UNIVERSITY OF CALIFORNIA SAN DIEGO

Singing fin whales tracked acoustically offshore of Southern California

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in

Oceanography

by

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The Thesis of Leah McLean Varga is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

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DEDICATION

My thesis is dedicated to my brother, Jesse Varga. Thank you for inspiring me to pursue science, and always encouraging my nerdy side. Thank you for putting up with my passion for charismatic marine mammals, and thank you for always reminding me that the marine inverts are pretty cool, too. I always have and always will appreciate your unwavering support, your hilarious jokes, and your friendship.

EPIGRAPH

for whatever we lose
(like a you or a me)
it's always ourselves
we find in the sea

e.e. cummings

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ABSTRACT OF THE THESIS

Singing fin whales tracked acoustically offshore of Southern California

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Fin whales (*Balaenoptera physalus*) produce a stereotyped low frequency call (15-30 Hz) that can be detected at great range and is considered song when produced in a repeated pattern. These calls, referred to as 20 Hz calls, were localized and animals were tracked using a kilometer-scale array of four passive acoustic recorders deployed at approximately 800m depth, northwest of San Clemente Island in the Southern California

Bight. A total of 4969 calls were localized over four continuous weeks during late fall of 2007. The average estimated source level for the localized calls was 190.9 ± 7.4 dB peak-to-peak re 1μPa^2 at 1m. The majority of the calls in these data were in the form of a doublet song pattern, with average inter-pulse intervals (IPI) 13s and 18s. The tracks were the first to be recorded for singing fin whales transiting alone using passive acoustic monitoring. Acoustic tracking of fin whales provides insight into the ecology and behavior of the species. Estimating call source levels help future predictions of how these whales are impacted by anthropogenic noise. Call source level, along with calling behavior, provide important parameters required for population density estimation. Furthermore, studying fin whale song patterns may aid in distinguishing different subpopulations.

INTRODUCTION

Fin whales (*Balaenoptera physalus*) are found throughout the world's oceans, and are known to produce a stereotyped high amplitude and low frequency call centered at 20 Hz (Watkins *et al.*, 1987). These 20 Hz calls are produced as a pulse that lasts about 1 second, largely have the same frequency and temporal characteristics for different regions, and can be detected at distant ranges (McDonald *et al.*, 1995; Širović *et al.*, 2007; Širović *et al.*, 2013; Oleson *et al.*, 2014). Fin whales produce the 20 Hz pulse in two different patterns: song and call-counter call (Watkins *et al.*, 1987; McDonald *et al.*, 1995; McDonald and Fox, 1999; Širović *et al.*, 2013; Buccowich, 2014; Oleson *et al.*, 2014). Song are 20 Hz calls produced in a regular pattern, and are associated with reproductive behaviors, as only males have been recorded producing them (Thompson *et al.*, 1992; Croll *et al.*, 2002; Delarue *et al.*, 2013; Buccowich, 2014; Oleson *et al.*, 2014). An irregular pattern of 20 Hz pulses is considered call-counter call, and is likely used more for general communication, and a way of maintaining contact between individuals (McDonald *et al.*, 1995; McDonald and Fox, 1999).

The northeast Pacific, including the waters off the coast of Southern California, hosts a resident fin whale population (Širović *et al.*, 2013; Buccowich, 2014). Year-round presence of this population allows use of acoustic monitoring to track individual animals, as well as to characterize calling behaviors. Passive acoustic monitoring (PAM) has certain advantages for studying and tracking marine mammals, including fin whales (McDonald and Fox, 1999; Delarue *et al.*, 2013; Wiggins *et al.*, 2013). PAM can be used to collect long-term datasets, in all weather conditions and oceans, and can record continuously day and night (Delarue *et al.*, 2013; Wiggins *et al.*, 2013). PAM is non-invasive, and consequently has a low risk of impacting the behaviors of the whales, unlike other methods, such as tagging and ship surveys (Moore and Barlow, 2011; Goldbogen *et al.*, 2014). A limitation of using fixed PAM devices is that they only report on the presence of calling whales; the whales, for example, could be present in the area, but not calling (Širović and Hildebrand, 2011).

Fixed PAM, using bottom-mounted instruments to record sounds, is an effective technique for tracking fin and other baleen whales (McDonald *et al.*, 1995; Širović *et al.*, 2007; Simard and Roy, 2008; Wilcock, 2012; Soule and Wilcock, 2013; Weirathmueller *et al.*, 2013). In the northeast Pacific, ocean bottom seismometers (OBSs), which are designed to record low frequency sounds (<50 Hz) from earthquakes and anthropogenic sources, have been used to track fin whale 20 Hz pulses on large spatial scales (McDonald *et al.*, 1995; Wilcock, 2012; Soule and Wilcock, 2013; Weirathmueller *et al.*, 2013). In the northwest Atlantic, a large array of five autonomous hydrophones moored at mid-water depths was used to localize calling fin and blue whales (Simard and Roy, 2008). In the Southern Ocean, Acoustic Recording Packages (ARPs) were used to locate calling fin and blue whales at great ranges (Širović *et al.*, 2007). Using underwater acoustics to track calling fin whales provides insight into their population size, structure and distribution, as well as into their ecology and behaviors (McDonald and Fox, 1999).

The source level of fin whale calls has been estimated by monitoring with PAM techniques at a variety of location (Watkins *et al.*, 1987; Charif *et al.*, 2002; Širović *et al.*, 2007; Weirathmueller *et al.*, 2013). In the North Atlantic, fin whale 20 Hz call source levels were reported at 160-186 dBrms re 1 μPa at 1m (Watkins *et al.*, 1987). In the eastern North Pacific, the source levels were calculated as 171 dBrms re 1 μPa at 1m (Charif *et al.*, 2002) and 189 ± 5.8 dBrms re 1 μPa at 1m (Weirathmueller *et al.*, 2013). Recorded source levels in the Southern Ocean were 189 ± 4 dBrms re 1 μPa at 1 m (Širović *et al.*, 2007). Source level along with calling behavior provide important parameters required for population density estimation from passive acoustic recorders, as well as estimates for the detection range of this species (McDonald and Fox, 1999; Charif *et al.*, 2002; Širović *et al.*, 2007).

Fin whale song is characterized as a patterned sequence of 20 Hz pulses, with repeating inter-pulse intervals (IPIs) of similar timing, most commonly in the form of a singlet or a doublet (Watkins *et al.*, 1987; Hatch and Clark, 2004; Oleson *et al.*, 2014). A singlet song has one consistent IPI, while a doublet song has two repeating IPIs, one typically shorter than the other (Oleson *et al.*, 2014). Only male fin whales have been recorded producing these songs, suggesting that they serve a reproductive purpose (Croll *et al.*, 2002). The IPI duration of fin whale song varies slightly across different geographic regions, indicating possible delineation in populations (Hatch and Clark, 2004; Delarue *et al.*, 2009; Castellote *et al.*, 2012; Oleson *et al.*, 2014). In the North Pacific, fin whale song most commonly occurs during the fall and winter months (Watkins *et al.*, 2000; Oleson *et al.*, 2014).

In this study we used PAM to track singing fin whales and to acoustically characterize their calling behaviors off the coast of Southern California. Whale localizations and call source levels aid in behavioral studies and density estimation research, and studying fin whale song helps to distinguish populations, and their respective movements and ecology.

METHODS

Study Site and Data Collection

Passive acoustic data were collected using a large aperature array of High-frequency Acoustic Recording Packages (HARPs - (Wiggins and Hildebrand, 2007). Four HARPs were deployed in about 800 meters of water in a square configuration 1 km per side off the northwestern side of San Clemente Island in the Southern California Bight (Table 1, Figure 1). The HARPs recorded for a continuous four-week period, from November 10 to December 7, 2007. The recorders are bottom-mounted, capable of being deployed for a long period, and can record day and night (Wiggins and Hildebrand, 2007).

Localization of fin whales using an array requires precise estimates of recorder positions (Wiggins *et al.*, 2013). The HARP depths and positions were estimated using a ship-based global positioning system (GPS) and acoustic transponder survey from the R/V Sproul with locations to within 5m root-mean-square (rms) (Wiggins *et al.*, 2013). The localization also requires clock synchrony between the instruments. HARPs have low clock drift rates, aiding in this synchronization (Wiggins and Hildebrand, 2007). Clock drift rates in this study ranged from -5.4×10^{-8} to 1.2×10^{-8} (Wiggins *et al.*, 2013).

