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The Southern California Bight (SCB) is a highly productive ecosystem and thus, attracts a variety of cetaceans, including Bryde’s whales (*Balaenoptera edeni*). It also has areas of high human activity where ocean noise includes by sound from commercial shipping as well as from sonar activity. Several encounters of Bryde’s whales were tracked in this area using a large-aperture seafloor array of five High-frequency Acoustic Recordings Packages (HARPs), deployed from December 2010 to February 2011. Bryde’s whale Be4 calls were manually detected. Time-difference-of-arrivals (TDOAs) of a call between each hydrophone pair were computed by cross-correlating time series waveforms. A 10 km x 10 km area with 25-m grid spacing and homogeneous sound speed was used to calculate sets of modeled TDOAs for each grid point. To localize each whale call, the grid point with the smallest total least-squares difference between the set of measured and modeled TDOAs was used. Successive locations provide tracks from which sound source levels, swimming speeds, and calling rates can be estimated. These preliminary results provide a quantitative foundation required for sound impact studies as well as a population density estimate of this species in the SCB.

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1. INTRODUCTION

The Southern California Bight (SCB) is a highly productive ecosystem and thus, attracts a variety of cetaceans (Barlow et al., 2008), including Bryde's whales (*Balaenoptera edeni*) which are present primarily for foraging from spring until the beginning of winter (Kerosky et al., 2012). The SCB also has areas of high human activity where low-frequency (< 100 Hz) ocean noise includes sounds from commercial shipping (McKenna et al., 2012), and higher frequency (above 1 kHz) ocean noise includes sounds from nearby sonar activity (Hildebrand et al., 2011).

Bryde's whales produce a variety of geographically distinct low-frequency tonal calls (Oleson et al. 2003). In the SCB, the Be4 call (Figure 1) can be used as an indicator of Bryde's whale presence (Kerosky et al. 2012). This call is possibly a social call as it is often recorded in the presence of two or more animals (Oleson et al., 2003, Viloria-Gómora et al., 2015).

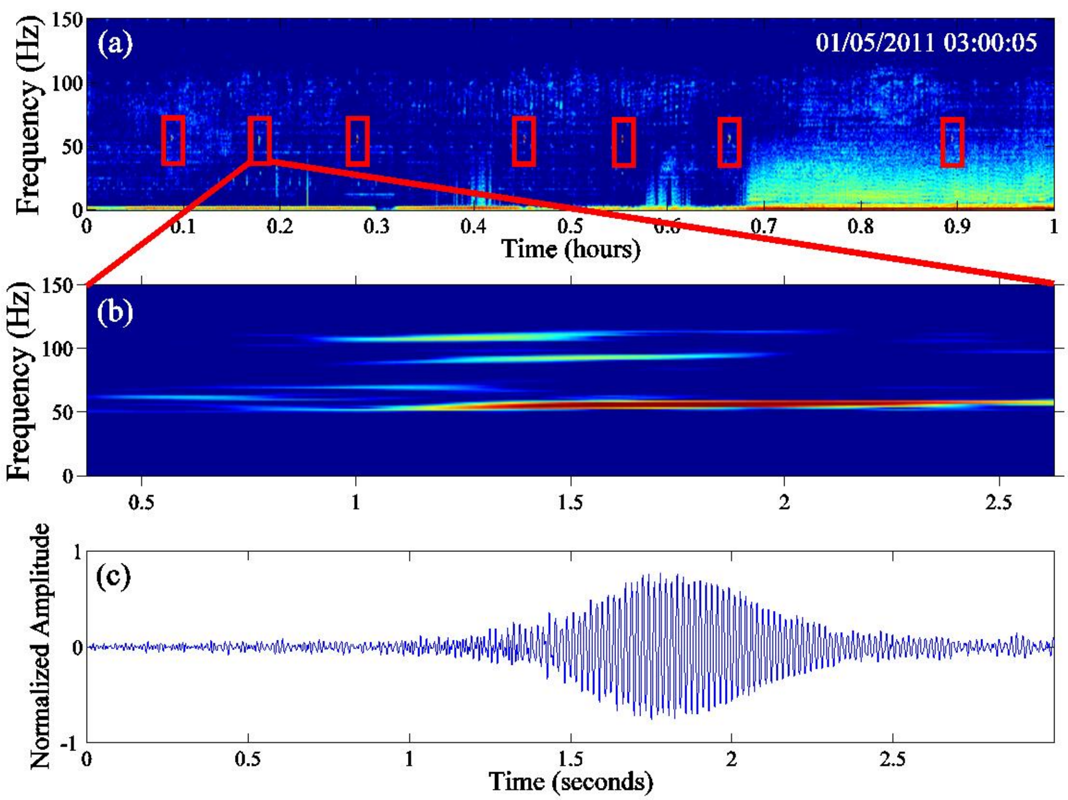

Figure 1. Bryde's whale Be4 calls in (a) long-term spectral average (LTSA) with calls highlighted with red boxes, (b) spectrogram (Hanning window, Fs = 2000 Hz, NFFT = 1500, overlap = 99%, band pass filter = 55-150 Hz), and (c) time series. Color for both (a) and (b) represents spectrum sound pressure level with warm colors as high levels and cool colors low levels.

