three sensor pairs afford redundancy and lower uncertainty in the estimated 3D direction. A tetrahedron configuration was chosen to provide symmetry so that angle errors would be evenly distributed given random source locations in the half-space above the seafloor.

B. Instrument

A seafloor-mounted high-frequency acoustic recording package (HARP) (Wiggins and Hildebrand, 2007) was modified into a small-aperture array tracking HARP by replacing the single channel analog-to-digital converter (ADC) with a four channel, 16-bit ADC with each channel sampled at 100 kSamples s^{-1}. The single, floating hydrophone also was replaced with a fixed array of four hydrophones, 3 m above the seafloor, arranged in a tetrahedron configuration with approximately 0.5 m sensor pair spacing or about 330 μs TDOA for a signal along a sensor pair axis (Fig. 3). The hydrophone array structure was made of low acoustic impedance polyethylene to minimize interferences and reflections from short wavelength signals, such as high frequency echolocation clicks. With a fixed sensor design, tilt and compass sensors were not used for the array attitude determination, instead sensor orientation was derived using recordings of acoustic sources at known locations.

C. Experiment

During May 2009, we deployed a tracking HARP on the seafloor approximately 1000 m deep offshore of southern

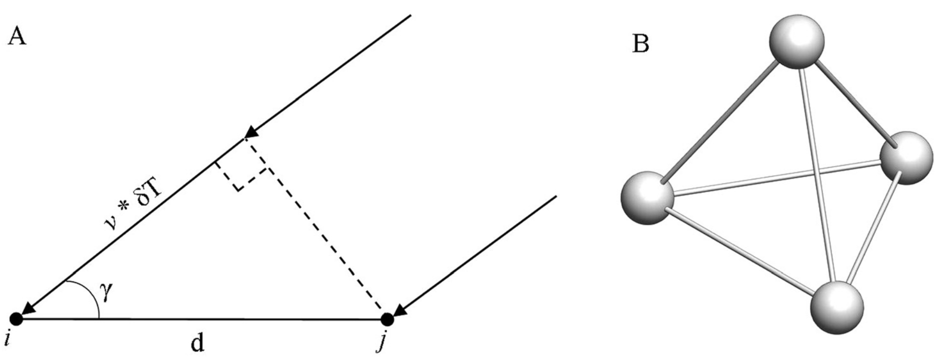

FIG. 2. (A) Geometry of plane wave arriving at two sensors i and j. (B) Sensor configuration for tetrahedron small-aperture array providing six pairs of TDOAs.

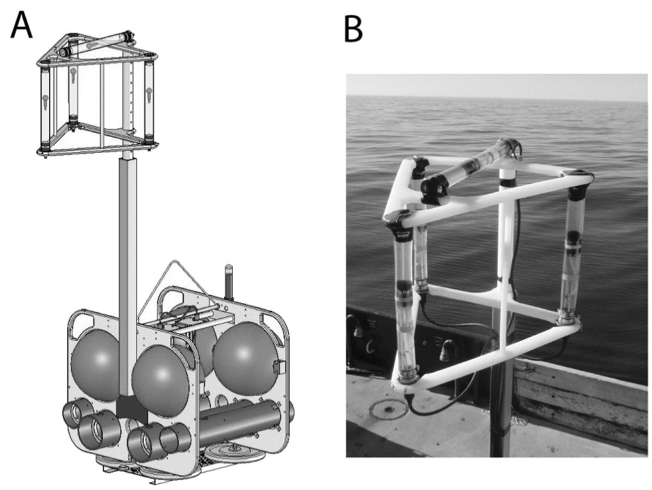

FIG. 3. (A) Schematic of tracking high-frequency acoustic recording package (THARP) with four-channel hydrophone array arranged in a tetrahedron configuration about 3 m above the seafloor. (B) Photo of tetrahedron array with sensors about 0.5 m apart.

