Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego

# Progress Report on the Application of Passive Acoustic Monitoring to Density Estimation of Cuvier's Beaked Whales


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Automatic detection of acoustic encounters has been completed for eight sites, and has provided verified encounters with Cuvier’s beaked whales. Currently underway is manual verification of individual echolocation frequency-modulated (FM) pulse detections. Mean group size distribution was determined by counting the number of overlapping echolocation sequences when the whales were close to the acoustic recorder, with a result of 2.4 animals mean group size. Density estimates for a single site (N) yielded a time series of weekly density estimates for 2009 – 2015 with average density of 1.93 ± 0.48 animals per 1000 km2 for click counting, and 1.72 ± 0.31 animals per 1000 km2 for group counting methods.

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# EXECUTIVE SUMMARY

Progress is reported on efforts to estimate the density of Cuvier's beaked whales (*Ziphius cavirostris*), using passive acoustic monitoring data collected with Navy support at sites in the Southern California Bight. Two methods for estimating weekly densities of beaked whales are presented, one based on the number of echolocation clicks detected (click counting) and the other based on the presence of clicks during 1-min time bins indicating the presence of animal groups (group counting). The click-based method requires an estimate of mean click production rate, while the group-based method requires the proportion of 1-min bins a group is vocally active. These parameters are obtained from tagging and tracking data collected for Cuvier's beaked whales in Southern California and other locations.

Automatic detection of acoustic encounters has been completed for eight sites, and has provided verified encounters with Cuvier's beaked whales. Currently underway is manual verification of individual echolocation frequency-modulated (FM) pulse detections. Mean group size distribution was determined by counting the number of overlapping echolocation sequences when the whales were close to the acoustic recorder, with a result of 2.4 animals mean group size. Density estimates for a single site (N) yielded a time series of weekly density estimates for 2009 – 2015 with average density of 1.93 ± 0.48 animals per 1000 $km^2$ for click counting, and 1.72 ± 0.31 animals per 1000 $km^2$ for group counting methods.

# INTRODUCTION

This project derives beaked whale densities within the Southern California region based on Navy-funded passive acoustic monitoring data, as a component of monitoring and reporting requirements and environmental planning.

Beaked whales are deep diving animals, difficult to census with conventional visual surveys. Cuvier's beaked whale (*Ziphius cavirostris*) has a cosmopolitan distribution in all except polar latitudes (MacLeod *et al.*, 2006) and may be the most abundant of all the beaked whales.

Several approaches have been presented to estimate beaked whale densities from passive acoustic monitoring data (Marques *et al.*, 2009; Moretti *et al.*, 2010; Kusel *et al.*, 2011; Marques *et al.*, 2013; Hildebrand *et al.*, 2015). All methods involved the estimation of the probability of detecting an acoustic cue made by a single animal or a group of animals. A cue counting approach was presented for estimating Blainville's beaked whale densities using a hydrophone array in the Bahamas (Marques *et al.*, 2009), where the cues were individual echolocation clicks and detection probability was estimated using animal-borne acoustic tags. Another form of cue counting was applied to the same dataset using the onset of echolocation by groups of diving whales as the cue (Moretti *et al.*, 2010). In this case, it was assumed that all groups of animals present within the study area were detected. Again using the same dataset, a Monte Carlo simulation was developed to estimate the probability of detecting calls as a function of distance (Kusel *et al.*, 2011) allowing density estimation to be conducted with single hydrophone sensors. An extension of this method was applied to two species of beaked whales in the Gulf of Mexico (Hildebrand *et al.*, 2015) using data collected over a three year time period to observe temporal trends. Two methods for estimating weekly densities of beaked whales are obtained from these data, one based on the number of echolocation clicks detected (click counting) and the other based on the presence of clicks during 1-min time bins, thereby indicating the presence of animal groups (group counting). The click-based method requires an estimate of mean click production rate, while the group-based method requires the proportion of 1-min bins a group is vocally active.

Although at least eight species of beaked whale are known to occur in Southern California waters, based on stranded animals (Mitchell, 1968; Dalebout *et al.*, 2007) and on acoustic monitoring data (Baumann-Pickering *et al.*, 2013; Baumann-Pickering *et al.*, 2014), the most common beaked whale species encountered off Southern California is Cuvier's beaked whale.

Cuvier's beaked whales produce characteristic echolocation sounds during foraging that are consistent across and between ocean basins (Zimmer *et al.*, 2005; Baumann-Pickering *et al.*, 2013). Cuvier's beaked whale typical echolocation sounds sweep up in frequency from 25 to 60 kHz over a 500 μs duration with a characteristic inter pulse interval of about 0.5 s and a peak frequency near 40 kHz. Beaked whales also produce buzzes in which the individual pulses are closer together in time, of shorter duration and do not sweep up in frequency. These buzzes are produced during the prey approach phase of feeding activity and are of lower source level than the regular echolocation pulses, making them more difficult to detect.

