

# Tracking dolphin whistles using an autonomous acoustic recorder array

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Dolphins are known to produce nearly omnidirectional whistles that can propagate several kilometers, allowing these sounds to be localized and tracked using acoustic arrays. During the fall of 2007, a km-scale array of four autonomous acoustic recorders was deployed offshore of southern California in a known dolphin habitat at  $\sim 800$  m depth. Concurrently with the one-month recording, a fixed-point marine mammal visual survey was conducted from a moored research platform in the center of the array, providing daytime species and behavior visual confirmation. The recordings showed three main types of dolphin acoustic activity during distinct times: primarily whistling during daytime, whistling and clicking during early night, and primarily clicking during late night. Tracks from periods of daytime whistling typically were tightly grouped and traveled at a moderate rate. In one example with visual observations, traveling common dolphins (*Delphinus* sp.) were tracked for about 10 km with an average speed of  $\sim 2.5$  m s<sup>-1</sup> (9 km h<sup>-1</sup>). Early night recordings had whistle localizations with wider spatial distribution and slower travel speed than daytime recordings, presumably associated with foraging behavior. Localization and tracking of dolphins over long periods has the potential to provide insight into their ecology, behavior, and potential response to stimuli. © 2013 Acoustical Society of America. [http://dx.doi.org/10.1121/1.4802645]

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## I. INTRODUCTION

Tracking cetaceans can provide information on their daily and seasonal movement behaviors, distributions, habitat use, and responses to environmental and anthropogenic stimuli. Various methods exist for tracking cetaceans including satellite and global positioning system (GPS) tags, ship-board and land-based visual surveys, and active and passive acoustic monitoring (PAM). Each of these methods has different strengths, which provide different perspectives on cetacean movement. PAM systems use the sounds that these animals produce to estimate their location with sequential locations providing tracks. Some of the potential advantages of using PAM systems to track cetaceans include monitoring over long periods (months to years), non-invasively, during day and night, world-wide, and during all weather conditions. Spatial arrays of PAM systems are arranged in many different configurations depending on focal species, study area, and monitoring goals. For example, locations and tracks have been made for sperm whales (*Physeter macrocephalus*) at U.S. Navy's Atlantic Undersea Test and Evaluation Center seafloor cabled-array (Giraudet and Glotin, 2006; Nosal and Frazer, 2007), blue whales (*Balaenoptera musculus*) using a sonobuoy array (McDonald

*et al.*, 2001), humpback whales (*Megaptera novaeangliae*) using towed arrays (Tiemann *et al.*, 2004), and fin whales (*Balaenoptera physalus*) with an array of autonomous seafloor recorders (McDonald *et al.*, 1995). Of the various PAM systems, autonomous acoustic recorders provide the best trade-off between portability and persistence, but they must be clock-synchronized and precisely located if they are to be used as individual elements in an array for tracking cetaceans.

Hydrophone sensors for PAM arrays are typically configured with km-scaled spacing, large enough for monitoring movements over hours, but small enough so that the same sound is received on multiple sensors allowing time delays to be used for sound source localization. To accomplish this, the sound source must be intense enough to be received by at least three sensors. To date, only large whales have been tracked with PAM arrays mainly because many baleen whale calls are intense, omnidirectional, and at frequencies low enough that signal attenuation is negligible. Sperm whale clicks, while being narrow-beam directional signals and at higher frequencies, are intense enough in directions off-axis of the main beam to overcome attenuation at km-scale ranges (Mohl *et al.*, 2003). Echolocation clicks from smaller cetaceans are lower intensity, spread energy across a wider frequency band, are at frequencies high enough that signal attenuation is significant (e.g.,  $-30$  dB km<sup>-1</sup> at 100 kHz; Fisher and Simmons, 1977), and have reduced levels

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off-axis of the click's narrow beam ( $-30$  dB at  $>30^\circ$  off-axis; Au, 1993). These signal characteristics require that array sensor spacing be much less than km-scale to receive the same dolphin click on more than three sensors (e.g., Hirotsu *et al.*, 2010; Wiggins *et al.*, 2012). Dolphin whistles, on the other hand, are nearly omnidirectional, have narrower band signals at lower frequencies (5–30 kHz) with less attenuation, and are intense enough to be recorded concurrently on multiple widely spaced sensors, making them well-suited for km-scaled arrays (Janik, 2000).