The HARP sample rate was 200 kHz, for an effective bandwidth of 10 Hz to 100 kHz. The data were decimated by a factor of 100, for an effective bandwidth of 1 kHz, allowing for faster analyses of low frequency sounds. Long-term spectral averages (LTSAs - Figure 2), of these data were created using *Triton*, a custom-built program for MATLAB (Wiggins and Hildebrand, 2007). The LTSAs were averaged in 1-Hz, 5-

second bins, and arranged sequentially, allowing for efficient analyses of the data in a time series format.

Data Analysis

To localize individual fin whale calls, the same 20 Hz pulse must be at a high enough signal-to-noise ratio (SNR) to be detected on all recorders. Once detected the time delay of the call between pairs of hydrophones is measured – there are six time delay hydrophone pairs for four hydrophones: 2-1, 3-1, 4-1, 3-2, 4-2, and 4-1. As a means of accomplishing both of these tasks, waveform time-series cross-correlation was calculated between hydrophones and the time delays were taken as peak correlations above an empirically defined threshold using MATLAB software routines. This cross-site approach employed a band pass filter of 10 to 40 Hz prior to cross-correlation, and used 2-second windows, with a 1-second overlap for the cross-correlations. The overlap minimized missed detections, but resulted in duplicate detections, which were filtered out.

The measured cross-site cross-correlation method time different of arrivals (TDOAs) of fin whale calls were used with a grid search minimization scheme to estimate the locations of calling whales. At each point in a 5 km x 5 km grid with 25 m resolution, TDOAs were calculated for the six hydrophone pairs. The calculated TDOAs were then differenced with the measured TDOAs to determine the best-fit location of the calling whale by using the minimum difference. The model space for the calculated TDOAs used a constant sound speed of 1490 ms^{-1} and therefore direct path ray propagation, and used a constant whale source depth of 30 m (Goldbogen *et al.*, 2014). The localization uncertainties were about ± 10 m. Measuring the arrival times of a signal at each instrument within an array is a common technique for localizing and tracking marine mammals (McDonald *et al.*, 1995; Wilcock, 2012; Wiggins *et al.*, 2013).

For cross-correlations with time lags above the threshold, the call peak-to-peak level and peak frequency were measured. The peak frequency of the call was important to record since these 20 Hz calls vary in frequency, and the peak frequency recorded by the detector influenced the transfer function value used for each call. The peak-to-peak level was important to record for estimating the source level of the calls. The standard sonar equation was used to estimate the source level of the calls:

$$SL = RL + 20\log_{10}(R),$$

where SL is the source sound pressure level, RL is the received sound pressure level, and R is the range from the whale source to hydrophone receiver, in meters. The values for R were calculated from the TDOA localization method. The received level was calculated by from the peak-to-peak level of the call, which was measured by the detector, and applying a frequency-dependent transfer function value. For calls with peak frequency above 20 Hz, a transfer function value of 72.9 dB re 1 $\mu Pa^2/counts^2$ was used to convert from the raw units to analog-to-digital (ATD) counts to pressure units µPa. For calls centered equal to or lower than 20 Hz, a value of 73.9 dB was used. I used $20\log_{10}(R)$ as the transmission loss term. Spherical spreading assumption was used because the array was relatively small in size, relative to the water depth. This SL calculation was performed for each instrument, resulting in four estimated source levels for each localized call.

Manual Song Analysis

Some calls were missed by the automatic detection method, so for the song analyses, the calls were manually logged. To quantify song, the IPI was calculated for songs from one instrument, which is a common method for determining song types in many baleen whale species, including fin whales (Watkins *et al.*, 1987; Buccowich, 2014; Oleson *et al.*, 2014). In this study we defined the IPI as the time from the start of one call to the start of the next call. For this analysis, one hour was chosen randomly from each of the 26 full days of recording. The first and last days of recording, November 10, 2007 and December 7, 2007, were not included since the instruments were not recording for the entirety of those days. For each of the randomly chosen hours, fin whale song was logged from the spectrogram window in *Triton*. The data were viewed as 120s segments, with spectrogram calculated using 5000-point fast Fourier transform, 95% overlap with a Hanning window, and with a band pass filter from 10 to 40 Hz. The start times were logged manually and at the same position on each call. The fin whale pulses were considered song and were logged if they followed certain parameters: a pattern of IPIs had to be apparent, the singing had to occur for a minimum of two minutes, and the quality of the calls had to be high enough that the pattern could be followed accurately by the analyst. The IPIs were calculated for the one-hour sections analyzed, and the shorter and longer IPIs were averaged separately since the song in these data was in doublet form.

In some instances, there were background calls within the same time frame. If the background calls were of low quality, then the targeted fin whale song could still be manually followed and logged. However, if the fin whale song pattern could not be distinguished from the background calls then the song was not logged. In some of these instances, the background calling may or may not have been song, but the overlapping of the calls from two or more fin whales made it difficult to separate the individuals, and therefore no calls were logged as song.

Individual Track Analysis

Four high-quality tracks from these data were analyzed at a greater detail for several acoustic and behavioral characteristics of the fin whale calling. (Table 2, Figures 3-6). The average swimming speed was calculated by using the distance traveled between the locations of consecutive localized calls, and the time duration between the same consecutive calls. The average call rate was calculated by dividing the number of detected calls by the time duration during the track. The average source level and average peak frequency were calculated using the automatic detector cross-channel correlation technique, just as with the entire set of fin whale calls. The average IPIs of the tracks were calculated using the same manual detection method as for the song analyses above. The tracks selected for these analyses had a high signal-to-noise ratio was high, the track lasted at least 30 minutes, and the locations were of high quality and close to or within the instrument array.

R/P FLIP

The R/P FLIP was stationed at the center of the array for a portion of the recording period, serving as a point for visual observations for another study on delphinid species (Wiggins *et al.*, 2013). No data from the R/P FLIP are included in this study, however the R/P FLIP was present and was detected. The automatic detector that was built to detect and localize the 20 Hz fin whale pulses within the array of HARPs also detected and localized the R/P FLIP when it was the dominant noise in the soundscape. These detections were removed from the results.

RESULTS

A total of 4969 calls were localized during the four-week recording period using the automatic cross-channel detector and grid search method. A larger number of signals were detected, but did not pass the filter and threshold level during the localization process. The average source level of these localized calls was 190.9 ± 7.4 dB re 1μPa^2 at 1m, peak-to-peak, ranging from 167.4 to 217.3 dB re 1μPa^2 at 1m (Figure 7). The source level estimates were plotted against the slant range of the locations, with four points representing each call, one per instrument (Figure 10). There was a slight increase in the estimated source level with an increase in slant range.

The average peak frequency of all the localized calls was 22.2 ± 4.2 Hz. There were three distinct call types within these data, separated by frequency and bandwidth. The higher frequency call type peaked around 22 Hz, and had a larger bandwidth spanning ~13-15 Hz. The middle frequency call type had a peak frequency of ~19 Hz, and a bandwidth of ~10 Hz. And finally, the low frequency call type, which was not nearly as common and tended to occur at the beginning or end of calling sequences, peaked around 17 Hz and had a narrow bandwidth.

Out of the 26 hours of manually analyzed data, 22 hours had clear and identifiable fin whale song, and a total of 1449 calls were manually logged as part of song. All of these hours had instances of doublet song. The average short IPI of the doublet song was 12.9 ± 0.0 s, and the average long IPI was 18.4 ± 0.1 s (Figure 8). The shorter IPI (~13 s) was more common than the longer IPI. There was also a common frequency component with this doublet IPI pattern. The short IPI (~13 s) typically followed a middle frequency call type (~19 Hz). The longer IPI (~18 s) typically followed the higher frequency call type (~22 Hz). Occasionally the song would omit the higher frequency call type, and would instead have an IPI ~22 s, between two middle frequency call types.