Passive acoustic monitoring can provide temporal and spatial distributions of beaked whales from recorded echolocation sounds over long periods at various locations. In this study, we evaluate Cuvier's beaked whale echolocation clicks from recordings at multiple sites within the Southern California Bight to provide a better understanding of beaked whale density and distribution.

## METHODS

Beginning in 2006, acoustic recorders have been deployed in the Southern California Bight region with sufficient bandwidth (100 kHz) to detect Cuvier's beaked whale echolocation FM pulses (Figure 1). All these site were examined for beaked whale signals within an ONR-funded project, but sites in water depths of less than ~500 m (e.g. sites A, B, C, G) were found to have few or no Cuvier's beaked whale echolocation signals. Sites in deep (~1000 m) water (E, H, M, N, R, S) were found to have ample Cuvier's beaked whale signals and are the focus of this study.

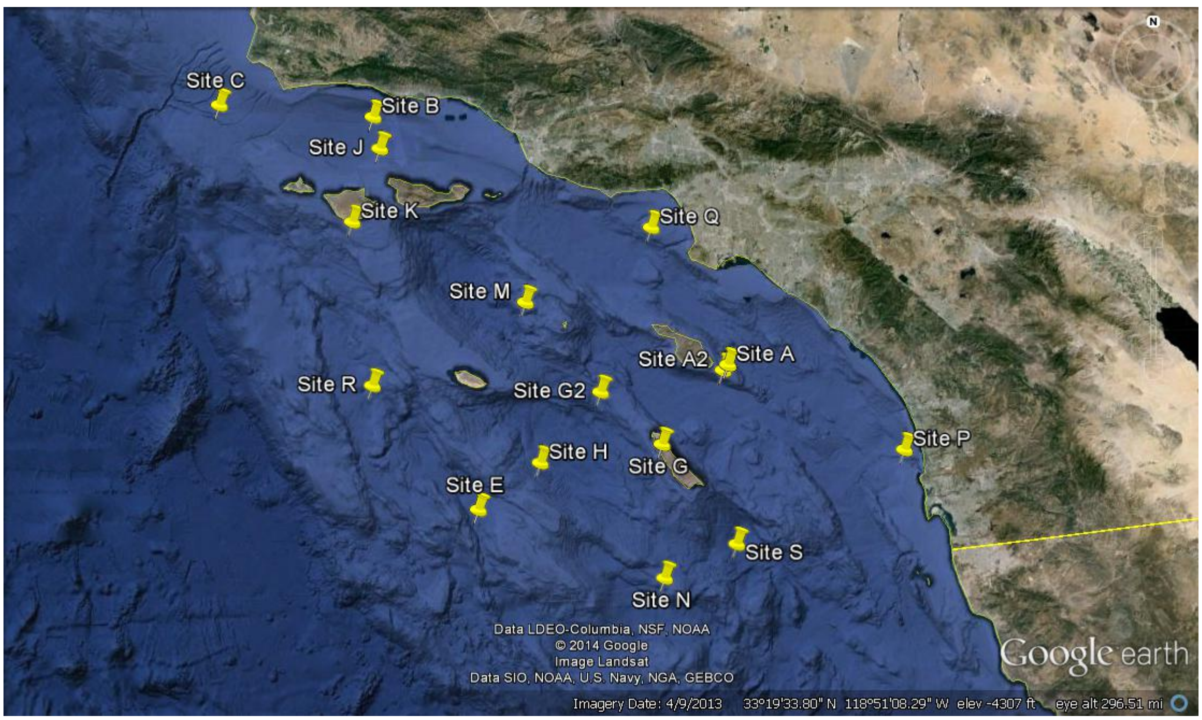


**Figure 1.** Acoustic recorder deployment sites around the Southern California Bight that were examined for Cuvier's beaked whale detections.

The autonomous recorders used for this study were High-frequency Acoustic Recording Packages (HARPs) described in Wiggins and Hildebrand (2007). All data were recorded at 200 ksamples/s with effective bandwidth of 10 Hz – 100 kHz. Selected recorders were calibrated at the U.S. Navy's TRANSDEC facility using reference hydrophones. The electronic noise floor at 40 kHz is approximately 40 dB re: 1 $\mu Pa^2$/Hz.

Beaked whale encounters, extended periods when beaked whale sounds were present in the data, were initially automatically detected and then classified to the species or signal type level with an analyst-assisted software (Baumann-Pickering *et al.*, 2013), also eliminating false encounters. The rate of missed encounters for this detector has been shown to be approximately 5% in Southern California (SOCAL) recordings based on comparison with manual analysis. All Cuvier's beaked whale acoustic encounters were reviewed in a second analysis stage to remove false detections of individual FM pulses and provide a consistent detection threshold. FM pulse detections occurred when the signal in a 10 – 100 kHz band exceeded a detection threshold of 121 dB pp re: 1 $\mu$ Pa. FM pulses within the acoustic encounters were manually reviewed using comparative panels showing long-term spectral average, received level, and inter-click-interval (ICI) of individual FM pulses over time, as well as spectral and waveform plots of selected individual signals. Within each encounter, false detections were removed by manual editing, for instance, when the detections were identified as being from vessels, sonars, sperm whales or delphinids, owing to inappropriate spectral amplitude, ICI, or waveform. In addition, this step provided another check on beaked whale species classification, and potentially remaining misidentified or false encounters were corrected or removed. We further examined randomly selected clicks and found an average false detection rate for individual clicks of ~3 %. These data were further divided into 1 min time-bins, and randomly selected time-bins were examined; an overall false detection rate of <1% for entire 1 min time-bins was found.