We deployed a km-spaced, seafloor array of four autonomous acoustic recorders offshore of southern California to monitor and track whistling dolphins (Fig. 1). In the center of the array, the research platform (R/P) floating instrument platform (FLIP) manned with visual observers was moored to provide daytime focal follows of passing cetaceans, including monitoring their surface behavior to correlate with acoustic cues. In this paper, we describe the experiment, our data analysis techniques, and show examples of whistling dolphins' tracks that are characteristically different depending on the time of day, potentially indicating diel behavioral differences.

## II. METHODS

### A. Experiment

During the fall of 2007, the R/P FLIP (Fisher and Spiess, 1963) was deployed along with four autonomous high-frequency acoustic recording packages (HARPs; Wiggins and Hildebrand, 2007), northwest of San Clemente Island offshore of southern California. R/P FLIP provided a platform for a fixed point visual survey of marine mammals

during daylight hours and acoustic monitoring via hydrophone arrays day and night during a four-week deployment from 10 November through 10 December.

The four HARPs were deployed approximately 1000 m north, east, south, and west of R/P FLIP in a square array configuration on the seafloor at approximately 800 m deep (Fig. 1; Table I). The HARPs sampled continuously at 200 kHz for an effective bandwidth of 10 Hz to 100 kHz. To localize acoustic sources, arrays require precise estimates of sensor positions. HARP positions and depths were determined to within 5 m root-mean-square (rms) from a ship-based survey conducted by the deployment ship (R/V Sproul) using concurrent GPS locations and transponder two-way travel times with a least-squares inverse calculation (e.g., Creager and Dorman, 1982). The array aperture was chosen with the goal of correlating the acoustic recordings with visually observed surface behaviors of passing small odontocetes. Marine mammal visual and acoustic surveys conducted from R/P FLIP offshore of southern California have shown that large groups of delphinids (hundreds or more) can be visually identified to about 6 km, and whistles can be recorded up to about 8 km.

Clock synchronicity between instruments is essential for localizing with arrays. HARP clocks have low drift rates to aid in this synchronization. Drift rates were measured by comparing HARP clock pulses to a high-precision (100 ns resolution) satellite clock before and after deployment. Clock drifts were then confirmed using 11 kHz pulses triggered by an Inter-Range Instrument Group-B clock from R/P FLIP at GPS recorded positions to the HARPs for recording. Drift rates ranged from  $-5.4 \times 10^{-8}$  to  $1.2 \times 10^{-8}$ .

To correlate surface behavior and visually observed dolphin locations with acoustically derived tracks, observers recorded animal sightings from a platform at the top of R/P FLIP, 26 m above the water during daylight hours when Beaufort Sea state was six or less. Pairs of visual observers used binoculars to establish bearing and reticle of sightings, which were then converted to positions from R/P FLIP. Species identifications were confirmed by two observers on a lower platform, using "big eye" binoculars and digital photography (Henderson *et al.*, 2011).

Whistling is common among many delphinids (e.g., Oswald *et al.*, 2008). The potential dolphin whistlers for this study in the Southern California Bight were common (*Delphinus* sp.), bottlenose (*Tursiops truncatus*), Pacific white-sided (*Lagenorhynchus obliquidens*, PWS) and Risso's (*Grampus griseus*). PWS and Risso's dolphins whistle rarely, but have unique click structures allowing them to be distinguished using PAM data (Soldevilla *et al.*, 2008).