California. The focal species for our initial tracking experiment was Cuvier's beaked whale (*Ziphius cavirostris*), so we selected a site west of San Clemente Island on the west side of San Nicolas Basin where we have recorded thousands of beaked whale echolocation foraging dives over the past few years using single hydrophone HARPs (Fig. 1), and where many visual encounters with beaked whales have been made (Falcone *et al.*, 2009).

Additionally, there are five species of echolocating dolphin that are regularly observed offshore of southern California: short-beaked common (*Delphinus delphis*), long-beaked common (*Delphinus capensis*), Pacific white-sided (*Lagenorhynchus obliquidens*), bottlenose (*Tursiops truncatus*), and Risso's (*Grampus griseus*) dolphins. Pacific white-sided and Risso's dolphins have unique click structures from which they can be identified, whereas, distinctive click character has not been shown for common and bottlenose dolphins (Soldevilla *et al.*, 2008). However, since bottlenose dolphins are usually in small groups (1–30) (Shane, 1994) and common dolphins are in much larger groups of hundreds to thousands (e.g., Selzer and Payne, 1988) we presume that recordings with large numbers of non-distinctive clicks are from common dolphins.

To determine the attitude (pitch, roll, and yaw) of the tracking HARP hydrophone array, 12 kHz pings (i.e., 10 ms long pulses every 5 s) were sent from the Global Positioning System (GPS) configured R/V Robert Gordon Sproul as the ship was driven in a circle centered at the instrument with $\sim$1.5 km diameter, and driven along $\sim$1.5 km nearly orthogonal tracks intersecting directly above the instrument. Ship GPS locations for each ping provided 3D angles of incoming signals at known times. Hundreds of pings were recorded over the 45 min of the survey; however, we found ship propulsion noise at close ranges ($<$ 2 km) provided a larger time-bandwidth product signal resulting in better cross-correlations between channels than the acoustic pings, so GPS-located ship noise was used with the model described below to orient the small-aperture array. Knowing the attitude of the array allows the tracks to be correlated with bathymetry or other local oceanographic features that may provide insight on how these features affect the animals' movement and their use of the area.

While precise geographic localization was not needed for this experiment, the ship GPS locations and co-occurring pings were used with the HARP's acoustic release transponder (EdgeTech/ORE, http://www.edgetech.com/ore-offshore, last viewed 15 November 2011) to precisely locate the tracking HARP at 32° 50.477′N, 119° 10.256′W 1005 m depth within 4 m root-mean-squared (RMS) error using two-way acoustic ranging travel times in a least-squares inverse (e.g., Creager and Dorman, 1982).

D. Data processing

The tracking HARP's $\sim$2 TB (25 days) of continuous data were converted into four-channel wav format files for detailed analysis. These wav files were similar to standard acoustic wav files, but included additional information required for processing such as precise timing for each file and instrument latitude, longitude and depth. The wav files were used to make long-term spectrograms (Wiggins and Hildebrand, 2007) providing an overview of the data on the scale of hours and depicting acoustically active periods such as beaked whale foraging dives and dolphin clicking encounters. These active periods were noted and used for tracking.

After identifying echolocation start and end times, the data were band-pass filtered (20–50 kHz) to minimize low-frequency sounds. Using the waveform data, a threshold of 6 dB above background noise was set for which short duration impulsive sounds above this threshold were detected. One millisecond of data before and after each detection were used for cross-correlating each sensor pair, providing six measured TDOAs (1–2, 1–3, 1–4, 2–3, 2–4, 3–4) with 10 μs resolution (i.e., 100 kSamples s^{-1}). To estimate array attitude, TDOAs for GPS-located ship noise were also measured, but instead using low frequency ($<$20 kHz) sound without band-pass filtering and 1 s windows.