The next step was to determine the number of detections per unit effort. We collated the effort data and the count data by creating time bins of one week over the on-effort periods at each site. Then we associated detection counts and 1 min bin counts with each one of these weeks. A one-week period was chosen to provide a sufficient number of 1 min time-bins (10,080) for density estimation.

## *Density Estimation*

The goal of the analysis was to provide a density estimate for beaked whale species by site at the finest temporal resolution possible. We determined the animals' presence and the number of detected clicks during each 1 min time period for which we had data, and then averaged over a weekly time interval. We estimated animal density using distance sampling-based methods (Marques *et al.*, 2013) with both time-bin detection (group-based) and click detection (cue-based) approaches.

### *Group Counting*

A group counting approach for density estimation requires detection of the presence of animals within a set of short time windows, along with knowledge of the detectability of clicks produced by the group. It further relies on knowledge of both the mean group size ($\hat{s}$) and group vocalization behavior. Using a group counting approach, the estimated animal density $D_{kt}$ at site *k*, during week *t* is:

$$\widehat{D}_{kt} = \frac{n_{kt}\,(1-\hat{c}_k)\;\hat{s}}{\pi \quad w^2 \hat{P}_k \;\; \hat{P}_v \;\; T_{kt}} \qquad (1)$$

where $n_{kt}$ represents the number of time intervals (1 min windows) that groups were detected at site k during week *t*, and $T_{kt}$ represents the total number of time intervals that were sampled at site *k* during week *t*. The probability of detecting a group within a horizontal radius of size *w* (beyond which no detections are assumed possible) is $P_k$, and the probability of a group being vocally active in a 1 min window is $P_v$. To account for an imperfect detection process $c_k$ is the proportion of false detections. At the beginning and end of deployment periods, at least two days of data were required to produce a weekly estimate, otherwise data were associated with the adjacent weekly estimate. Varying effort across weekly estimates was accounted for by $T_{kt}$ in equation (1). The variance was obtained using the delta method approximation (Marques *et al.*, 2009), and confidence intervals were obtained from the estimated variance by assuming that density follows a log-normal distribution to preclude negative values (Marques *et al.*, 2009).

***Click Counting***

A cue-based approach for density estimation requires counting the number of detected clicks, along with knowledge of the click production rate ($r$) for individual animals and the detectability of individual clicks. Given $n_{kt}$ detected cues (echolocation clicks) in a time period $T_{kt}$ (sum of time periods at site $k$ during week $t$), animal density $D_{kt}$ can be estimated by:

$$\widehat{D}_{kt} = \frac{n_{kt}\,(1 - \hat{c}_k)}{\pi\, w^2 \widehat{P}_k\, T_{kt}\, r} \qquad (2)$$

where $P_k$ is the probability of detecting a vocal cue that is produced within the radius $w$ from the site $k$, and $c_k$ is the proportion of false detections.. Variance is obtained using the delta method approximation, as above.

***Group Size***

Estimates of beaked whale group size were derived from acoustic encounters based on overlapping click sequences with consistent ICIs. It was not possible to estimate group size for each encounter, so we instead selected beaked whale encounters with high received amplitude, suggesting that the animals were located near to the acoustic sensor, and applied the mean group size derived from this procedure to the entire dataset. We estimated the number of animals in selected groups by counting the number of overlaying echolocation sequences in the time series, looking for amplitude changes and consistent ICIs. The basic assumption of this approach is that all animals in a group vocalize and are detected simultaneously at least at some point, so we can use the number of overlapping sequences as an estimate for group size. We assume that the sample collected by this method is representative of the group sizes present in the population.

***Vocal Activity***

Both the click counting and group counting methods require knowledge of vocal activity to estimate beaked whale density. The click-based method requires an estimate of mean click production rate ($r$), while the group-based method requires the proportion of 1-min bins a group is vocally active ($P_v$). Both of these must be averaged over the entire cycle of diving and resting.

Estimated click rates ($r$) were obtained from the product of the mean proportion of the dive cycle spent clicking, and the inverse of the ICI. Ideally, these data would be obtained at the site the animals are being studied, but the scarcity of Cuvier's beaked whale acoustic tag data (Johnson and Tyack, 2003) means that we must use an estimate of the proportion of time an individual animal spent clicking (24.3%) derived from a variety of sites (Hildebrand *et al.*, 2015). In contrast, the ICI was estimated from the acoustic recordings in this study. A distinct peak is seen for the ICI, and the mode of the distribution was taken as the estimate.