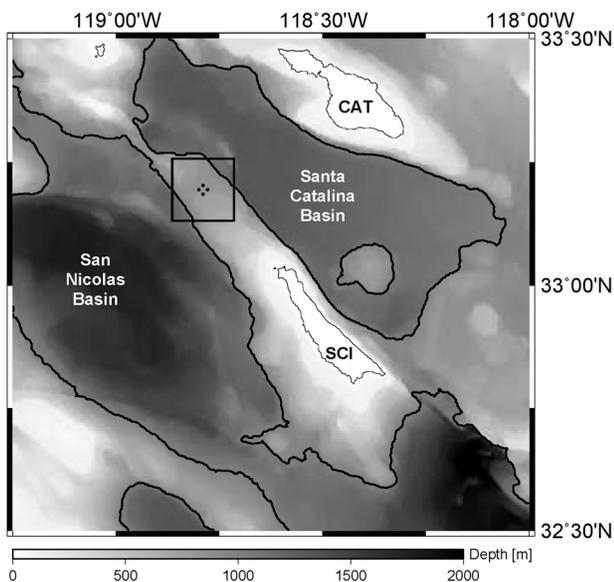


FIG. 1. Regional bathymetric map of the study site offshore of southern California. The  $14 \times 14$  km box is the monitoring site northwest of San Clemente Island (SCI) and southwest of Santa Catalina Island (CAT) on the ridge between the eastern Santa Catalina Basin and the southwestern San Nicolas Basin. R/P FLIP is centered 1000 m from the four small black circles, 800 m deep HARPs (Table I). The thick contour is 1000 m deep, the thin contour is the coastline, and darker shading is deeper. Box shows location of Figs. 5 and 6.

TABLE I. Array positions from acoustic-GPS localization ( $\pm 5$  m rms).

	Latitude (N)	Longitude (W)	Depth (m)
HARP 1 (N)	$33^\circ 12.182'$	$118^\circ 47.351'$	853
HARP 2 (E)	$33^\circ 11.649'$	$118^\circ 46.688'$	837
HARP 3 (S)	$33^\circ 11.102'$	$118^\circ 47.308'$	788
HARP 4 (W)	$33^\circ 11.627'$	$118^\circ 47.961'$	846

*Tursiops* are found in small (average 20 individuals) groups (Defran *et al.*, 1999), and although they are common to the area, they were not observed visually during this study. *Delphinus* sp. are highly vocal and social animals, are often found in large (hundreds to thousands) groups (e.g., Selzer and Payne, 1988), and were the most frequently observed dolphin during this study. Two species of common dolphin, *D. capensis* and *D. delphis*, are present offshore of southern California, but no attempt was made to distinguish between the two for this study. We therefore assume that recordings with ubiquitous whistling and non-distinctive clicks are from common dolphins.

## B. Data analysis

Periods of dolphin acoustic activity (i.e., whistles and echolocation clicks) were identified using long-term spectral averages (LTSAs) of the recordings. LTSAs are composed of long duration (5 s) averaged spectra arranged sequentially into a spectral time series similar to a spectrogram, and provide an efficient method of evaluating large acoustic data sets for periods of increased acoustic activity across a wide band of frequencies (Wiggins and Hildebrand, 2007). Periods, or bouts, of acoustic activity were categorized into three acoustic behavior types: mostly whistles, both whistles-clicks, and mostly clicks. Waveform data of bouts containing whistles were bandpass filtered from 5 to 20 kHz to minimize sounds beyond the whistle frequency band (Oswald *et al.*, 2003). These data were transformed into the spectral domain as standard spectrograms to be used for tracking.

A common method for localizing a sound source using a large aperture array is to measure the sound arrival times at the different array elements. The time difference of arrival (TDOA) for each array element pair provides an angle to the sound's incoming wave, and these angles are used to estimate location either using inverse or forward modeling techniques (e.g., Zimmer, 2011). Whistle TDOAs were calculated as the time-lag peak of cross-correlating concurrent standard spectrograms from each HARP recording with the other three instrument recordings, resulting in six TDOAs from the four instruments. A 5-s spectrogram duration was chosen based on typical whistle durations and array geometry (i.e., maximum TDOA). Because spectrograms are essentially digital images with an estimate of sound spectrum level for each time-frequency pixel, parameters used to calculate the spectrograms influence the cross-correlation time-lag peak amplitude and temporal resolution. A 25-ms (5000-point) discrete Fourier transform (DFT) with 50% overlap was applied to balance large correlation peaks with signal temporal resolution. Spectrogram "contrast" (gain) and "brightness" (offset) were adjusted to visually optimize signal-to-noise ratio (SNR) of recorded whistles. The cross-correlation process was repeated consecutively on 5 s intervals throughout each whistle bout. For each of the six TDOAs within a 5 s window, the most intense whistle with the largest time-bandwidth product is used for estimating location. Since individual whistles were not explicitly detected and often multiple whistles occurred during the 5 s

window, widely spaced whistling animals could result in localizations with large uncertainties, so localizations with mean error greater than 125 m (84 ms) were discarded allowing locations to be considered as an average for a tightly spaced group or individual animal during the windowed period.