A model of calculated TDOAs was produced for a source at each azimuth and elevation angle in one degree increments over a sphere of unit radius (i.e., $180 \times 360 = 64\,800$ sets of six TDOAs). The minimum of the squared differences between these calculated sets of TDOAs and the measured TDOAs was used in a forward model to estimate the azimuthal and elevation angles for the detected pulses, clicks and ship noise; essentially, a simplified version of model-based processing was employed to estimate the source direction (e.g., Tiemann *et al.*, 2004). For estimating array attitude, directions from ship noise TDOAs were fit to the GPS-derived ship directions by adjusting roll, pitch and yaw of the array. Straight-line, non-refracting raypaths (isospeed model) from ship to tracking HARP were used because refraction effects were minimal. Using a sound speed profile calculated from a temperature profile (Chen and Millero, 1977) measured during the HARP deployment, less than 2% horizontal range error between straight and refracted paths was estimated for angles greater than 13° from horizontal. All ship locations were between 90° (directly above the HARP) and 45° allowing straight-line paths to be used without significant error. The best fit array heading was yaw = 160° ± 3° clockwise rotation around vertical axis from north, and no roll or pitch, consistent with a presumed seafloor slope of less than 3°.

To provide map-view tracks of beaked whales and dolphins, different techniques for each were used. For Cuvier's beaked whales during the initial phase of a foraging dive while an animal is transiting from the sea surface to the seafloor, the vertical decent rates from tagged animals have been shown to be highly consistent at 1.5 m s^{-1} (Tyack *et al.*, 2006). Dividing this rate by the arc-tangent of the elevation angle rate of change provides an estimate of the range to the animal as it nears the seafloor. This starting range combined with the concurrent azimuth angle forms a starting location for a track. The starting location was used with successive azimuth angles and an assumed horizontal travel speed to estimate successive locations, forming map-view tracks of beaked whales at depth. An average at-depth horizontal travel speed of 1.0 m s^{-1} (3.6 km h^{-1}) was used for Cuvier's beaked whale based on foraging closing speeds and dead reckoned tracks from tagged animals (Johnson *et al.*, 2008; Johnson *et al.*, 2009). It is unlikely that the true horizontal speed is constant and variation in the speed would cause the track to expand or contract.

Dolphins travel at or near the sea surface relative to the seafloor-mounted instrument. Simultaneous elevation and azimuth angles were used to define a 3D bearing which intersects the sea surface resulting in an estimated source location via trigonometric calculations. Successive 3D angle intersections with the sea surface were used to provide tracks of clicking dolphins. If the dolphins are producing clicks at greater depth, then the track will decrease in horizontal range toward the instrument position.

III. RESULTS

On 15 of the 25 days of recordings, there were a total of 20 beaked whale echolocation bouts lasting from a few minutes to tens of minutes. Some of these bouts appear to be from a single animal while others are clearly from two different beaked whales on independent paths. Some bouts had only a few hundred low amplitude detections and appear to be distant but others had several thousand detections with varying amplitudes. Evaluation of echolocation pulse duration, start and end frequency, frequency sweep rate, and inter-pulse interval reveal that these sounds are from Cuvier's beaked whales (Johnson *et al.*, 2004; Zimmer *et al.*, 2005).

On 20 of the 25 recording days, a total of 43 dolphin click bouts were recorded with most bouts occurring during nighttime hours. Five of these bouts were from Risso's and Pacific white-sided dolphins with the remaining bouts coming from dolphins without characteristically distinguishable clicks (i.e., bottlenose and common). Six of the click bouts were intense and included 20 000–100 000 clicks over one to three hour periods always between 0300 and 0900 GMT (i.e., nighttime), and were presumed to be from common dolphins based on the large number of clicks.

A. Beaked whales

On 31 May 2009, four separate beaked whale foraging dives were recorded, with the third one spanning over 40 min and almost 6000 echolocation detections. Azimuth and elevation angle tracks were estimated for each of these detections in the third bout, and along with received amplitude, are plotted versus time (Fig. 4). We designate separate tracks of echolocation as being from separate animals, based on the consistency of timing and amplitude within the click trains. Two distinct tracks with different azimuths are shown as they each move to the north over a time span of about 30 min. The two animals start and end the echolocation portions of their dives about 10 min apart. Their initial elevation angles decrease to near 0°, suggesting that both animals dive to the seafloor (Fig. 4 east animal A before 17:20 and west animal B before 17:28) and then make small elevation changes near the seafloor throughout the rest of their foraging dives. Arrival angles below 0° elevation are likely reflections off the instrument package or seafloor and have been omitted. The received signal levels (amplitudes) rise and fall over time; this pattern may be related to beam directionality and heading (i.e., orientation) of the echolocating animals relative to the tracking HARP.