Passive acoustic monitoring (PAM) with an array of sensors can be used to track vocalizing marine mammals to study their behavior, including changes in response to man-made noise. The preliminary results presented below are a first step towards calculating call source levels and rates, as well as swimming speeds and inter-call interval. These will provide a quantitative foundation required for sound impact studies as well as a population density estimate of this species in the SCB.

2. METHODS

A. EXPERIMENTAL SETUP

A large-aperture seafloor array of five High-frequency Acoustic Recordings Packages (HARPs) (Scripps Institution of Oceanography) with approximately 1 km element spacing was deployed over a two-month period from December 2010 to February 2011 in the SCB at a depth of approximately 1300 m (Figure 2). The northern (N) and western (W) HARPs were each equipped with a volumetric array of four hydrophones each sampling at 100 kHz (Gassmann et al., 2015; Wiggins et al., 2012); however, only the first channel of each HARP was used here for localization. The center (C), eastern (E) and southern (S) HARPs were each equipped with a single hydrophone sampling at a frequency of 200 kHz (Wiggins and Hildebrand, 2007). Hydrophone sensitivities and transfer function calibrations for all HARPs were performed at the Scripps Whale Acoustics Laboratory and at the U.S. Navy's Transducer Evaluation Center facility in San Diego, California. HARP locations were estimated by applying a least-squares inverse to two-way travel times of pings travelling between the acoustic release transponder of each HARP and a GPS-tracked ship shortly after array deployment (Wiggins et al., 2013). Clock drift rates varied across the HARPs ranging from 8.8×10^{-10} to 2.8×10^{-9}, resulting in an overall drift of 5 – 15 ms over the duration of the 63 day recording.

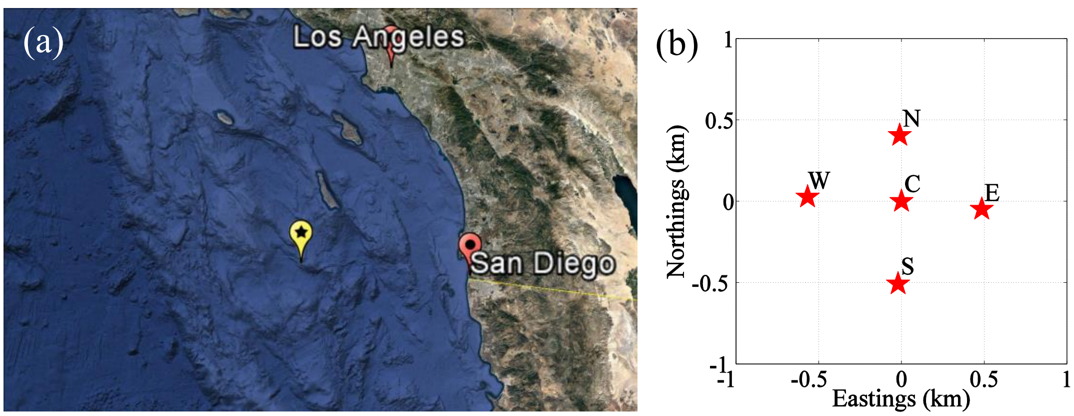

Figure 2. (a) Location of the seafloor array (yellow star) in the Southern California Bight. (b) Map of the seafloor array with five HARPs (red stars) geo-referenced to HARP C (32° 22.194 N, 118° 33.774 W).

B. TWO-DIMENSIONAL LOCALIZATION

A trained human analyst scanned all recorded data for the presence of Bryde's whale Be4 calls using the MATLAB-based acoustic analysis software package *Triton*, to view long-term spectral averages (LTSAs), spectrograms, and time series waveforms (Wiggins and Hildebrand, 2007). A 4^{th}-order elliptic bandpass filter from 55 to 65 Hz was applied to each detected call to minimize non-call sounds outside of this band. Time-difference-of-arrivals (TDOAs) of calls were computed between hydrophone pairs by cross-correlating time series waveforms. TDOAs that exceeded the maximum possible TDOA for hydrophone pair separation were excluded from the minimization. A 10 km x 10 km area with 25-m grid spacing and homogeneous sound speed was used to calculate sets of modeled TDOAs for each grid point. Whales were assumed to be calling at a depth of 30 m. A harmonic mean sound speed of 1486.3 m/s was used, based on a conductivity, temperature and depth (CTD) cast conducted at the location of HARP E at the start of the study period. To find the location of each calling Bryde's whale in Cartesian coordinates, the grid point with the smallest total least-squares difference between the set of measured and modeled TDOAs was used.