The TDOAs were used in a forward modeling, least-squares, best-fit optimization algorithm based on the software package *Ishmael* (Mellinger, 2001). The model assumed a linear ray path and a constant sound speed (1490 m/s, based on mean daily conductivity temperature depth cast data from R/P FLIP). The algorithm was run on 180 h of dolphin encounter data obtained from 576 h of continuous, simultaneous recordings. Visual observations from a daylight encounter with *Delphinus delphis* were compared with concurrent acoustic tracks.

In this study, dolphins were assumed to vocalize in the top 30 m of the water column (Hastie *et al.*, 2006), and the maximum acoustic range from the center of the array (i.e., R/P FLIP position) was limited to 7 km, thus the possible localization volume was 30 m × 14 km × 14 km. Allowing a larger area did not significantly alter localizations. Tracks for encounters were generated by plotting successive localizations. Morning civil twilight (sun 6° below the horizon) is approximately at 1400 (all times in Greenwich Mean Time) and evening civil twilight is around 0200 for November at the study site.

## III. RESULTS

Out of the 30 days of recording, each day had at least one of the three types of bouts with most of the nighttime bouts containing mostly clicks or whistles-clicks, and most of the daytime bouts containing mostly whistles only (Fig. 2). An LTSA from 17 November during the transition from night to day shows the change in acoustic behavior of a

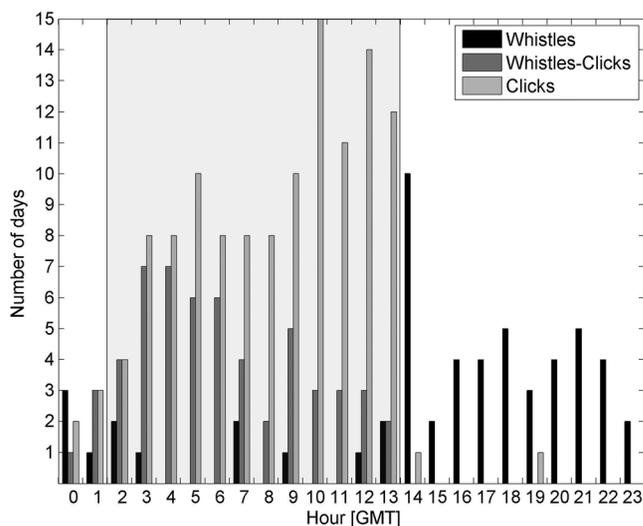


FIG. 2. Hourly dolphin acoustic behavior over one month from spectrogram evaluation of the northern HARP. Shaded light gray period from 0200 to 1300 is nighttime. Black indicates mostly whistling, dark gray is whistling-clicking, and medium gray is mostly clicking behavior. Whistling is predominately during daytime hours, whereas, mostly clicking increases and whistling-clicking decreases throughout the night until daybreak.

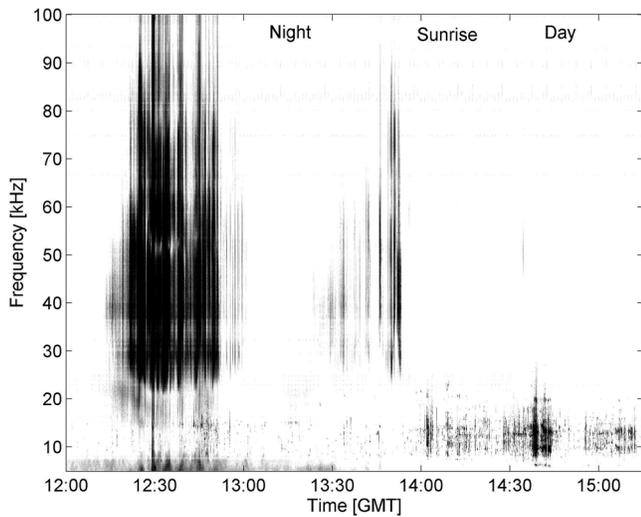


FIG. 3. LTSA of a bout of dolphin acoustic activity ( $\sim 3$  h). The long duration spectrogram starts at 1200 GMT and shows mostly clicking (25 kHz–100 kHz) activity with some whistling (10 kHz–15 kHz). At morning civil twilight (1400 GMT), the acoustic behavior changes to intense mostly whistling (7 kHz–20 kHz).

