

## **AUTOMATED PASSIVE ACOUSTIC TRACKING OF DOLPHINS IN FREE-RANGING PODS**

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*Abstract: Research in passive acoustic detection and localization of marine mammals has largely focused on isolated cases of single or few individuals. However, many marine mammals, such as dolphins, characteristically aggregate in large pods. In addition, dolphins vocalize frequently, emitting broadband clicks and frequency-modulated whistles, which, coupled with a large number of individuals, further complicates the detection and localization problem. Using acoustic data collected on a high-frequency horizontal line array deployed near the Southern California Offshore Range (SCORE), automated tracking of individual dolphins within large pods is achieved by exploiting time differences of arrival and frequency-domain beamforming. Visual observations are used to corroborate acoustic localization results and to describe dolphin vocalization and group behavior patterns.*

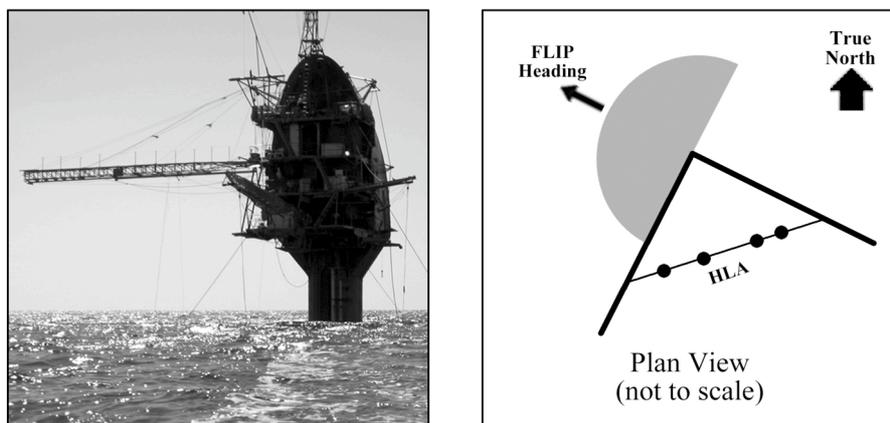
### **1. INTRODUCTION**

Detection and localization of marine mammals using passive acoustics has been an increasingly active area of research to advance general knowledge of marine mammals and to support conservation and mitigation efforts. Such research has almost exclusively focused on isolated cases of single or few individuals [1, 2]. However, many abundant marine mammals, such as dolphins, aggregate in large pods and also actively vocalize, making them prime candidates for the application of passive acoustic techniques.

In this paper, the area of study was near a U.S. Navy training range off the coast of California, a location rich in odontocete activity. Over the course of three weeks, the vocalizations of several species of dolphins (*Delphinus delphis*, *Delphinus capensis*, and others) were recorded on a high-frequency horizontal line array (HLA), and visual observations by trained marine mammal observers were collected concurrently. Automated tracking of individual dolphins within pods numbering as many as several hundred individuals was achieved. Dolphin clicks were detected by a constant false alarm rate (CFAR) detector and localized using the time differences of arrival between sensors. Dolphin whistles were detected using a frequency-based energy detector, and isolated whistles were then localized with frequency-domain beamforming. The resultant bearing-time records of numerous clicks and whistles combined with visual observations suggest that fast-traveling groups of dolphins rely primarily on whistling to communicate while slowly-traveling groups of dolphins rely upon clicking to aid in feeding.

## 2. EXPERIMENT

The SCORE23 (Southern California Offshore Range) Experiment took place in August and September 2004 northwest of San Clemente Island about 75 miles off the coast of San Diego, California where the *R/P FLIP* was placed in a three-point moor. Visual observers were stationed on the upper deck and on a tower mounted on top of *FLIP*. A four-element, 0.9-m aperture, minimum redundancy HLA was deployed between *FLIP*'s port and face booms at approximately 30 m depth (refer to Figure 1).



*Fig. 1: Photo of the R/P FLIP moored near San Clemente Island off the California coast during the SCORE23 Experiment (left). Plan view of FLIP and the array orientation (right).*

Even in a three-point moor, *FLIP*'s heading constantly changes due to winds and currents. *FLIP*'s heading was noted throughout the experiment, subsequently interpolated, and applied as a time-dependent bearing correction to the array. Visual and acoustic observations were made concurrently from sunrise to sunset, weather permitting.

## 3. DATA ANALYSIS

Dolphins produce a variety of sounds which can be categorized as broadband clicks or frequency-modulated whistles. During the SCORE23 Experiment, it was not uncommon for thousands of clicks and whistles to be heard on the HLA each day. To process such a large number of signals, an automated detection and localization system for each type of signal was necessary. Several methods to passively detect and localize marine mammals currently exist. However, most have been used to study whales [3–5], a few have been applied to dolphins [6–8], but none had been used to investigate such a large, free-ranging population as that encountered at SCORE, a site considered to be an odontocete feeding ground.