To account for group clicking behavior, records of simultaneously tracked Cuvier's beaked whales were examined from southern California acoustic array data (Wiggins *et al.*, 2012; Gassmann *et al.*, 2015).

Combined with acoustic tag data, these yield a 47% probability of group clicking over the time span of a detection bin, averaged over the dive cycle (Hildebrand *et al.*, 2015).

***Detection Range***

The maximum range at which beaked whale echolocation can be detected can be estimated with knowledge of source level and directivity and the threshold level of the detection method. The directionality of echolocation from the whale reduces the likelihood of detecting any one echolocation pulse. The dispersion of direction among a group of animals will increase the likelihood of detecting the group as a whole. Simulations that predicted beaked whale detection probability as a function of horizontal range were developed for the click based and the group based methods by combining information on animal behavior and environmental sound propagation, following the approach of Kusel *et al.* (2011). The models calculated the detection probability for a single echolocation click as a function of range from the acoustic sensor, and the probability of detecting echolocation from a group of animals, as described in (Hildebrand *et al.*, 2015). For these models a source level of 225 ±3 dB pp re: 1 μPa @ 1 m was used with a click directivity of 24-28 dB pp (@ 40 kHz) based on tracking data for Cuvier's beaked whales off southern California (Gassmann *et al.*, 2015).

# PROGRESS TO DATE

## *Acoustic Detections*

Automatic click detectors, as described in Baumann-Pickering *et al.* (2013), were run for sites A2, E, G2, H, M, N, R, and S (Figure 1). The detector output is given as the daily average number of 1 min bins with detections per month (Figure 2). These data suggest that the presence of Cuvier's beaked whale varies by site and includes seasonal trends with lower number of detections in the fall (Figure 3) as described in Baumann-Pickering *et al.* (2015).

The process of manual verification of automatic detections is currently underway. This involves verifying that individual detections are properly classified as Cuvier's beaked whales. Figure 4 gives an overview of progress to date for sites E, H, M, N, R, and S, with somewhat more than half of these data verified. These data collectively represent 21 years of cumulative acoustic recording effort, with over 91 instrument deployments, resulting in 257 TB of raw data. The verified click rate and fraction of 1 min bins with detections for site N, between 2009 – 2015, are shown in Figure 5. These are the raw data used for the click counting and group counting methods for density estimation (respectively).