group of dolphins from whistling-clicking to mostly whistling (Fig. 3).

One-hour LTSAs (10 kHz–100 kHz) from the four recorders show that dolphin broadband, high frequency, highly directional echolocation clicks are not concurrently recorded on each instrument, but lower frequency, narrower bandwidth, omnidirectional whistles are, allowing these signals to be used for tracking using km-scale arrays (Fig. 4, left panels). Over a shorter period and narrower band

(5 kHz–20 kHz), spectrograms (4 s) show the same individual whistles recorded with slightly different arrival times on the four HARPs (Fig. 4, right panels).

Spectrograms, such as those depicted in the right panels of Fig. 4, were cross-correlated providing TDOAs for the six pairs of hydrophones. TDOAs were then used to estimate positions with sequential positions often defining tracks. For example, whistles from daytime recordings provide TDOAs that often result in tightly spaced tracks (Fig. 5). In this 70-min track of almost 600 localizations from 21 November, the dolphins traveled at an average rate of about  $2.5 \text{ m s}^{-1}$  ( $9 \text{ km h}^{-1}$ ). They start southwest of the array about 3 km, head southeast, then northeast, and north until they are almost above the southern HARP. From there, the group heads northeast in a serpentine-fashion and around 1900 they are sighted three times by the visual observers. Around fifteen and thirty minutes later, the group is re-sighted heading northeast away from R/P FLIP. This group of about 100 animals, including calves, was identified as common dolphin (*Delphinus* sp.) traveling northeast at a moderate rate (directional leaping, moderate swim speeds, some white water) with tight (less than one animal length apart) spacing (Henderson *et al.*, 2011). The concurrent co-location of dolphin visual sightings and acoustic localizations suggests these are the same group transiting through the area.

Nighttime bouts have a different acoustic character than daytime bouts, with mostly clicking and some whistles-clicks at night to mostly whistling during daylight hours (Figs. 2 and 3). Furthermore, nighttime tracks are characteristically different from typical daytime tracks. For example, a 2-h early nighttime track from a whistle-click recording on 17