C. CALL SOURCE SOUND PRESSURE LEVEL CALCULATION

Call source sound pressure level (SL) was calculated from the sonar equation as the sum of the received sound pressure level (RL) and the transmission loss (TL). It was only computed for calls recorded at HARP C. The peak-to-peak RL of a call was measured over the 90% of the cumulative signal energy. A calibration of 71.0 dB re counts^2/µPa^2 in the 55-65 Hz band was applied to the measured RL to correct for this HARP's hydrophone sensitivity. TL was estimated from the localized horizontal range (r) as follows:

$$TL = \begin{cases} 20\,log_{10}\left(\frac{r}{r_0}\right)\ if\ r < d, \\ 20\,log_{10}\left(\frac{d}{r_0}\right) +\ 10\,log_{10}\left(\frac{r}{d}\right)\ if\ r > d, \end{cases} \quad (1)$$

where the first term is for spherical spreading, the second term is for cylindrical spreading, d is the water depth in meters and was 1263 m and r_0 is the reference range of 1 m. The mean SL was calculated after the estimated source amplitudes were converted to dB.

3. PRELIMINARY RESULTS

A. BRYDE'S WHALE LOCALIZATIONS

Multiple Bryde's whale calling sequences were localized, possibly indicating movement of animals over the calling period (Figure 3). On December 10, 2010, for example, there were at least two calling Bryde's whales present within an 18 km^2 area for approximately an hour, separated by about 3 km (Figure 3a). On December 27, 2010, there was at least one calling Bryde's whale, but additional Bryde's whales could have been calling within a 4.5 km^2 area for approximately two hours (Figure 3b). On December 31, 2010, there appeared to be a calling Bryde's whale travelling northbound along the eastern edge of the seafloor array, but it is possible there were additional calling whales in the vicinity (Figure 3c).

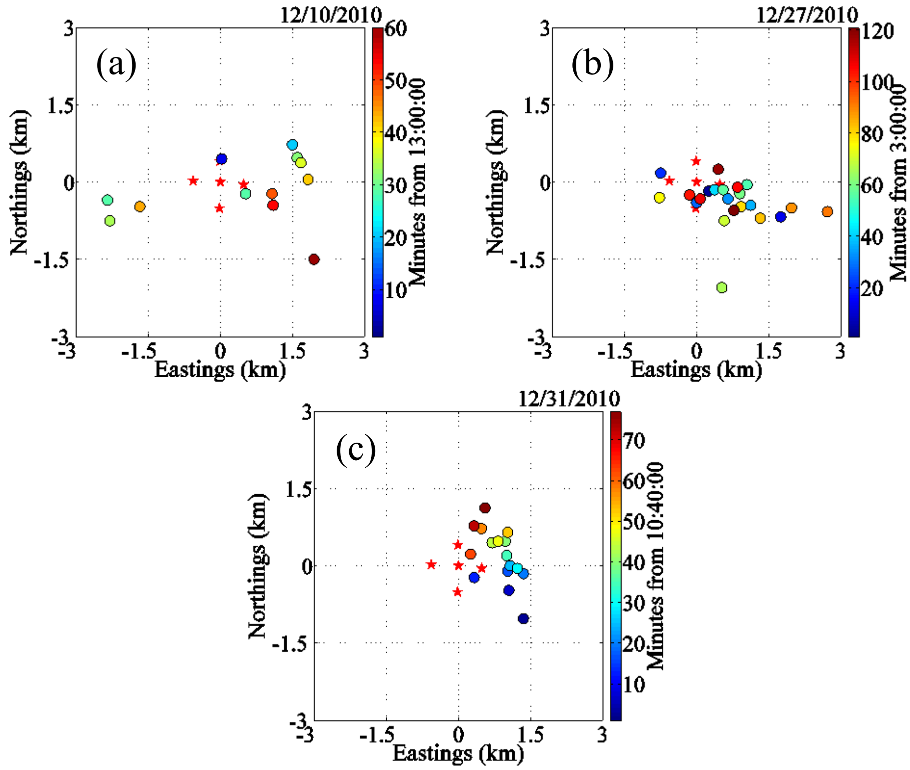

Figure 3. Locations of Bryde's whale calls detected in the Southern California Bight on (a) December 10, 2010 for approximately an hour, (b) December 27, 2010 for approximately two hours, and (c) December 31, 2010 for approximately an hour and 15 minutes in an 18 km² area. Color of each location indicates the time of the call relative to the first call in the sequence. Red stars indicate the location of each of the five HARPs geo-referenced to the center HARP (32° 22.194 N, 118° 33.774 W).