### 3.1 Clicks

The observed clicks were of very short duration,  $\sim 50 \mu\text{s}$ , and highly broadband, extending the full 96 kHz bandwidth of the HLA. (Some dolphin clicks are known to have peak frequencies over 100 kHz [9].) A constant false alarm rate (CFAR) detector was used to detect the clicks. First, the CFAR detector whitened the data so that the samples shared similar statistics, making it possible to apply a constant detection threshold to all samples.

Next, a multiple pass, moving average with a split window tuned to the width of the clicks was applied, yielding the following figure of merit:

$$\text{FOM}(n) = \frac{x(n) - m_x(n)}{\sigma_x(n)} \quad (1)$$

where  $x$  is the click time series,  $m_x$  is the local mean of  $x$ , and  $\sigma_x$  is the local standard deviation of  $x$  estimated by the moving-average process. By associating clicks on one sensor with clicks on another sensor, one can then map the difference in arrival times to bearing.

### 3.2 Whistles

The observed whistles were of longer duration, on the order of 1 s, and frequency-modulated, with fundamental frequencies between 5 and 20 kHz. Whistles vary greatly in duration and bandwidth but are readily identifiable in a spectrogram. Therefore, whistles were detected in the frequency domain by analyzing spectrograms for energy above an empirically-derived threshold and tracking those peaks that remained within a frequency band of  $\pm 500$  Hz for successive time windows. Once a track was identified, frequency-domain, planewave beamforming was performed where beamformer output can be expressed as:

$$B(f, \theta) = \left| \sum_{n=1}^N \exp \left[ j(2\pi f / c) d_n (\sin \theta - \sin \theta') \right] \right|^2 \quad (2)$$

for sensor  $n$ , signal frequency  $f$ , speed of sound  $c$ , interelement spacing  $d_n$ , estimated arrival angle  $\theta$ , and hypothesized arrival angle  $\theta'$ . In Equation 2, a bearing of  $0^\circ$  refers to an arrival angle broadside to the array. The resultant frequency-azimuth output  $B$  is then summed over frequency, thus averaging out grating lobes which vary with frequency and revealing a distinct mainlobe that serves as the estimate of bearing for that whistle.

## 4. RESULTS

Bearing estimates obtained from whistles and clicks as described in Section 3 were plotted as a function of time. In addition, visual observations were overlaid upon the bearing-time records (BTR's) to (a) verify bearing estimates derived acoustically and (b) explore possible correlations between types of vocalization and behavior. Figures 2 and 3 show BTR's for two consecutive days, September 8<sup>th</sup> and 9<sup>th</sup>, respectively, during the SCORE23 Experiment. Bearing is plotted relative to true north with corrections for the rotation of FLIP, as described in Section 2. In these figures, blue dots represent bearing estimates derived from whistles, green dots represent bearing estimates derived from clicks, and red lines represent visual observation tracks with group identification-number labeled at the beginning of each sighting. For the sake of the discussion that follows, specific features are marked with capital letters.