Near-seafloor starting ranges were estimated from a 1.5 m s^{-1} vertical decent rate and the initial dive elevation angle to be 150 and 500 m for the east and west beaked whales, respectively. Tracks were estimated from these initial ranges and successive azimuth angles and plotted with corresponding times overlaid on a bathymetry map of the area (Fig. 5). Both animals transit in a similar northerly direction along slightly different isobaths (1000 m for west animal and 1010 m for east animal). The beaked whale to the east of the tracking HARP travels a path using more turns than the animal to the west.

B. Dolphins

On 23 May 2009, a group of common dolphins passed by the tracking HARP; one two-hour bout (0700–0900 GMT) of over 50 000 detected clicks was used to estimate azimuth and elevation angles (Fig. 6). The azimuth shows a single dominant track with a few less prominent tracks that converge and diverge over time. The elevation angles initially span <30°, but increase to 30°–60° for about 20 min and then return to < 30°. The time of maximum elevation angle (0807) is the presumed closest-point-of-approach (CPA). Elevation angles below 0° are likely bottom reflections and scatter and are omitted. Received signal level amplitudes increase and then stay high over about a 40 min period, before decreasing again. The period of maximum elevation (CPA) occurs during the latter portion of the period of maximum received level, suggesting a directional character to the source signal (i.e., higher amplitudes as the dolphins are oriented toward the tracking HARP). When compared to the sensor depth at about 1000 m, the dolphin echolocation depths are assumed to be at or near the sea surface. Constraining their depths to the sea surface allows horizontal locations to be estimated from azimuth and elevation angles [Fig. 7(A)]. After removing outliers, median values of