All four tracks analyzed with more detail were about an hour or less from start to finish, and the number of calls localized in the tracks ranged from 75 to 136 (Table 2, Figures 3-6). The average speeds from the four identified tracks ranged from 1.4 to 2.8 ms^{-1} with a median of 2.1 ms^{-1}. The call source level of the tracks ranged from 192.9 to 202.1, with a mean value of 198.8 dB re $1\mu Pa^2$ at 1m, peak-to-peak. The average peak frequency was 22.1 Hz, with a range from 20.9 to 23.6 Hz. The mean call rate was 1.8 calls/min, with a range of 1.5 to 2.2 calls/min. The song from these four tracks fit relatively well into the song pattern of the rest of the data, with an average short IPI of 12.6 s, ranging from 12.0 to 12.9 s, and an average long IPI of 18.4 s, ranging from 18.0 to 19.5 s. The IPIs from Track 1 are plotted separately, illustrating the 13s/18s doublet pattern on a smaller timescale (Figure 9).

DISCUSSION

The tracks presented here are the first for individual singing fin whales using passive acoustic monitoring to our knowledge. Fin whales have been effectively tracked in the past, but the calls have not been categorized, or were categorized as call-counter call, not song (Watkins *et al.*, 1987; McDonald *et al.*, 1995; Wilcock, 2012; Soule and Wilcock, 2013; Weirathmueller *et al.*, 2013). These tracks are examples of individual fin whales singing alone, not of multiple whales singing together. The fact that this is a single animals is supported by the relatively steady amplitude between the two main frequency call types, and also the high-resolution track showing just one whale traveling while singing.

Song

The fin whale song analyzed in these data is a doublet song sequence, with a 13s/18s IPI song pattern. Off the coast of Southern California, fin whale song changed through an increase in the doublet IPI over a four year recording period from 2008 to 2012 (Buccowich, 2014). The shorter IPI started at 12.0 ± 1.2 s and ended at 17.7 ± 0.6 s, while the longer IPI started at 17.6 ± 1.6 s, and ended at 23.2 ± 2.6 s (Buccowich, 2014). Our 13s/18s doublet IPI from the year 2007 fits relatively well into this overall song pattern, at the shorter end of the dual IPI range.

However, the 13s/18s doublet song from our data is overall shorter than an earlier study (2000-2003) in this region, where doublet songs ranged from ~18s/24s to ~27s/33s, with the IPIs increasing throughout each calling season, and then resetting at the beginning of the following season (Oleson *et al.*, 2014).

Although the 13s/18s doublet pattern was fairly consistent and ubiquitous throughout these data, there were occasional variations in the song. These variations in the song, for example when a higher frequency note was omitted, could be simply explained by the singing whale skipping the higher frequency note and continuing to sing with just a middle frequency note before proceeding back to the 13s/18s doublet pattern.

Other dual IPI calling patterns have been reported for fin whales, but have not been attributed specifically to a single whale singing. A 24s/13s dual IPI calling pattern was recorded in the northeast Pacific, but was hypothesized to be from two individual whales calling at two different frequencies, not one individual singing whale (Soule and Wilcock, 2013). A closer look at the tracks and the amplitudes of the two call frequency types may either support or negate this hypothesis. If the two call types differ in physical position in the array as well as in relative amplitude, then that would support the theory that the 24s/13s dual calling pattern was produced by two calling whales, one singing at a higher frequency and one at a lower frequency (Soule and Wilcock, 2013). But if the tracks and amplitudes cannot be distinguished, then this calling pattern could be attributable to one singing fin whale.

In some studies, reported instances of fin whales call-counter calling could be examples of fin whales singing. Three fin whales transiting together, from one sequence of 20 Hz calls lasting about eight hours in late August, 1990, were reported as call-counter calling (McDonald *et al.*, 1995). The sequence of 20 Hz calls was localized, and it was concluded that three individuals were calling, several kilometers apart from one another (McDonald *et al.*, 1995). However, from the time series and corresponding spectrogram of the three calls associated with the three whales (a, b, and c), there were most likely two individuals calling and transiting together, one of which was singing. The calls reported as whales “a” and “b”, when analyzed together, are likely from one whale’s doublet song, with a short IPI of ~13 s and a long IPI of ~19 s, which is similar to the doublet song from our results. This theory is based on the short spectrogram and time series in the paper, and could either be supported or refuted after further analysis of longer sequences of 20 Hz calls from the dataset.

Assessing the relative amplitude of a series of calls recorded on an array of acoustic recorders is instrumental in determining if one or more whales are calling, as discussed above in reference to previous studies reporting call-counter call (McDonald *et al.*, 1995) and two whales calling together with a 24s/13s dual pattern (Soule and Wilcock, 2013). More efforts should be made to better determine why and in what context fin whales sing. If males are the only fin whales to sing (Croll *et al.*, 2002), do they sing alone, do they sing in groups, or both? Understanding the role of singing in fin whale populations will provide insights into the calling behaviors and ecology of the species.

Fin whale song, whether produced by one or more individuals, has been used as an indicator of population dynamics, and recorded differences in song parameters and characteristics have delineated different fin whale populations (Hatch and Clark, 2004; Oleson *et al.*, 2014). These distinctions may lead to more effective management practices in the future, catered to the needs of the differing subpopulations.

Localizations

A cross-channel time-series correlation approach used in this study to localize fin whales resulted in fairly accurate time delays and corresponding tracks. The small array size allowed for good signal to noise ratios for the calls on all four instruments. This, paired with the synchronized clocks, allowed for accurate time delay calculations and location estimates, resulting in smooth tracks. Before this approach was developed, these data were analyzed by cross-correlating a synthetic kernel with each of the time series from the four instruments, and then matching the detections from each instrument to estimate the time delays. This method produced more variable tracks with a higher margin of error. Fin whale 20 Hz calls are not identical; they vary in the frequency bandwidth and the amplitude, so using a synthetic kernel to detect the calls resulted in many false negatives and false positives.

Fin whales were tracked with an array of OBSs on the Juan de Fuca Ridge in the northeast Pacific, and three methods were used for localizing the calls: grid search, double difference with automatic arrival times, and double difference using cross-correlated arrival times (Wilcock, 2012). The fin whale tracks from all three methods were plotted simultaneously for a direct comparison of the accuracy of the results (Wilcock, 2012). Using the double difference technique, both automatic and cross-correlation, produced far more accurate and detailed tracks than the grid search method (Wilcock, 2012). While the double difference technique was not necessary in our own localization process to obtain fairly accurate and detailed tracks, it is an effective means for localizing calling fin whales in studies that employ larger arrays (Wilcock, 2012).

Array Design and Source Level

The array used in this study is smaller than those used in other baleen whale tracking studies, but this smaller size allowed for higher resolution of call locations. Three fin whales that were reportedly call-counter calling were tracked using an array of OBSs, spaced 4-6 km apart (McDonald *et al.*, 1995). Several 20 Hz fin whale calling sequences were also tracked using OBSs, spaced 6-10 km apart (Wilcock, 2012; Soule and Wilcock, 2013). Although our track durations are shorter because the localization quality decreases outside of the array, our level of detail within the array is high due to the closer spacing of the instruments.

The average source level in this study was 190.9 ± 7.4 dB re 1μPa^2 at 1m, peak-to-peak, which is on the higher end of previously reported source level values for this species. In the northeast Pacific, the average fin whale 20 Hz call source levels range from 171 dBrms re 1 μPa at 1m (Charif *et al.*, 2002) to 189 ± 5.8 dBrms re 1 μPa at 1m root-mean-square (Weirathmueller *et al.*, 2013). Having a good estimate of fin whale source level allows for an estimation of the detection range of these animals, which is important for understanding fin whale communication ranges, and their susceptibility to the impacts of anthropogenic noise (Širović *et al.*, 2007).

The smaller array size in this study could account for the slightly higher source levels; the overall transmission loss estimates may be lower and the received levels higher than in other studies where the instruments are spaced farther apart. In future studies aiming to track calling baleen whales, we suggest a set of nested arrays, with the groups of instruments spaced 5-10 km apart from one another. Fin whale 20 Hz calls propagate at great ranges (Watkins *et al.*, 1987; McDonald *et al.*, 1995; Širović *et al.*, 2007) therefore a larger array with nested instruments will allow for potentially more tracks of fin whales without the risk of losing detail.