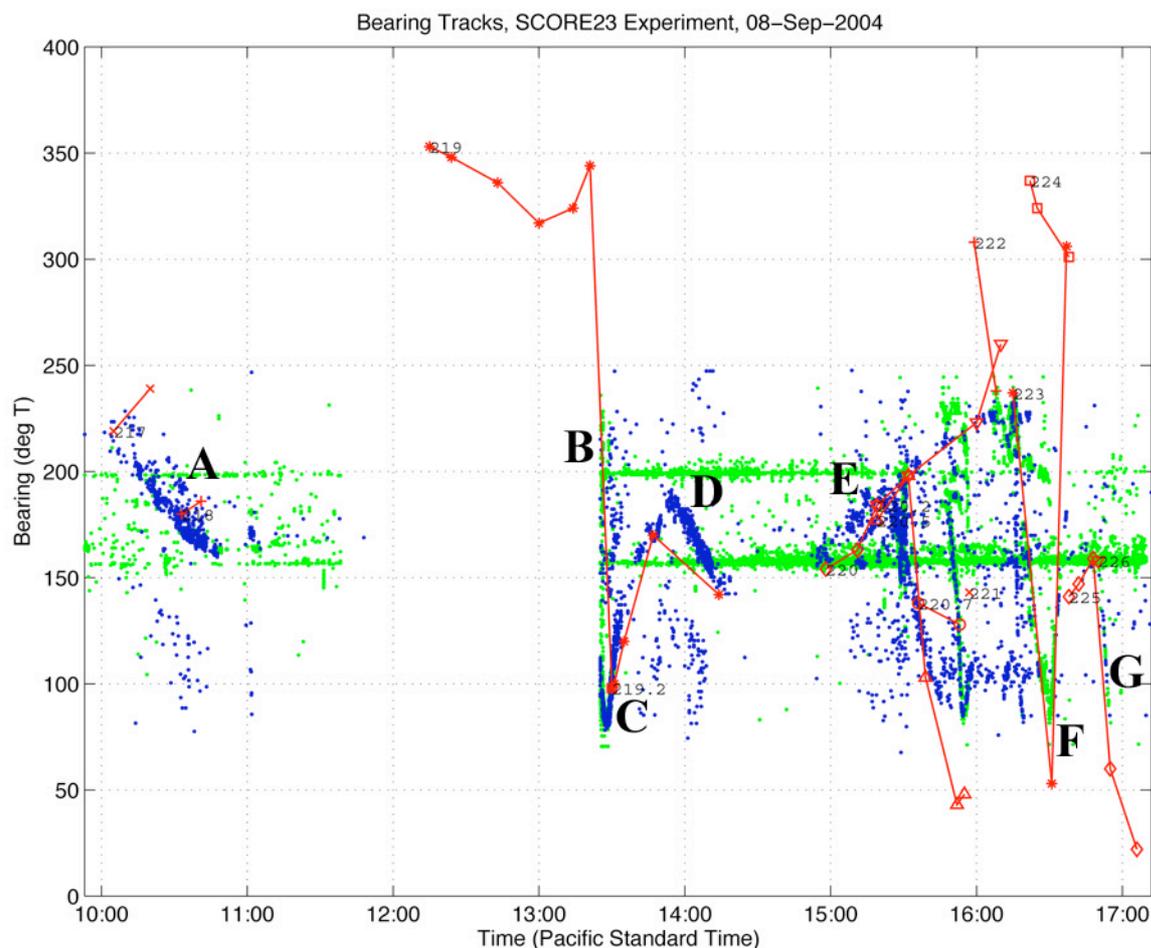


Fig. 2: BTR for September 8<sup>th</sup>. Blue dots represent whistles, green dots represent clicks, and red lines indicate visual observations with group identification-number labeled at the beginning of each sighting. Capital letters denote features of interest.

First, note that the horizontal click “tracks” in Figures 2 and 3 are noise artifacts. Specifically, the apparent “track” at  $\sim 155^\circ$  T (T meaning relative to true north) is actually common-mode noise on the array; it consistently appears broadside. The second “track” at  $\sim 200^\circ$  T is hypothesized to be occasional broadband noise emanating from *FLIP* since it always appears  $45^\circ$  from broadside of the array, corresponding to *FLIP*’s location. Second, the visual observations are relatively undersampled in time; therefore, the red lines should be viewed as general trends in dolphin movement. Despite this shortcoming, the visual observations often coincide very well with acoustic tracks and also provide information on dolphin behavior as well as location. Third, the brief periods lacking bearing estimates in both figures correspond to gaps in acoustic data collection during the experiment.

In Figure 2, Feature A is described by visual observers as two groups of 150 and 275 individuals at a range of 4–5 km. Considering their distant range and bearing rate, the dolphins were likely traveling at a fairly brisk pace. It is worth noting that these animals were solely whistling, the method of vocalization associated with fast travel throughout the SCORE23 Experiment. Feature B represents 350 *Delphinus delphis* within 1 km of *FLIP*, hence, their extreme bearing rate. These dolphins were both clicking and whistling, but at C were noted as traveling fast and ceased clicking in favor of almost exclusively whistling by Feature D. According to observers, the group at E was likely a continuation of the group at D

along with the addition of 250 individuals but, by E, the group began splitting up. This “fission-fusion” grouping pattern has been witnessed frequently in dolphin communities [10] and is also seen in the acoustic tracks here. Both clicking and whistling resume until, at F and G, 10–30 *Delphinus delphis* remain, slowly traveling and milling and, notably, clicking.