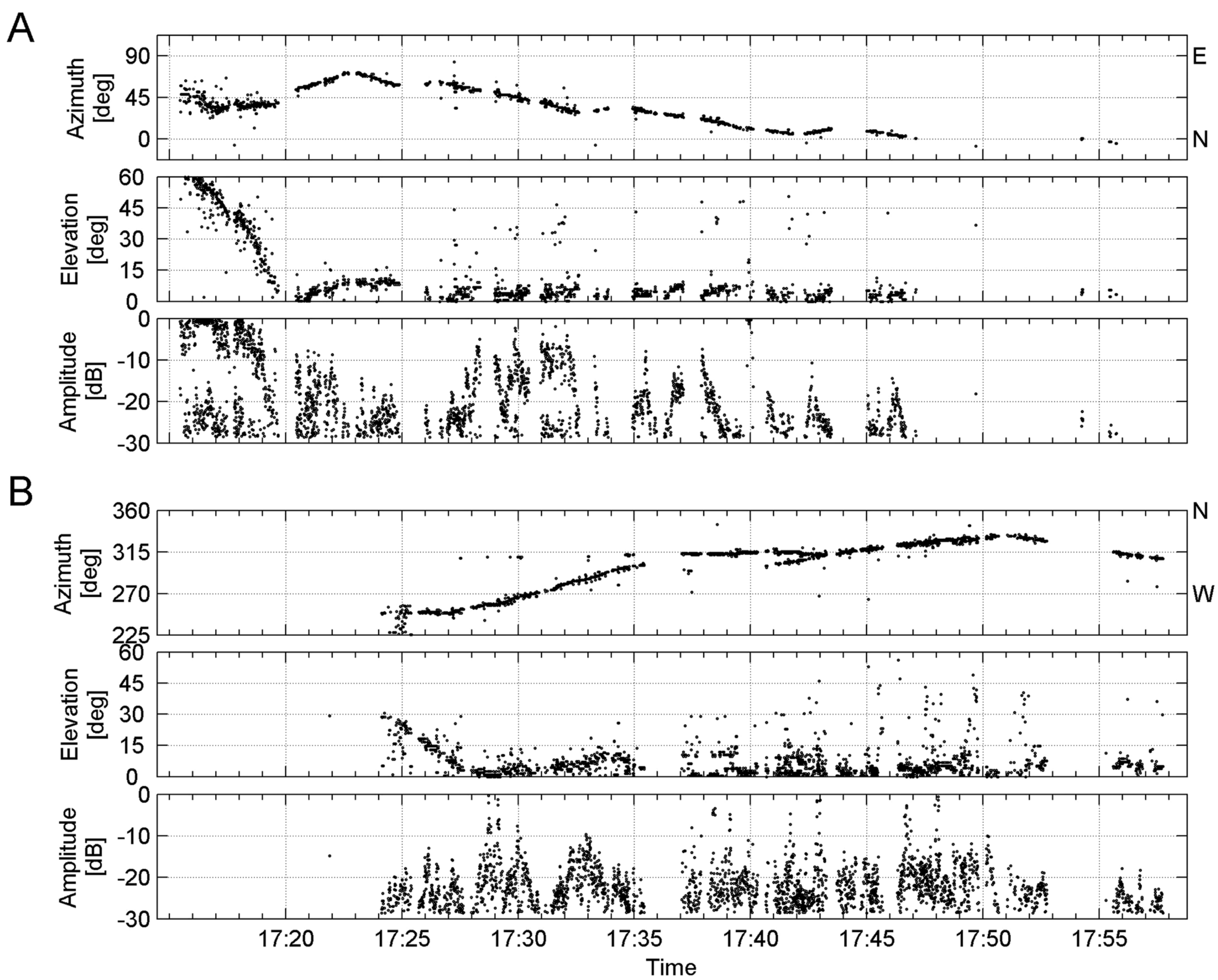

FIG. 4. Analysis of echolocation clicks from two separate beaked whales (A = east and B = west) during a simultaneous dive near the tracking HARP: azimuth (top) and elevation (middle) angles and received amplitudes (bottom) over a 43 min period. Times are GMT on 31 May 2009.

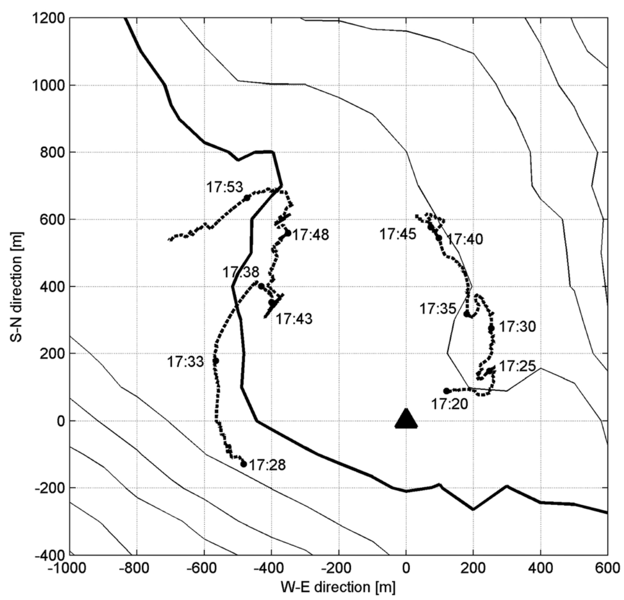

FIG. 5. Tracks of two beaked whales (dashed lines) using azimuth and elevation angles from Fig. 4, assuming a vertical descent rate of 1.5 m s^{-1} and horizontal swim speed of 1.0 m s^{-1} (3.6 km h^{-1}). Circles indicate time along track. The triangle depicts the four-channel tracking HARP location. The thick contour is at 1000 m and the other contours are separated by 10 m with deeper seafloor to the upper right and shallower to lower left.

surface locations every three minutes were used to estimate a surface track of the group. Standard deviations from each three minutes along the track were used for error ellipse major and minor radii to show how the spread of the group changes over time [Fig. 7(B)]. The group starts west of the tracking HARP and travels south increasing its spread until about 0750 when a large change in heading to the northeast brings the dolphins close to the instrument in a tightly clustered group. The group passes south of the sensor and has a CPA of less than 1000 m range around 0809. The group then proceeds to move eastward and then spreads out as it travels north. The average speed for the group along the track was 2.2 m s^{-1} (7.9 km h^{-1}).