The spread in the source levels may be due to instrument differences, as well as sound speed and propagation variability in the water column (Figure 10). The variability also could be due to uncertainties in the horizontal and vertical location of the source. The detections recorded by the HARP instrument 3S have a calculated slant range of ~760 m, shorter than the other instruments by a noticeable amount (Figure 10, red points) because this 3S instrument is the shallowest of the four instruments, at just under 800m, while the other three HARPs are in water depths greater than 800m. This shallower position caused the detections to have a shorter slant range, i.e. the instrument was slightly closer to the calling whales due to the depth.

Individual Tracks

The four tracks analyzed with more detail show the variability in the movements of the singing fin whales, and give an encompassing snapshot of the typical movement and calling behaviors estimated from these data. The swimming speeds calculated from our data are similar to previously reported fin whale swimming speeds. In the northeast Pacific, the average swimming speeds for calling fin whales were reported as ranging from 5-14 kmh^{-1} (McDonald *et al.*, 1995), as approximately 8 kmh^{-1} (Wilcock, 2012), and ranging from 1-12 kmh^{-1}, with a mean of 4.3 kmh^{-1} (Soule and Wilcock, 2013).

The breaks seen in the tracks are hypothesized to be breathing gaps, meaning the whale stopped singing to surface for a series of breaths, before diving back to its singing depth. These breaks are most apparent in Track 1 (Figure 3). Another possibility for some of the breaks is that the whales take a pause in the singing. For example, in Track 3, the whale takes a lengthy, almost 15-minute pause in the song, before resuming its song while swimming in what appear to be clockwise circles (Figure 5). It is most likely the same whale singing before and after the pause because the SNR is high and there is only one song sequence apparent in the data.

The whales from these tracks were singing very similar songs, all in the 13s/18s doublet pattern. However, there is variability in the call rate, ranging from 1.5 to 2.2 calls per minute. This variability may be due to the differences in the number and length of breathing gaps. These breathing gaps or pauses in the singing were included in the call rate calculations, thereby potentially lowering the call rate estimates. Another source of variability may be the occasional omission of 20 Hz calls within the song, with the higher frequency calls being omitted more often than the middle frequency calls. These omissions changed the IPI, and subsequently the call rate.

Biases and Sources of Error

A notable source of error was the accuracy of the detector; the cross-channel automatic detector missed true positive calls and recorded false positive calls within the data. However, reliable tracks and calling parameter estimates were calculated from these results. The sample size in this study is on the smaller side, especially when compared to other studies that have longer time series of data, and larger arrays (McDonald *et al.*, 1995; Wilcock, 2012; Soule and Wilcock, 2013; Weirathmueller *et al.*, 2013). However, these results, although small in sample size, are high in detail and accuracy.

Concerning the locations, a whale calling within the boundaries of the array, or within 500 to 1000 m of the array boundaries can be more accurately localized using the time delay method. Whales calling farther outside of the array produce time delays that result in higher uncertainty in the source location. This is true for the smaller array used in this study, as well as for larger arrays where the instruments are spaced further apart (McDonald *et al.*, 1995; Wilcock, 2012).

CONCLUSIONS

Using HARPs and other fixed passive acoustic monitoring devices to track calling whales is an important technique for monitoring and assessing the movement and calling behaviors of these animals. Localizing the calls can provide insight into the whales' responses to stimuli, including those that are anthropogenic. Source levels also aid in determining the detection range of these species. Quantifying fin whale song in different regions will help efforts to distinguish populations, and to direct future management practices. Studying fin whale song is also important to better understand the behaviors of these species, as so far only males have been reported singing (Croll *et al.*, 2002).

These tracks are the first reported examples of single fin whales singing using passive acoustic monitoring. The song pattern, with a 13s/18s doublet IPI, matches other song patterns studied in the northeast Pacific. The source level estimates are similar, although slightly higher, than previously reported source levels for fin whales around the world and in the northeast Pacific. The localizations, although limited by the size of the array and length of the overall dataset, are highly detailed and provide insight into the movements and behaviors of singing fin whales offshore of Southern California.

This thesis, in part, is currently in preparation for submission. Varga, L.M, Wiggins, S.M., Hildebrand, J.A. Singing fin whales tracked acoustically offshore of Southern California. The thesis author was the primary investigator and author of this material.

TABLES

Table 1. Instrument positions from acoustic-GPS localization (±5m rms).

	Latitude (N)	**Longitude (W)**	**Depth [m]**
HARP 1 (N)	33° 12.182′	118° 47.351′	853
HARP 2 (E)	33° 11.649′	118° 46.688′	837
HARP 3 (S)	33° 11.102′	118° 47.308′	788
HARP 4 (W)	33° 11.627′	118° 47.961′	846

Table 2. Characteristics of four tracks: Date, duration of track, number of calls, mean swimming speed, mean source level, mean peak frequency, call rate, and mean short and long IPIs.

	Date	**Track Duration [min]**	**# of Calls**	**Mean Speed [m/s]**	**Mean Source Level [dB re 1μPa^2 @ 1m]**	**Mean Peak Frequency [Hz]**	**Call Rate [calls/min]**	**Mean Short IPI [s]**	**Mean Long IPI [s]**
Track 1	18-Nov	62	136	1.4 ± 0.1	201.4 ± 2.3	20.9 ± 2.7	2.2	12.8 ± 0.1	19.5 ± 0.2
Track 2	23-Nov	41	75	2.4 ± 0.3	198.9 ± 4.0	23.6 ± 3.9	1.8	12.7 ± 0.2	18.1 ± 0.4
Track 3	29-Nov	55	81	2.8 ± 0.3	202.1 ± 2.8	21.4 ± 2.5	1.5	12.9 ± 0.1	18.1 ± 0.3
Track 4	3-Dec	54	88	1.7 ± 0.2	192.9 ± 1.6	22.5 ± 4.7	1.6	12.0 ± 0.1	18.0 ± 0.2