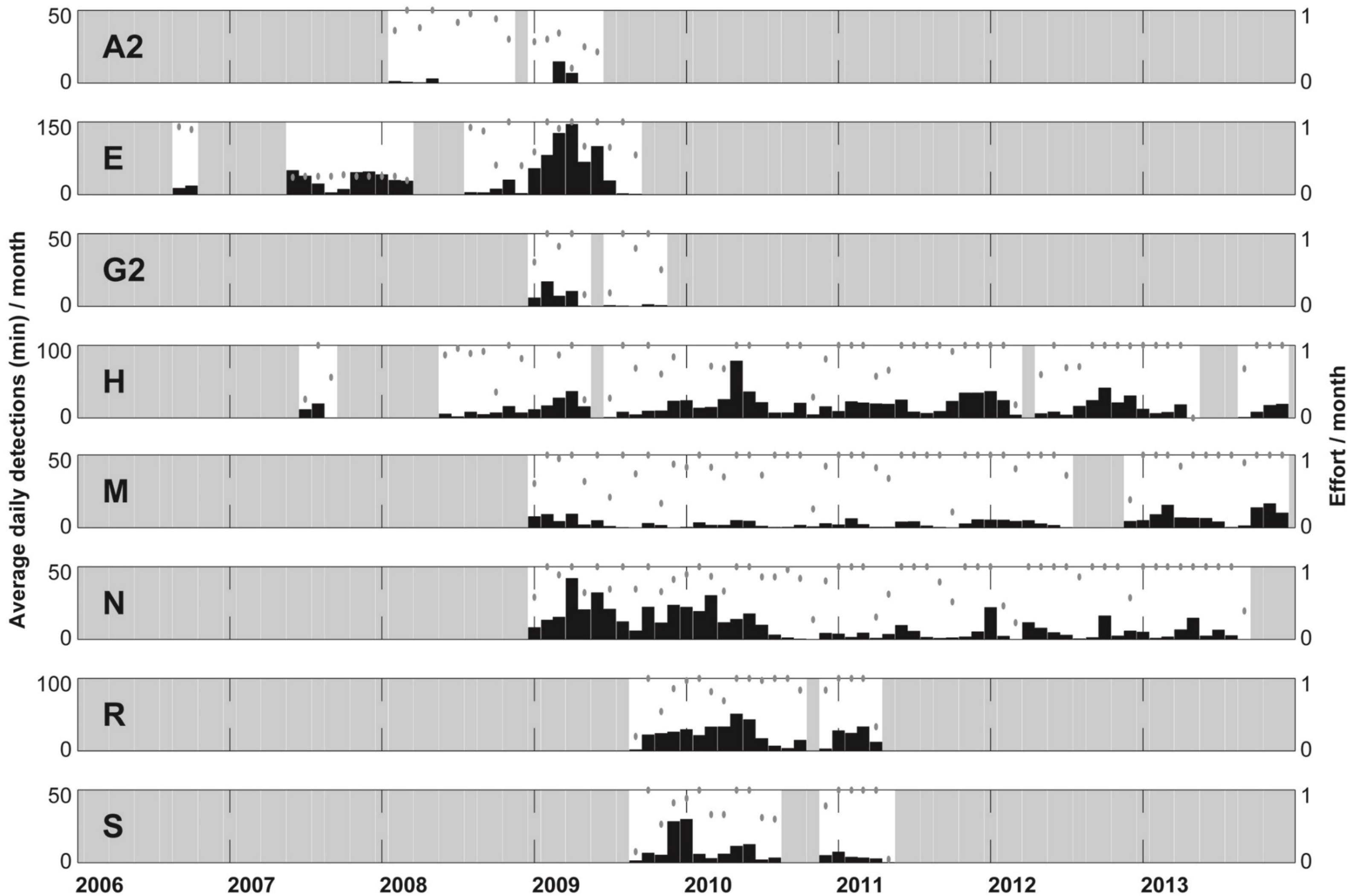


**Figure 2.** Output of Cuvier's beaked whale automatic detector by site (A2, E, G2, H, M, N, R, and S) given as the daily average of 1 min bins with detections. Note differences in vertical scale for some sites. After Baumann-Pickering *et al.* (2015).

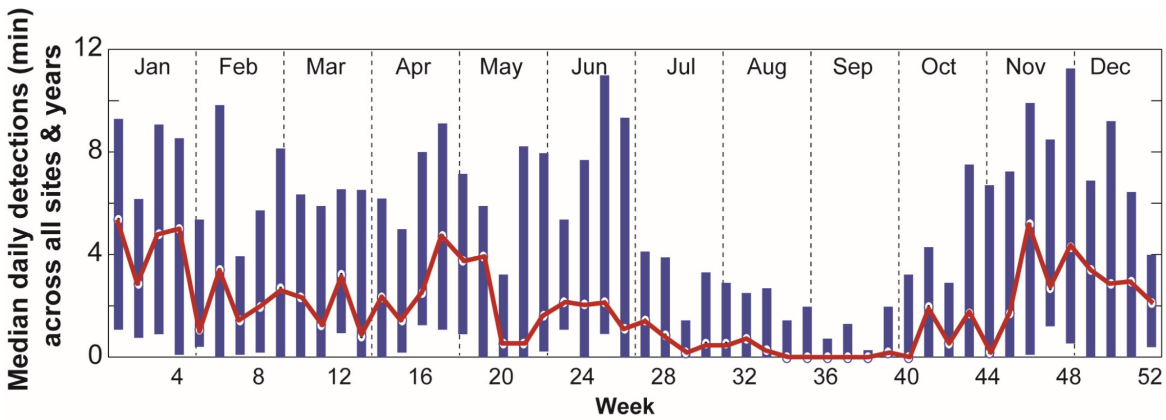


**Figure 3.** Seasonal trend of Cuvier's beaked whale presence in the Southern California region, from Baumann-Pickering *et al.* (2015). Blue bars show median and 1st and 3rd percentiles, red line follows median.