IV. DISCUSSION

A. Instrumentation

The additional sensors needed for the small-aperture array require additional data storage (and batteries) if the sample rate and recording durations are to remain similar to single hydrophone autonomous recorders. Since the tracking HARP system was a proof-of-concept instrument modified from a standard single-hydrophone HARP, the data storage

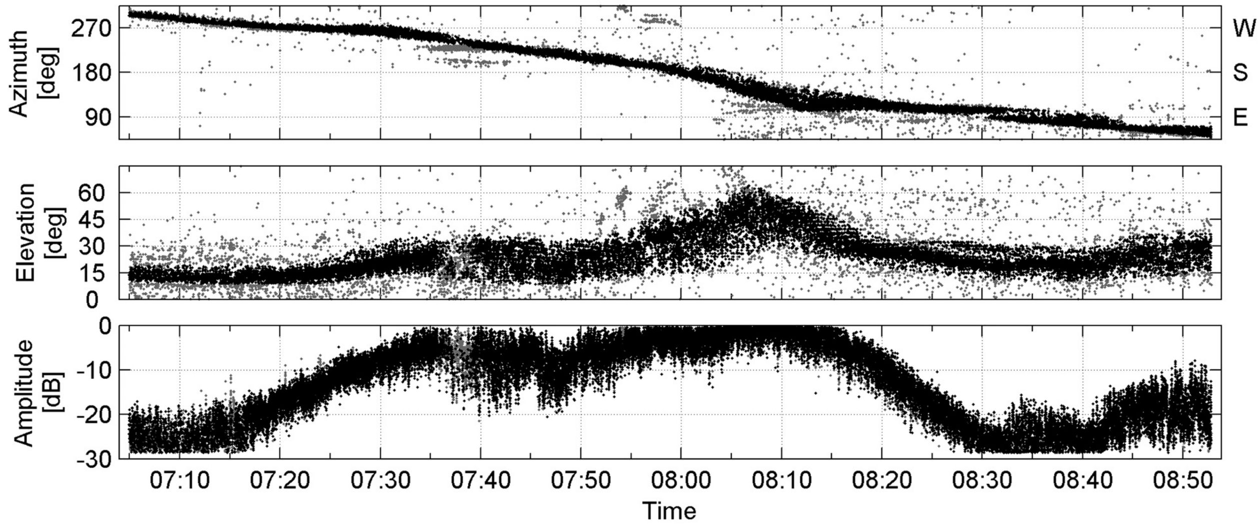

FIG. 6. Azimuth, elevation and received amplitude plots for a two hour echolocation bout presumed to be from common dolphins. Azimuth and elevation tracks for the dolphin group as a whole are apparent. Outliers (gray) were removed for sea surface track estimation (Fig. 7). Times are GMT on 23 May 2009.