FIGURES

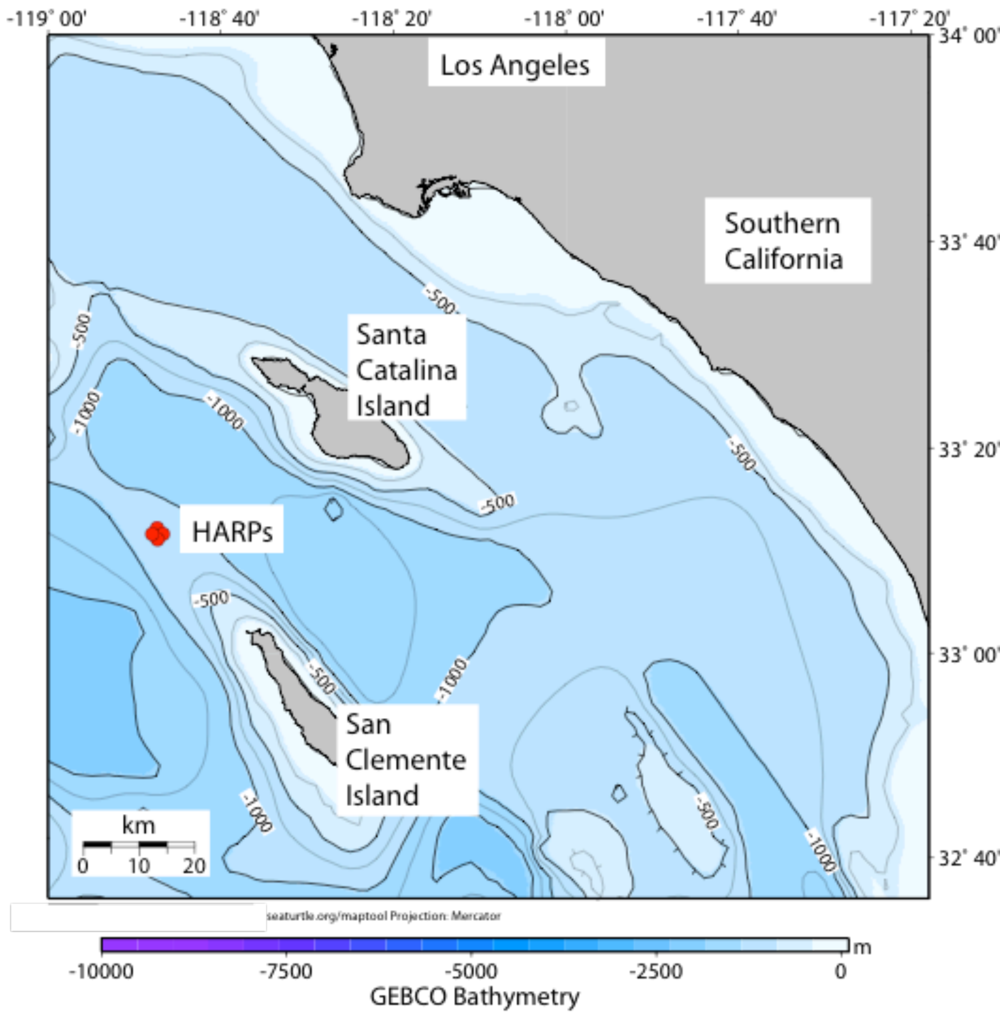

Figure 1. Bathymetric map of the seafloor surrounding the study site, and the four HARP instruments. Color is bathymetric depth.

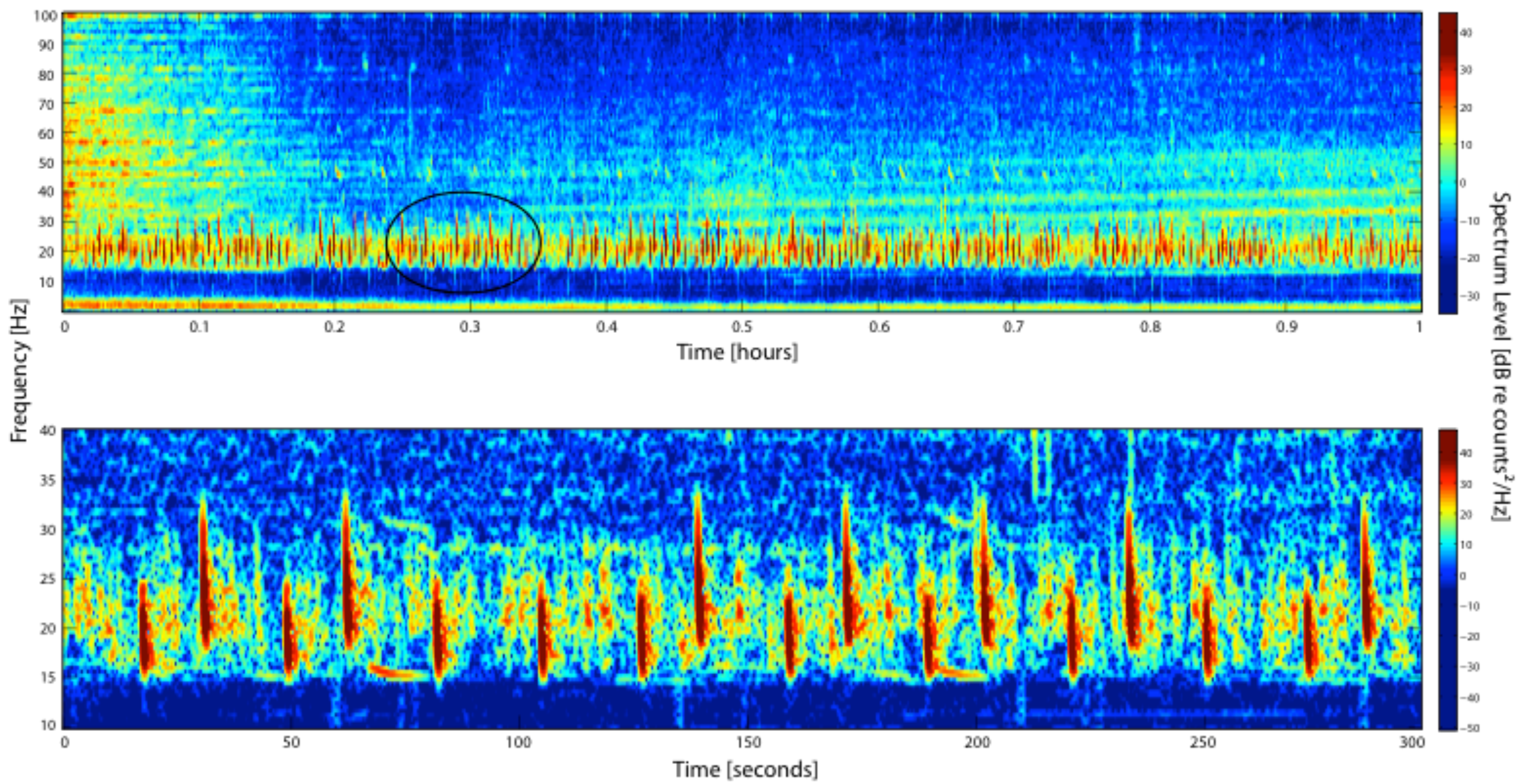

Figure 2. Long-term spectral average (top) from the HARP 3S, on 18 November 2007, at 08:00 GMT. Black circle corresponds to the section of data shown in the spectrogram (bottom). Data were band pass filtered in the spectrogram from 10-40 Hz. Hanning window with 95% overlap, 5000-point FFT.

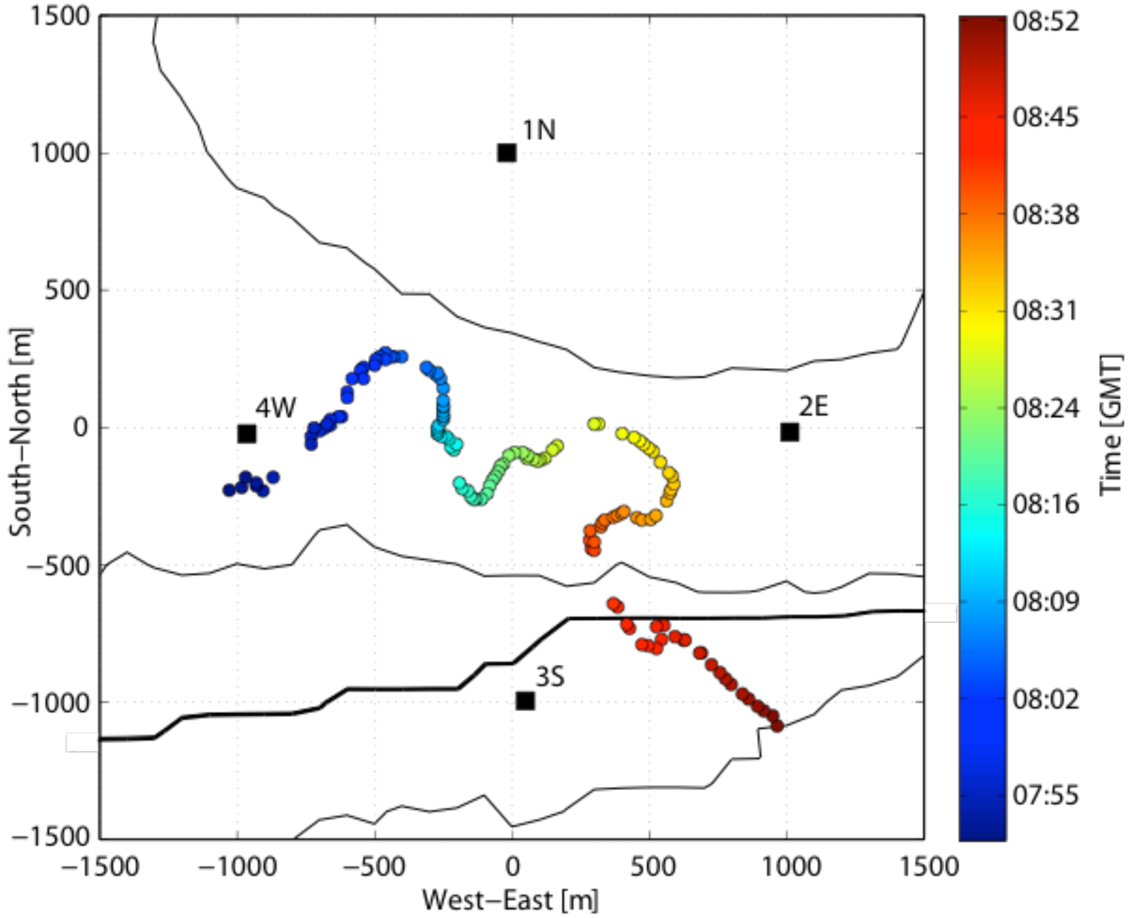

Figure 3. Track 1 from 18 November 2007, lasting from 07:51 to 08:53 GMT. Color shows the time of call localizations. Thicker line is 800m, with 25m contours, deeper to the North. Black squares are HARPs.