B. ESTIMATES OF CALL SOURCE SOUND PRESSURE LEVEL

Bryde's whale Be4 call source sound pressure levels ranged from 158.1 to 191.4 dB peak-to-peak re 1 µPa @ 1 m over 55-65 Hz (Figure 4). The mean SL was 170.1 ± 6.9 dB peak-to-peak re 1 µPa @ 1 m over 55-65 Hz. The median SL was 168.5 ± 6.9 dB peak-to-peak re 1 µPa @ 1 m over 55-65 Hz.

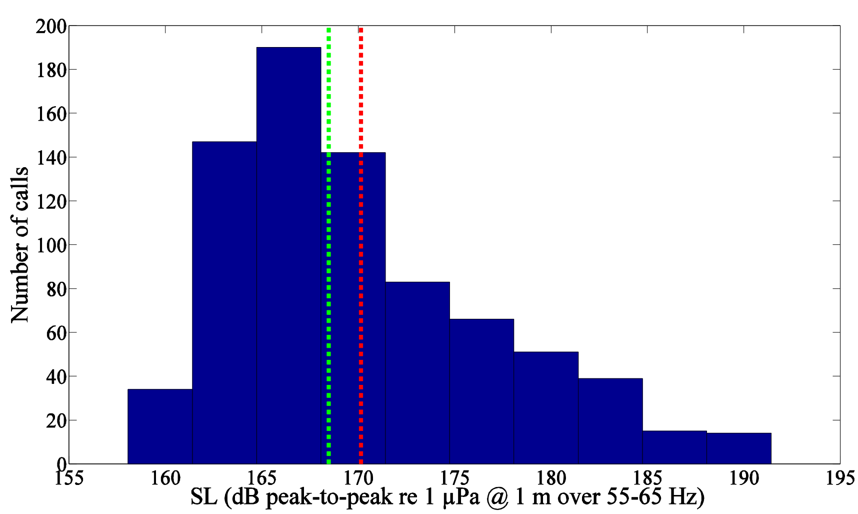

Figure 4. Histogram of Be4 call source sound pressure levels (SL) (n = 781) for calls recorded at HARP C. Red dashed line marks mean value. Green dashed line marks median value.

4. DISCUSSION

These are preliminary results that require further refinement to generate better estimates of Bryde's whales calling locations. For one, more robust constraints are needed on TDOAs. These could include manual identification of the main peak before cross-correlations to ensure that TDOAs are not calculated using secondary peaks of nearly equal amplitude to the main cross-correlation peak. Additionally, it is important to note that location uncertainty increases outside of the array, getting worse the farther out the locations are. This is a possible explanation for the apparently erratic swimming behavior observed in Figure 3b, if those calls were produced by a single individual.

These first estimates of Bryde's whale Be4 call source sound pressure levels were similar to other Bryde's whale call SLs (e.g., Be9 call $SL_{peak\text{-}to\text{-}peak} = 155 \pm 14$ dB re 1 µPa @ 1 m; Širović et al. 2014). However, they are much lower than source levels of blue (*B. musculus*) or fin whales (*B. physalus*) calls. Using an average of the SL calculated at all five HARPs in addition to correcting the localization errors discussed above will provide more reliable estimates of Bryde's whale call SL. Further, a more robust calculation of transmission loss could be implemented. Cylindrical spreading as well as spherical spreading were used here as some ranges were greater than the water depth. An empirical estimation of the environment-dependent transmission loss coefficient could be implemented by estimating its value from the relationship between the received levels and the ranges of Bryde's whale calls similarly to Širović et al. (2007). A more sophisticated propagation model such as the Effects of Sound on Marine Environment Range-dependent Acoustic Model (ESME-RAM) simulator could also be used to calculate TL (Širović et al., 2015).

Once reliable tracks are established, inter-call interval, swimming speed, and calling rate can be also be estimated from tracks. Known boundary conditions for these behavioral metrics can also be used to help define the start and end of a track. For example, if the inter-call interval (i.e., the amount of time between the end of a call and the start of the subsequent call) is greater than 15 minutes, a new track will be started. Swimming speed can be calculated by dividing the Euclidean distance between successive localizations by the elapsed time between those calls. If the swimming speed is unrealistic (i.e., > 30 km/h), locations will be excluded from the track and a second track will be started. Additionally, one would expect location to location speeds to be similar. Finally, track calling rate can be calculated by dividing the total number of calls in a track by the time interval between the first and last call in a track. This type of localization does not allow for a definitive determination whether there is only one calling animal, or if there are two animals that may be calling in close proximity to each other. Therefore, a high calling rate could be indicative of the presence of multiple individuals.

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