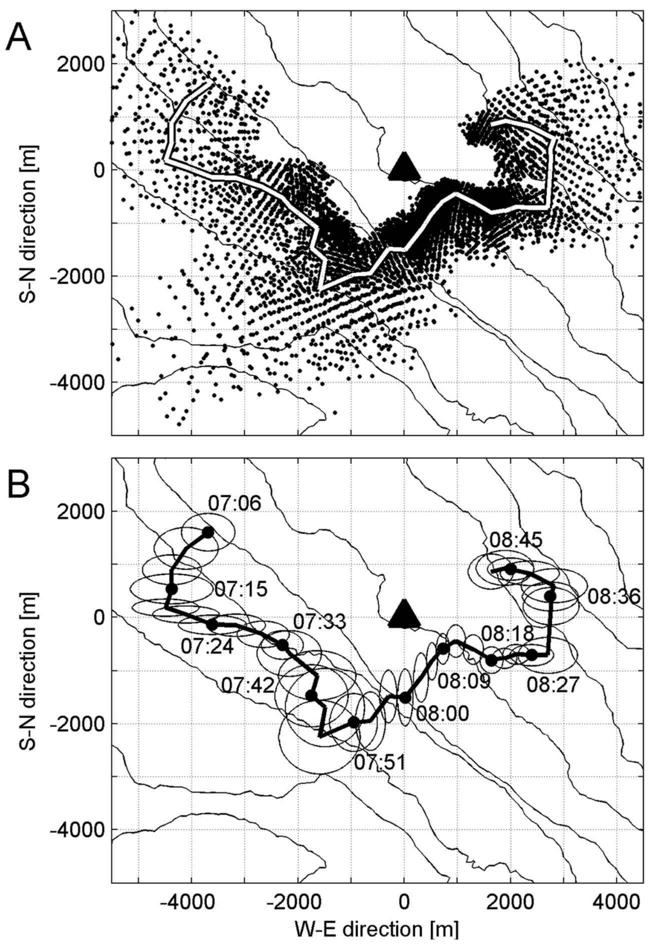

FIG. 7. Plan view of dolphin group track using azimuth and elevation angles from Fig. 6 and assuming the dolphins are at or near the sea surface. (A) Location black dots were calculated from Fig. 6 angle black dots (gray outliers removed). Median locations were calculated every three minutes to provide an estimated track (white with black outline). (B) Black solid circles indicate time along track and standard deviation error ellipses show group spread. The triangle depicts the four-channel tracking HARP location near the 1000 m contour. Other contours are separated by 100 m, deeper to the upper right and shallower to lower left.

and battery capacity were fixed, and we chose to sample one-half as fast and for one-half the duration compared to a standard HARP. Nonetheless, 100 kSamples s^{-1} per channel for about one month was sufficient to get tens of sessions of foraging beaked whales and echolocating dolphins.

Knowing the array attitude (roll, pitch, and tilt) is necessary to interpret the tracking results relative to geographic, oceanographic, and anthropogenic features such as bathymetry, prey distributions, and ship passage events. To simplify and expedite electronic and software development and to make data analysis more straightforward, we used a fixed geometry for the hydrophone array allowing propeller noise from our GPS-located support ship to be used to calibrate the array attitude. One disadvantage of this approach was that our array was only about 3 m above the seafloor and 2 m above the recording package. This resulted in many seafloor reflected signals. Also, the instrument was difficult to recover and deploy with a fixed array-mast (Fig. 2) compared to a standard single hydrophone HARP where the sensor is tethered about 10 m above the instrument package on a line with a float. A similar approach could be applied where the small-aperture array is buoyed above the seafloor package or attached in-line with a typical oceanographic mooring, but compass and tilt sensors would need to be integrated, and sampled throughout the deployment, to correct for array attitude changes from subsurface ocean currents.

While most of the negative elevation angles from the beaked whales and presumably all of the ones from the dolphins are from reflected paths and were filtered from the plots presented here, there is geometric information in these angles which potentially could be used to estimate 3D locations for beaked whales and perhaps dolphin depths from multi-path analysis (e.g., McDonald *et al.*, 1995; Cato, 1998; Sirovic *et al.*, 2006). On the other hand, a second strategically placed tracking HARP would provide a second set of 3D angles with which to cross-fix with the first set and provide locations (Hirotsu *et al.*, 2010).