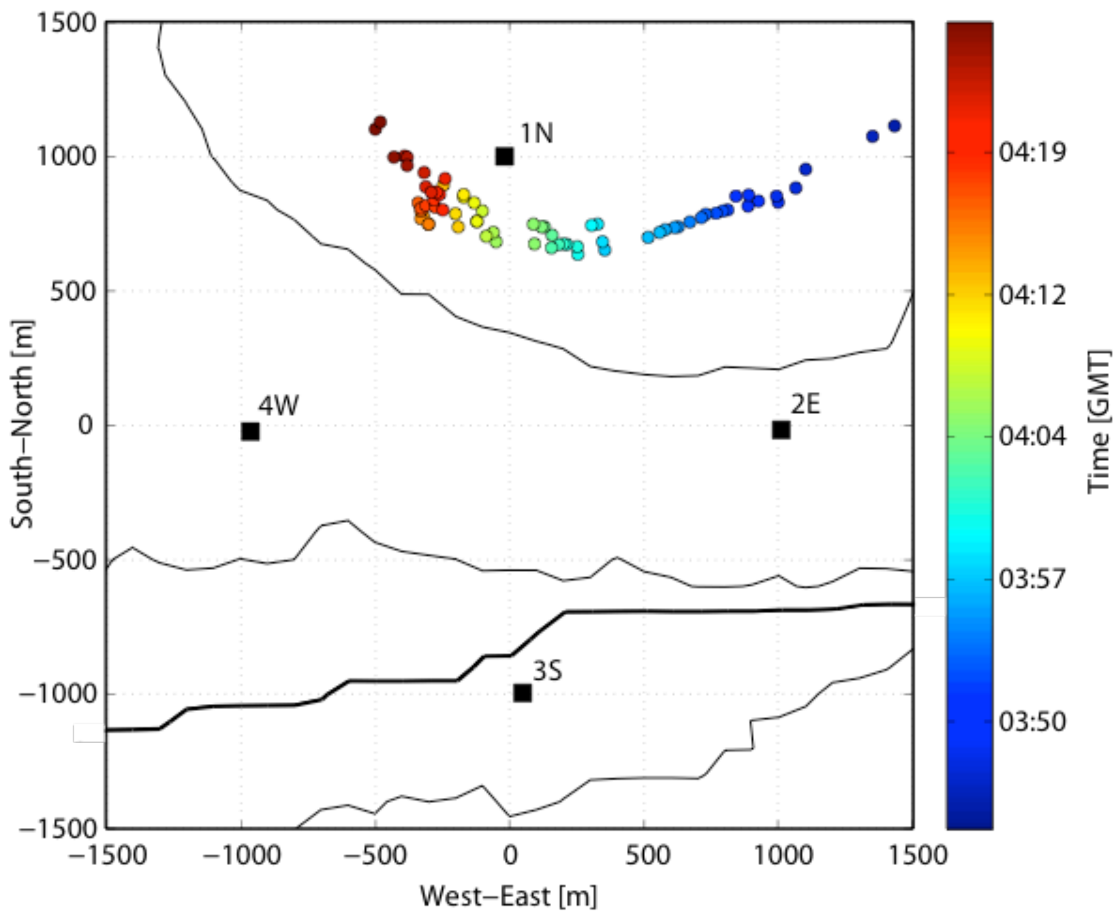

Figure 4. Track 2 from 23 November 2007, lasting from 03:44 to 04:25 GMT. Color shows the time of call localizations. Thicker line is 800m, with 25m contours, deeper to the North. Black squares are HARPs.

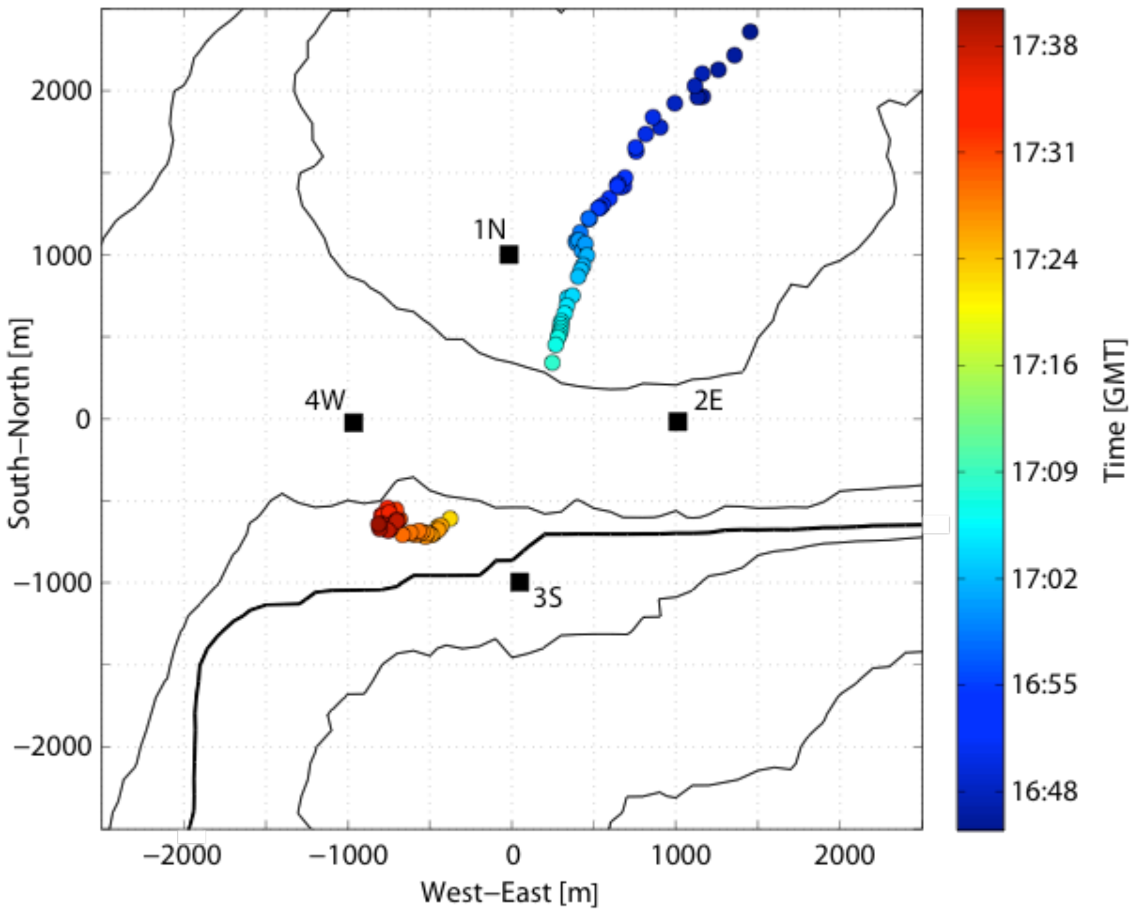

Figure 5. Track 3 from 29 November 2007, lasting from 16:45 to 17:40 GMT. Color shows the time of call localizations. Thicker line is 800m, with 25m contours, deeper to the North. Black squares are HARPs.