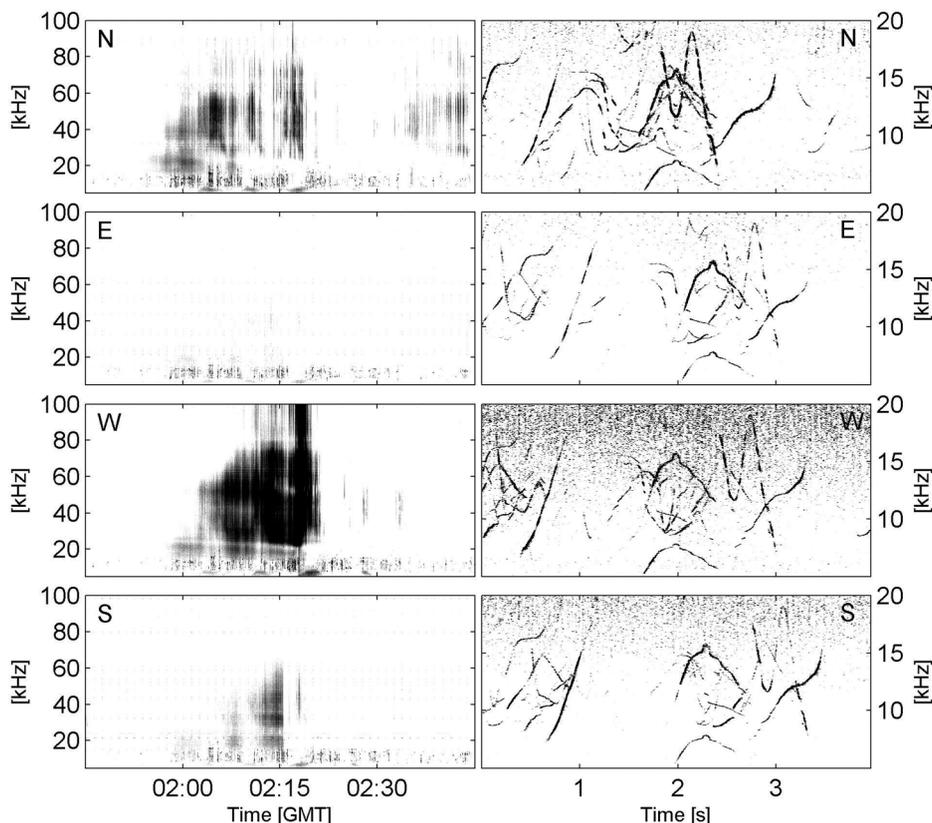


FIG. 4. Wideband (10 kHz–100 kHz), one-hour LTSAs (left panels) and four-second, narrowband (5 kHz–20 kHz) spectrograms (right panels) from four concurrent nighttime HARP recordings. The dolphins appear to be heading mostly toward the west instrument with some directed toward the north and to a lesser extent to the south recorder. The spectrograms of whistles are from about 02:15 GMT. LTSAs and spectrogram gains, including hydrophone sensitivities, are the same across recordings. LTSAs were calculated with a Hanning window, 2000-sample DFT and 5 s spectral averages. Spectrograms were calculated with a Hanning window, 20000-sample DFT and 50% overlap.

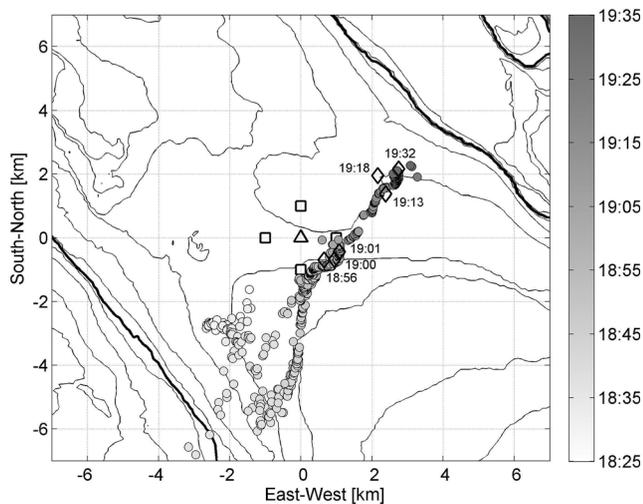


FIG. 5. Map view of 70-min daytime dolphin track from 575 whistle localizations. Filled circles are dolphin whistle locations with shading corresponding to the time scale bar at the right. HARP and R/P FLIP locations are squares and triangle, respectively, occupying a ridge between two basins. Visual observations from R/P FLIP of *Delphinus* sp. are depicted as diamonds and are labeled with sighting time. The thick contour lines are 1000 m deep with thin lines at 50 m increments.

November with about 300 localizations shows many short tracks over a wide area with slow overall group movement to the north of the array, then southwest, and finally to the east (Fig. 6).

## IV. DISCUSSION

### A. Technique

To our knowledge, the large-scale tracks presented here are the first for free-ranging whistling dolphins using a km-scale hydrophone array. The spectrogram approach to obtaining TDOAs uses all whistles occurring during a time window, so localizations and tracks can be only considered as coming from a group, although individuals would be tracked if only one animal were whistling during each