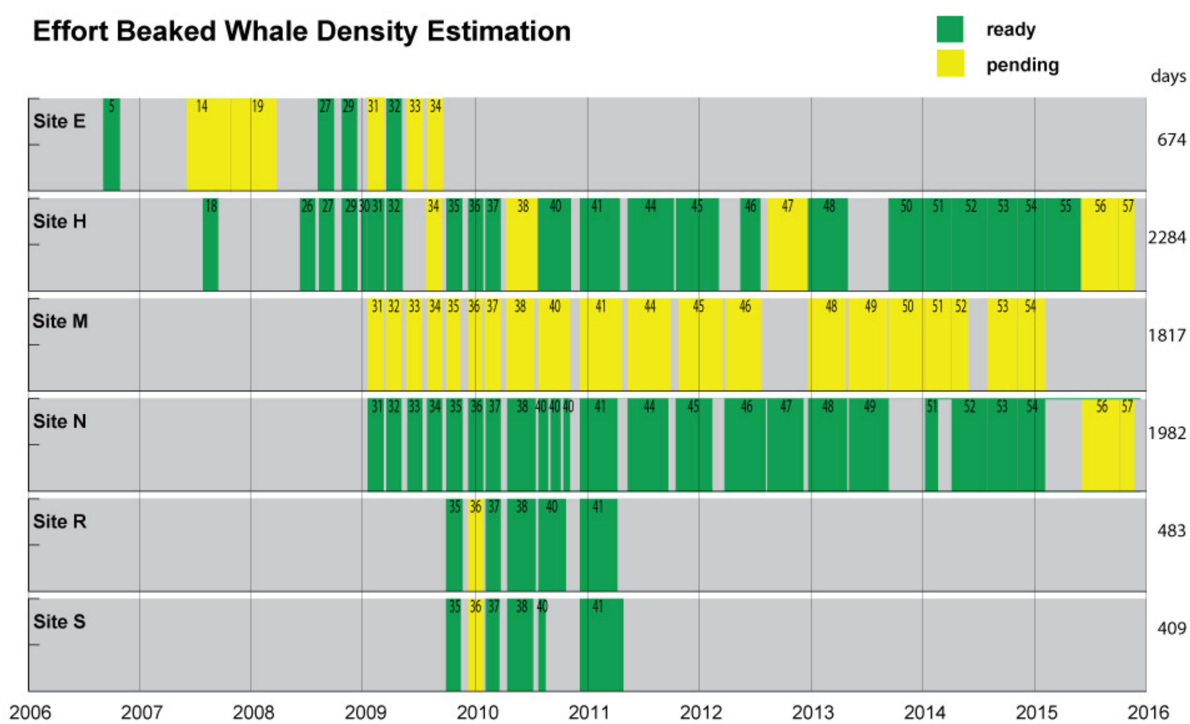


**Figure 4.** Effort to date in detailed editing of Cuvier's beaked whale echolocation detections.

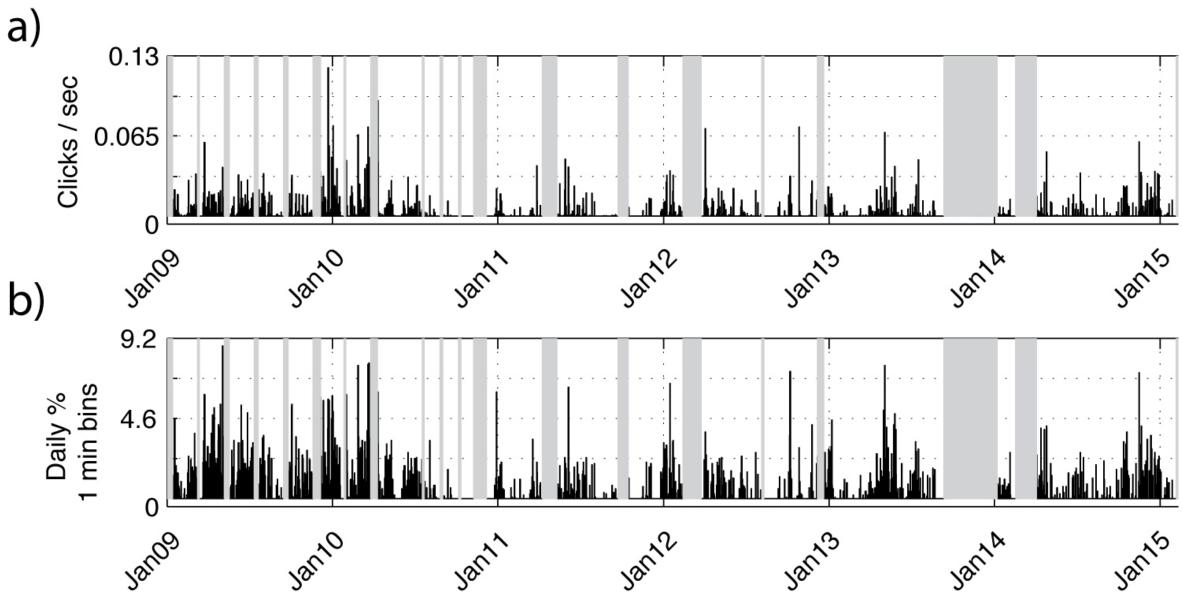


**Figure 5.** Analyst verified daily detections of Cuvier's beaked whale at site N between 2009-2015 as: a) average number of clicks/sec and b) fraction of 1 min bins with detections per day. Shaded regions lack data.

## *Group Size*

A total of 265 Cuvier's beaked whale encounters with high received levels were examined and group size was estimated from their consistent ICI and slowly varying amplitudes. About 75% of the group sizes were one to three animals and the mean group size was 2.4 animals (Figure 6). These are similar to Cuvier's acoustic group size estimates (n = 2.1, 1.7, & 2.0) obtained from sites in the Gulf of Mexico (Hildebrand *et al.*, 2015). As a comparison, the Cuvier's mean group size estimated from visual surveys off the US West Coast was 1.8 animals (Moore and Barlow, 2013). An alternate method (Falcone *et al.*, 2009) estimated a Cuvier's beaked whale mean group size of 3.8 animals (SD 2.4) based on visual surveys in Southern California, but this estimate is not directly comparable to the acoustic groups size estimate presented here, since they considered adjacent groups of animals that were not synchronously diving as a single unit.