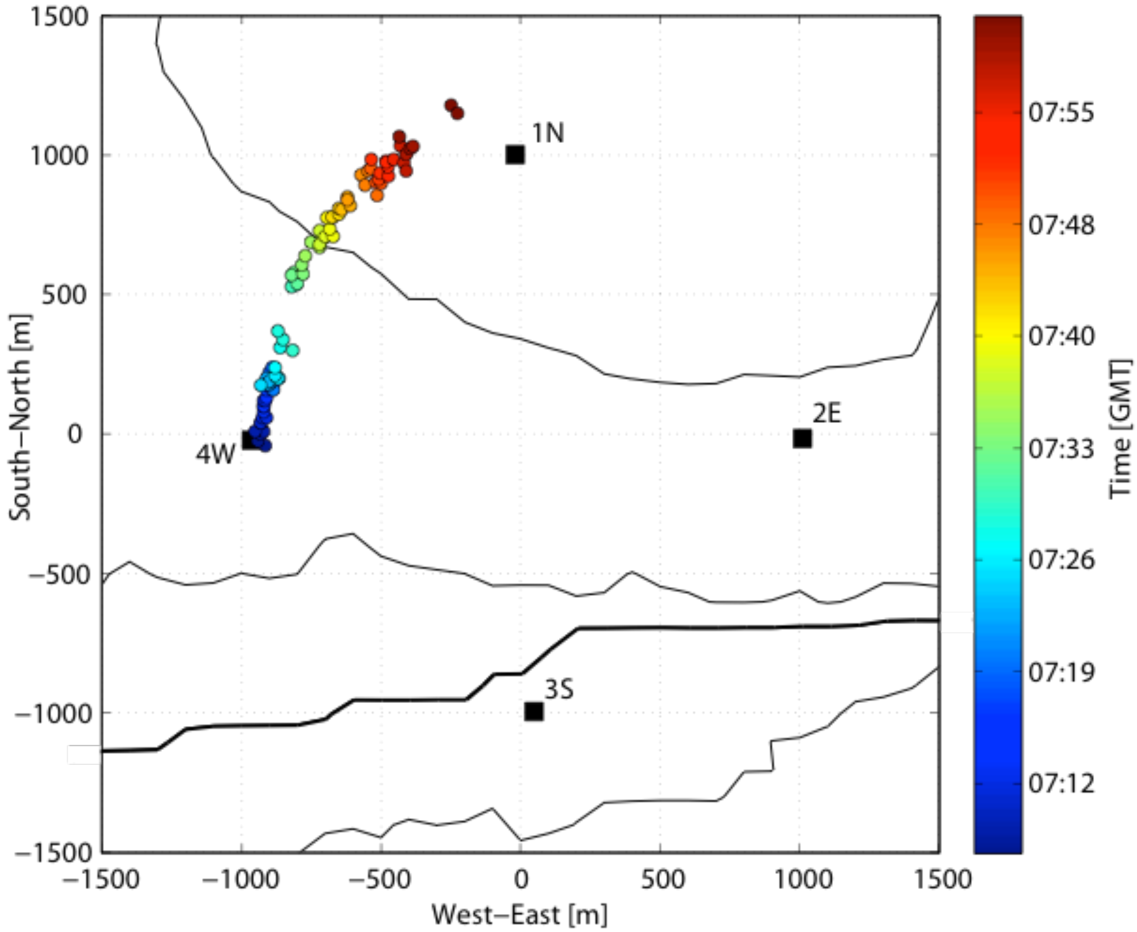

Figure 6. Track 4 from 3 December 2007, lasting from 07:07 to 08:01 GMT. Color shows the time of call localizations. Thicker line is 800m, with 25m contours, deeper to the North. Black squares are HARPs.

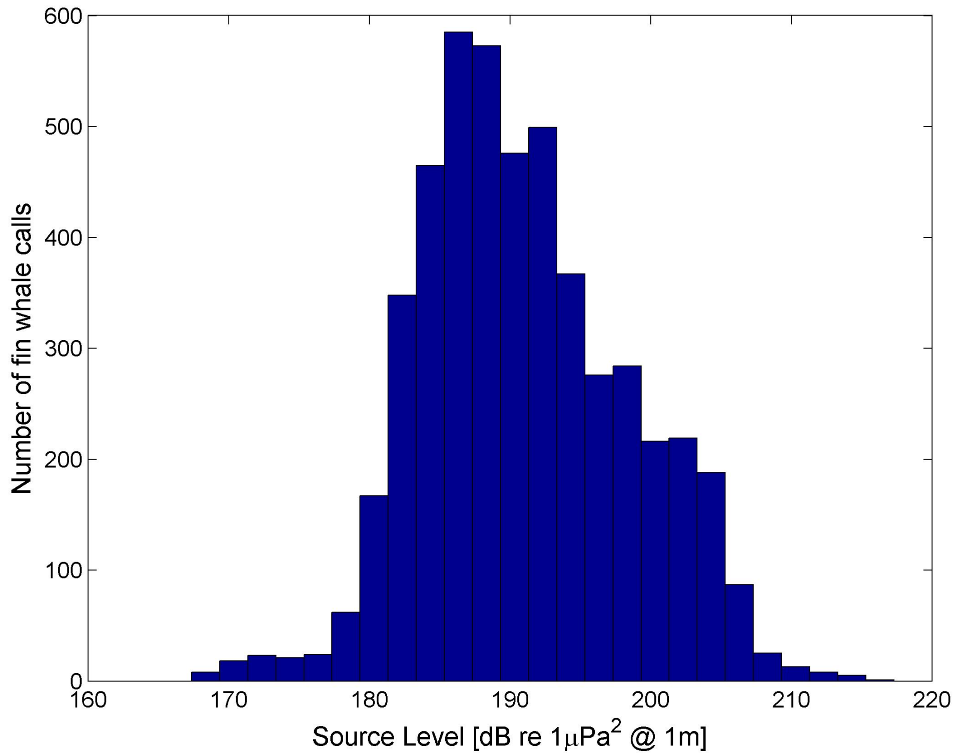

Figure 7. Distribution of call source levels, with a mean of 190.9 ± 7.4 dB re 1μPa^2 at 1m, peak-to-peak. Each individual reported call source level is an average from the four instruments.

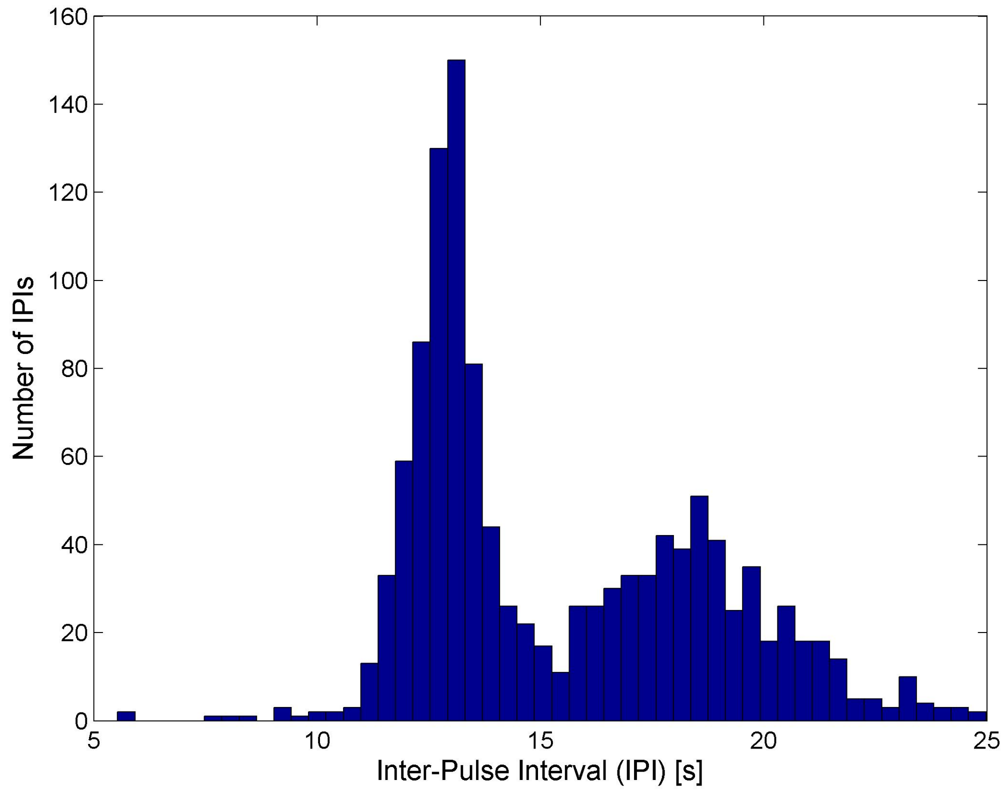

Figure 8. Inter-pulse intervals (IPI) for all manually analyzed song. The bimodality indicates a clear 13s/18s doublet song pattern.