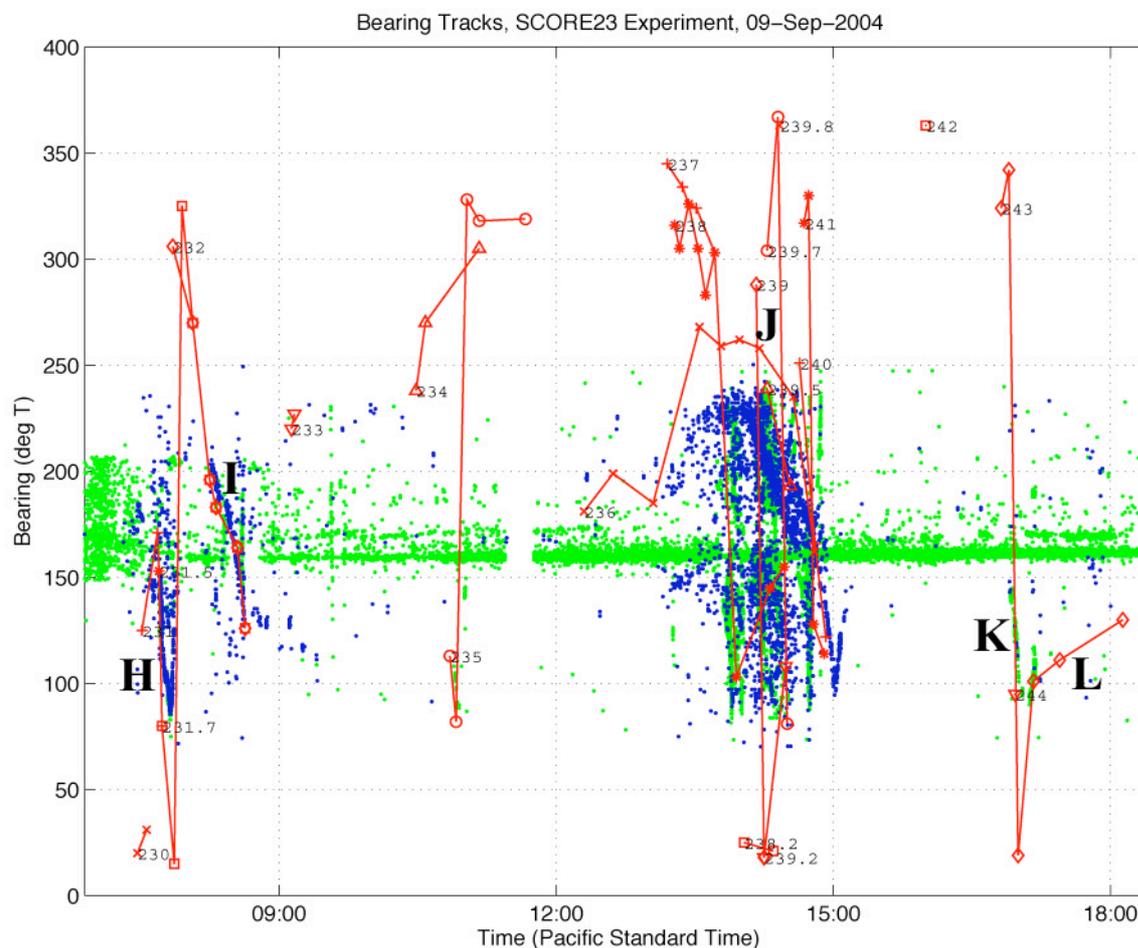


Fig. 3: BTR for September 9<sup>th</sup>. Blue dots represent whistles, green dots represent clicks, and red lines indicate visual observations with group identification number labeled at the beginning of each sighting. Capital letters denote features of interest.

In Figure 3, there is again good agreement between visual and acoustic observations. The activity during the first two hours of the morning involve the repeated splitting and joining of groups from 10’s to ultimately 100’s of (275) individuals. At H, there is concurrent whistling and clicking. By Feature I, the large combined group of 275 individuals are engaged in fast travel, “lots of leaping,” and frequent whistling. As before, there appears to be a correlation between speed of travel and type of vocalization. Feature J is also comprised of numerous groups exhibiting “fission-fusion” behavior, most within 500 m in range, accounting for the quick change in bearings. Several groups are described as slowly traveling, milling, and/or feeding; note the click tracks. A couple of widely-spread whistle tracks are also evident, as some groups are noted as traveling at a moderate pace past FLIP. Feature K is a group of 30 *Delphinus delphis* milling within 500 m of FLIP, probably feeding on a baitball sighted earlier in the same location. Clicking is the virtually only form of vocalization here, most likely being used to detect, recognize, and localize prey. Feature L shows these dolphins

traveling away from FLIP. Their vocalizations cease as they apparently quit their feeding activities and depart the area.

## 5. CONCLUSION

Passive acoustic detection and localization of free-ranging pods of dolphins on the order of hundreds of individuals was demonstrated. Using a four-element horizontal line array, click and whistle detectors coupled with estimated time differences of arrival and frequency-domain beamforming produced bearing-time records over multiple days. Combining acoustic tracking results with concurrent visual observations provided a unique view of free-ranging dolphins and their vocalization and behavior patterns, revealing that fast moving pods primarily whistle, perhaps as a form of communication among dispersed individuals, while slowly moving pods primarily click, presumably to localize their prey while feeding.

## ACKNOWLEDGMENTS

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