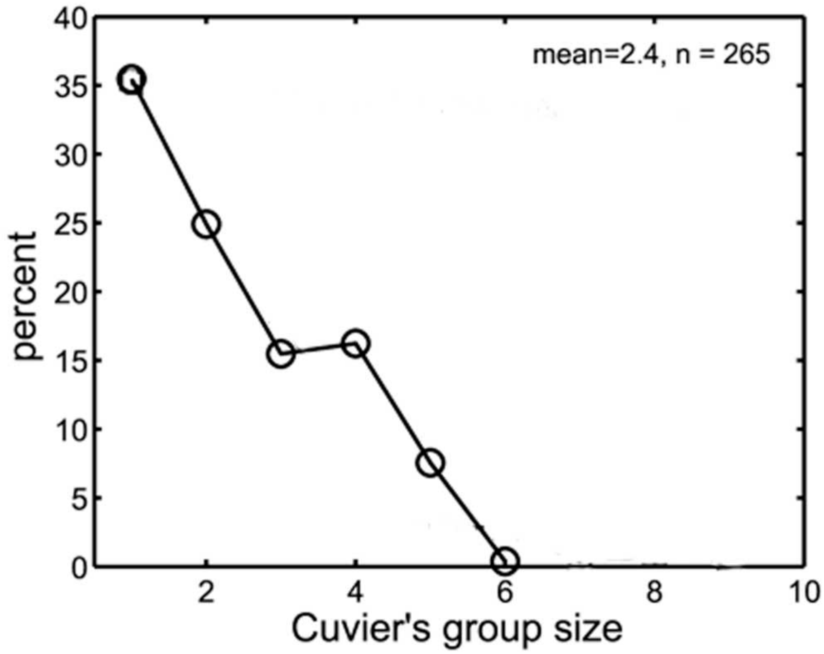


**Figure 6.** Acoustic group size estimates for Cuvier's beaked whales in the southern California region.

### *Vocal Activity*

Estimated click rates (*r*) for Cuvier's beaked whales were obtained from the product of the mean proportion of the dive cycle spent clicking (24.3% as described above), and the inverse of the ICI. For site N, a modal ICI of 0.483 s was observed (Figure 7). Therefore a click rate of 0.503 clicks/s is estimated, averaged over their dive cycles. Using acoustic data from the same sites and periods as used in the density estimate helps to make the click rates as applicable as possible.

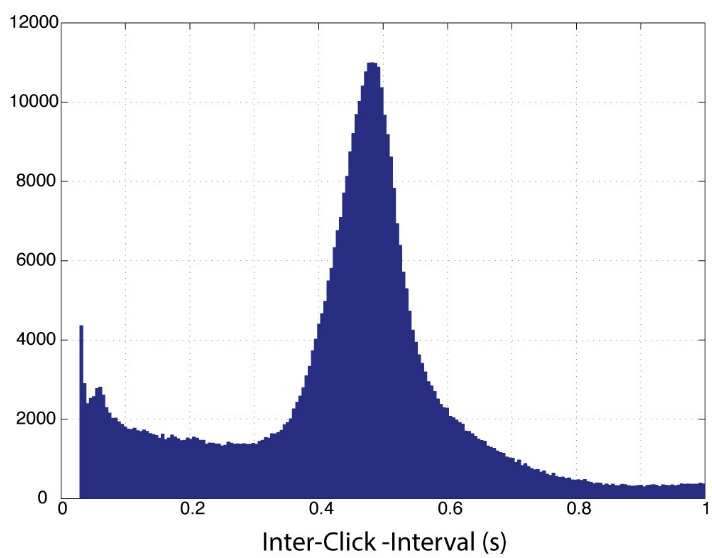


**Figure 7.** Inter-Click-Interval for Cuvier's beaked whales at site N. A total of 477,950 click intervals yielded a modal interval of 0.483 s.

### *Density estimate*

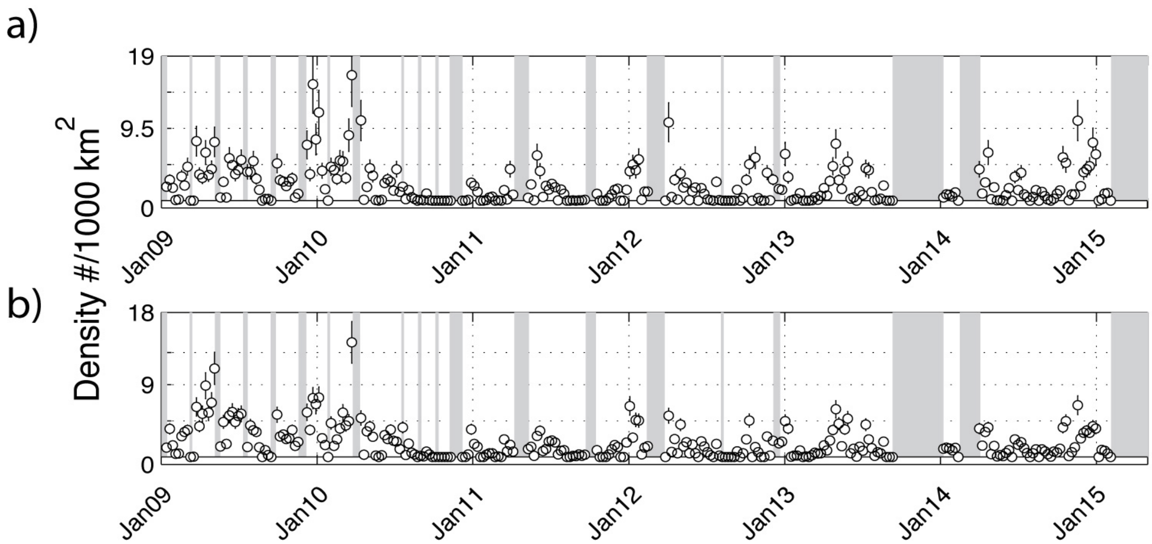


**Figure 8.** Density estimates (animals/1000 km$^2$) for Cuvier's beaked whales at site N between 2009-2015, from a) click counting method, and b) group counting method.