B. Tracks

In both the beaked whale and dolphin tracking examples, assumptions were made to provide details of their movements. Although these assumptions result in potential position errors, general trends in their movements are similar to what Johnson *et al.* (2009) have shown for foraging beaked whales and others have observed for dolphin surface travel (Conner, 2000). In the beaked whale angle and amplitude time series plots it appears the two animals were diving together, although the eastern beaked whale starts and finishes echolocation almost 10 min sooner than the western animal (Fig. 4). The east whale may have had more encounters with prey as its echolocation time series are less continuous than the west whale, suggesting the east whale had more prey capture attempts with low-amplitude buzzes as implied by time gaps in the echolocation sequence. Beaked whale buzzes can be up to 30 dB less intense than typical frequency swept echolocation clicks and would only be recorded if the animal were directly heading toward or was very near (< 100 m) the instrument (Madsen *et al.*, 2005). Also, the east animal turned more often (Figs. 4 and 5) and evaluation of the elevation angles show short-term changes suggesting up and down movements near the seafloor as seen with tagged foraging beaked whales during prey capture attempts (Johnson *et al.*, 2009).

The distributions of amplitudes appear about the same for the two whales, so the east whale intermittent pattern is probably not from the animal moving into and out of detection range, which presumably would require longer time periods to observe the variation. On the other hand, beaked whales emit their echolocation sounds in a narrow beam with up to 40 dB decrease in intensity between on-axis and off-axis ($> 10°$) clicks (Zimmer *et al.*, 2005), so the amplitude ramping up and down over one to a few minutes shown in Fig. 4 may be due to animal heading (i.e., beam direction) changes. The heading changes could explain the gaps in echolocations for the east whale, but similar amplitude changes are also shown for the west whale with fewer gaps in clicking and less turning or heading changes. We suggest that these gaps are probably due to the whale starting and stopping echolocation sequences, potentially implying foraging success or foraging method change by switching to lower amplitude (not detected) buzzes.

In the dolphin example, we presume that this species is common dolphin based on the large number of clicks and the click character of other known species in this area (Soldevilla *et al.*, 2008). Potentially, small sub-groups were joining and breaking off from the larger group, but the scatter in the data prevents this from being observed in detail (Fig. 6). As more is learned about common dolphin behavior through visual and acoustic observations, perhaps the scatter and small fission-fusion tracks can be used to estimate group size and dispersion during travel (i.e., group width and length).

The dolphin track is about 14 km long and spanned $\sim$2 h providing an average travel speed of about 7–8 km h^{-1} for the group (Fig. 7). The path partially circles the tracking HARP, starting in the northwest and traveling along the slope to the southeast, where it then goes across the bathymetric slope south of the instrument ending up in the northeast. Maximum detection range was about 5 km, probably dependent upon the direction of travel (i.e., dolphin echolocation clicks are narrow beam with the most intense direction forward of the animal). The extent of the dolphin track may be overestimated because the animals may be clicking deeper than at the sea surface; however, given the significant horizontal motion of these animals, they are likely not diving to great depths. The general pattern of the track will remain valid with smaller position errors as the track moves closer to being directly above the instrument. Developing statistics of received amplitude, location, and direction of travel from tracking HARPs provides maximum detection ranges to calling animals, an important parameter required to estimate population size from a single fixed-point hydrophone using distance sampling techniques (e.g., Buckland *et al.*, 2001).

V. CONCLUSIONS

A long-term acoustic recorder was modified to include a small-aperture hydrophone array with the goal of tracking marine mammals using a single passive acoustic recorder. The tracking HARP was deployed offshore of southern California at approximately 1000 m deep for about one month in a region with a known high occurrence of echolocating odontocetes. To illustrate the capabilities of the tracking HARP, two Cuvier's beaked whales were tracked simultaneously during a foraging dive. The whales dived to about 1000 m deep at different times, but both followed isobaths while presumably searching for prey. Common dolphins were tracked traveling near the sea surface. Two hours of nearly continuous dolphin echolocation clicks were mapped. By processing many tracks, statistics can be developed to describe free-ranging odontocete movement patterns for different parameters such as time of day, season, region, and oceanographic features. How these patterns may differ in the presence and absence of anthropogenic sources, such as ship noise, can also be studied. Furthermore, this technique has the potential to be used to develop acoustic detection probability versus range functions which are needed for estimating population density and abundance for marine mammals using passive acoustic monitoring methods.

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