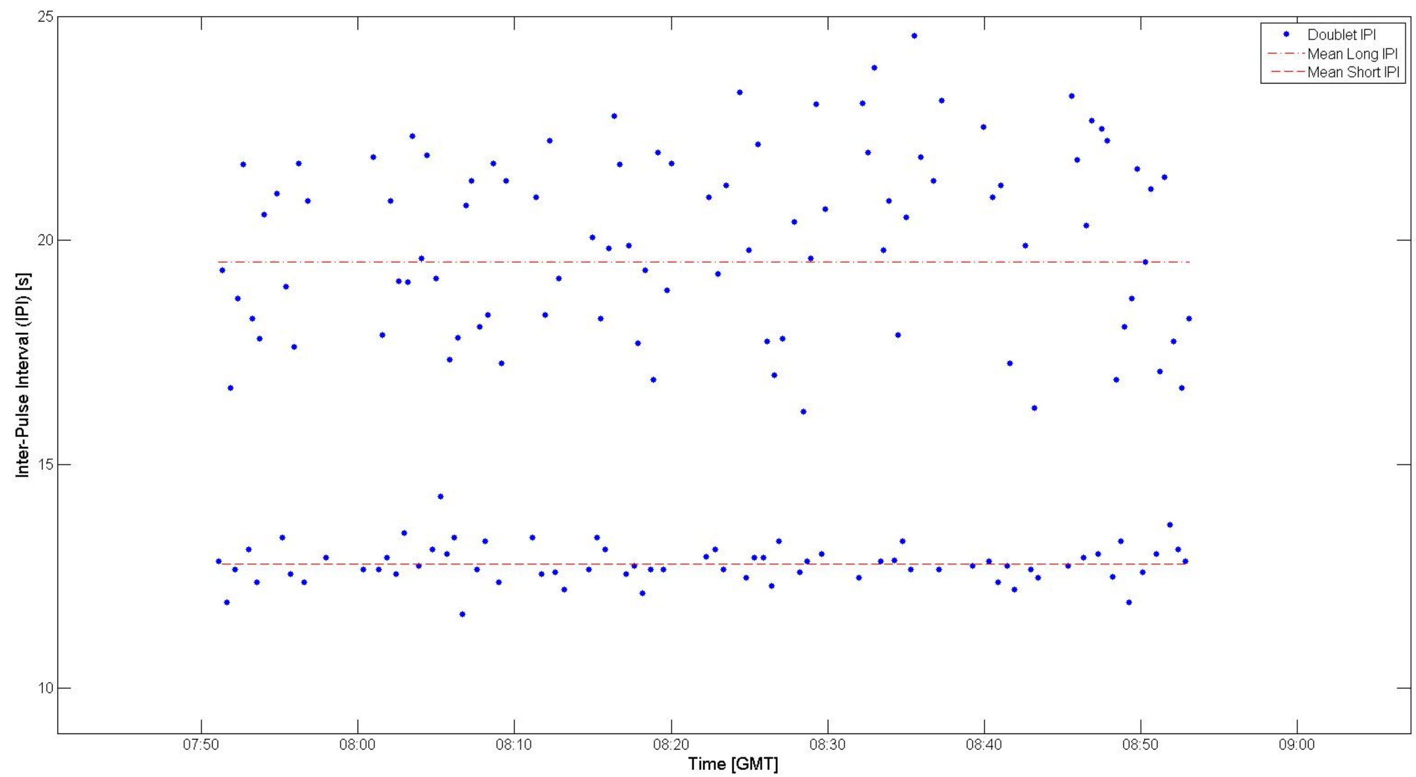

Figure 9. Doublet IPI song for Track 1, 18 November 2007 from 07:51 to 08:53 GMT. Red lines indicate the mean short and mean long IPIs for all manually analyzed song.

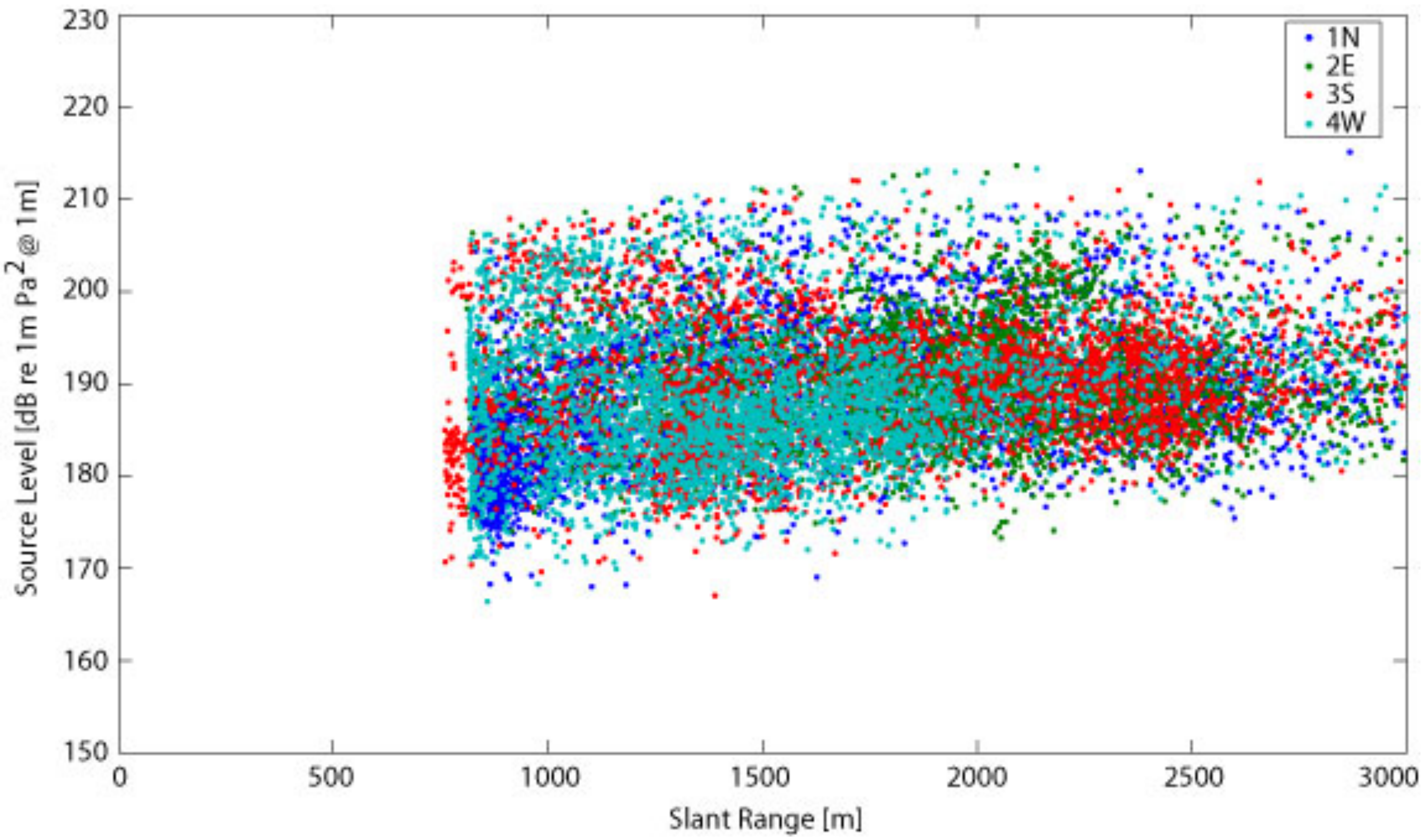

Figure 10. Source level estimates versus the slant range of the detected and localized 20 Hz calls. Each call has four plotted points, 1 per instrument.

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