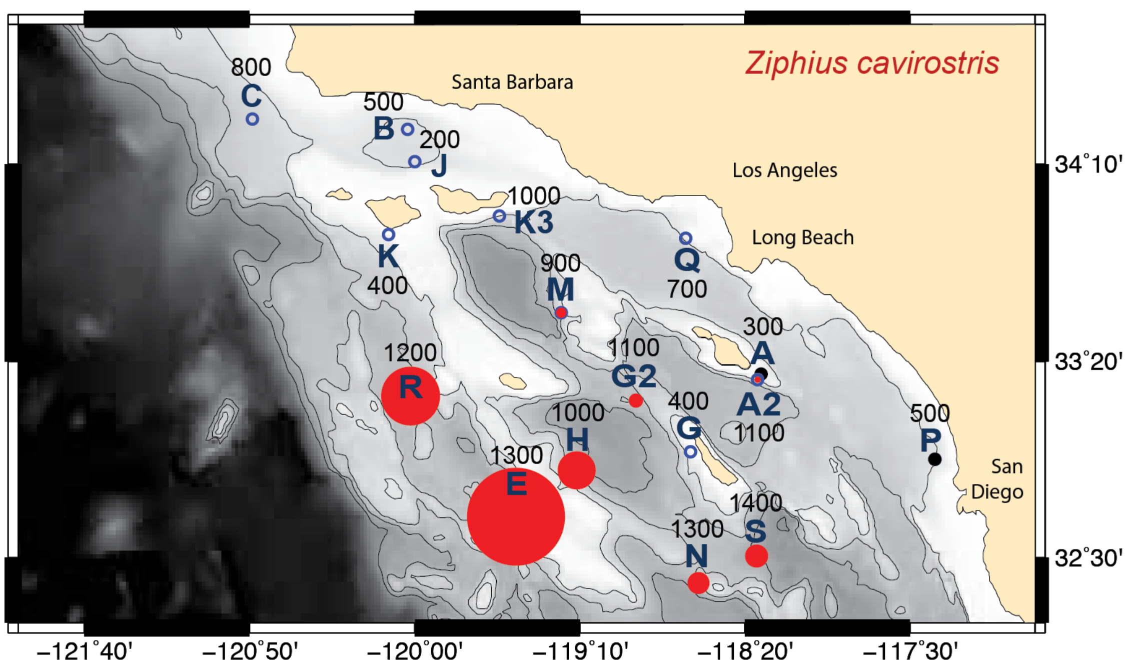


**Figure 9.** Relative density, based on total acoustic encounter durations normalize by effort, for Cuvier's beaked whales in the Southern California Bight. The circle size by each site gives the proportion of time bins with detections divided by the amount of time monitored. Site E with the largest circle had 45 minutes of average daily acoustic detections. The number above each site gives approximate bathymetric depth in meters. Preliminary results after Baumann-Pickering *et al.* (2015), data analysis continuing.

The click counting and group counting methods of weekly density estimates for Cuvier's beaked whales at site N are in general agreement (Figure 8), although the click counting method tends to have slightly more scatter in the weekly estimates. For 2009 – 2015, the average Cuvier's beaked whale density is 1.93 ± 0.48 animals per1000 $km^2$ for click counting, and 1.72 ± 0.31 animals per 1000 $km^2$ for group counting. When comparing density estimates from site N with previous work on relative densities using acoustic encounter durations across all passive acoustic monitoring sites in SOCAL (Baumann-Pickering *et al.*, 2015), (Figure 9), one can see that site N has a moderate density of Cuvier's beaked whale presence relative to sites to the west of it. Further density comparisons between sites will be possible after completion of manual FM pulse level data verification by analysts.

Cuvier's beaked whale population density estimates for the Pacific using visual methods include: 4.5 animals per 1000 $km^2$ (Ferguson *et al.*, 2006) for the Eastern Tropical Pacific, 3.8 animals per 1000 $km^2$ (averaged) for up to 300 nmi off the U.S. west coast (Barlow and Forney, 2007) and 6.2 animals per 1000 $km^2$ in Hawaiian waters (Barlow, 2006). These estimates are higher than the 1.7 – 1.9 animals per 1000 $km^2$ found at site N from acoustic data, although based on Figure 9, other sites in the Southern California Bight (e.g. sites E, H and R), are likely to increase the regional average.

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