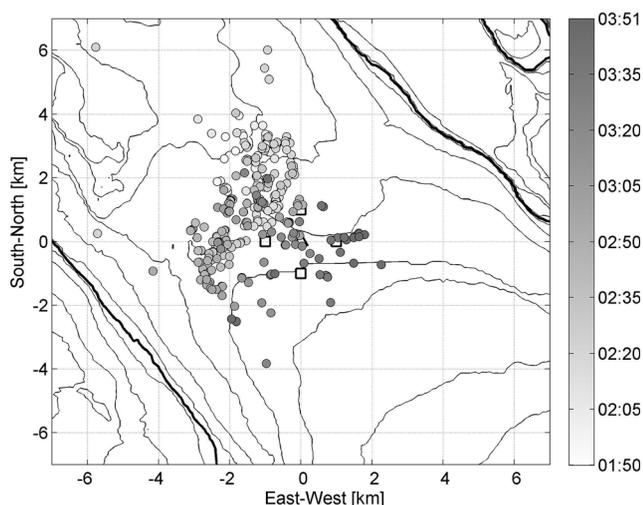


FIG. 6. Map view of 2-h nighttime dolphin positions from 325 whistle localizations. Filled circles are dolphin whistle locations with shading corresponding to the time scale bar at the right. HARP and R/P FLIP locations are squares and triangle, respectively, occupying a ridge between two basins. The thick contour lines are 1000 m deep with thin lines at 50 m increments.

window. Work has been done on isolating individual whistles from recordings (e.g., Roch *et al.*, 2011) and these methods applied to our array data may provide more detailed tracks from individuals; however, it may be difficult to separate unique whistles when there are large numbers of overlapping whistles as often observed during nighttime bouts (e.g., Fig. 4, right panel). Daytime tracks are often tight and move quickly in one direction (Fig. 5) suggesting minimal benefit from isolating individual whistles, but nighttime localizations, which are composed of shorter tracks presumably from spread-out sub-groups or individuals (Fig. 6), would likely benefit from tracking individual whistlers. However, whistle SNR is often reduced during nighttime by intense (on-axis) clicks as these broadband sounds extend down into the whistle frequency band and can cause the waveform to clip (Fig. 4, left panel, W).

### B. Acoustic behavior and tracks

Acoustic and surface behavior of dolphins is known to vary with time of day (e.g., Norris *et al.*, 1994; Benoit-Bird and Au, 2003; Soldevilla *et al.*, 2010; Henderson *et al.*, 2011), with foraging frequently occurring at night, often on the rising scattering layer, while travel and social behavior occurs primarily during the day. In this study, dolphins were found to predominantly whistle during the day, whistle and click in the early night, and predominantly click in the late night. In general, whistling is related to communication and clicking to foraging, suggesting these sound types may be associated with different movement patterns as seen in the example tracks from mid-day mostly whistling and early night whistling-clicking recordings. The daytime tracks were tightly clustered while the dolphins traveled at moderate rates, suggesting that mostly whistling is being used to keep the group closely spaced and moving in a common direction. The early night tracks are much more loosely spaced and spread over a wider area, while whistling occurs less frequently but over a longer period than daytime tracks. These characteristics coupled with the increased nighttime clicking suggest that the animals are foraging at night near the array. The daytime tracks are consistent with the visual observations of Henderson *et al.* (2011), who found travel to be the predominant common dolphin surface behavior during the day, with slower travel speeds and smaller groups in the morning and increasing group size and rates of travel throughout the day. In addition, that study found the highest number of whistles and longest whistle bouts were recorded during daytime traveling, whereas daytime foraging was rarely observed and occurred with the fewest number of whistles. The ability to acoustically track dolphin groups grants insight into nighttime behavior, as well as the transitions between behavioral states and the fission–fusion nature of group dynamics, which are difficult to capture through traditional visual observation methods.

## V. CONCLUSIONS

Three main types of dolphin acoustic activity were recorded for one month offshore of southern California: mostly whistling, whistling-clicking, and mostly clicking.

The occurrence of these three sound types was dependent on time of day, with mostly whistles typically occurring during the day, whistles-clicks during early night, and mostly clicks during late night. Since the localization technique presented relies on recorded whistles, the best tracks are from daytime hours often with closely spaced localizations and moderate travel speeds. Early night recordings have fewer whistles and increased noise from echolocation clicks, but the loosely spread localizations over longer periods may depict foraging behavior. Recordings from late night have too few whistles to be localized with this technique, but small aperture arrays with close (~1 m) sensor spacing could be used to track narrow-beam signals from clicking cetaceans (Wiggins *et al.*, 2012).

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