Gulf of Alaska fin whale calling behavior studied with acoustic tracking

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SUMMARY

A pair of fin whales (*Balaenoptera physalus*) were concurrently tracked in the Gulf of Alaska from their 40-Hz calls recorded on an array of passive acoustic monitoring instruments. Calls were produced during movement of the whales along convergent tracks, but following a close-approach (~500 m) between the whales, there was no extended period of close proximity. Call frequency, swim speed, and root-mean-square (rms) source sound pressure levels (SL) were different between the two animals. One whale called more frequently, more often, at a higher frequency and with higher SL, but had slower swim speeds than the other whale. The higher frequency calling whale's average SL was 186.0 dB re 1 μPa @ 1 m (rms) with a median call frequency of 51.1 Hz and swim speed of 2.7 m s^{-1}; whereas, the lower frequency calling whale had a median frequency of 40.2 Hz, SL of 175.1 dB re 1 μPa @ 1 m (rms), and swim speed of 3.1 m s^{-1}. Acoustic tracking arrays provide valuable information on calling fin whale behavior.

INTRODUCTION

Fin whales (*Balaenoptera physalus*), the second largest baleen whale and an endangered species, occur worldwide and are found in all major oceans (Reilly *et al.*, 2013). Fin whales produce two main types of stereotypical, frequency downswept, high-amplitude, short duration (<1 s) calls which are known by their primary frequencies as "20-Hz" and "40-Hz" calls (Watkins, 1981). The 20-Hz call, the most commonly reported fin whale sound, is considered to serve a social purpose for establishing and maintaining contact when produced in irregular sequences (Edds-Walton, 1997) or as a reproductive function when produced by males in regular sequences forming song (Croll *et al.*, 2002). Reported less frequently, the 40-Hz call occurs in irregular sequences and are more common during the summer, but its social context is not well understood (Watkins, 1981; Širović *et al.*, 2013).

Fin whale dive behavior has been described as two types: short dives of 2-6 min and longer dives of 6-14 min (Watkins 1981). Both the 40-Hz call, and occasional single 20-Hz calls, are produced more often during long dives, and at times when several whales are diving near each other. During these dives, sequences of 5 - 10 calls are produced, apparently by more than one animal, based on the character of the calls. Calls are not produced when fin whales are at the surface, leading to ~1 – 2 minute gaps between successive calls in a call sequence.

The 20-Hz call source sound pressure level (SL) has been reported as high as 189 dB re 1 µPa at 1 m (rms) (Širović *et al.*, 2007; Weirathmueller *et al.*, 2013), allowing the call to be detected at long distances (10's of km) and to be localized and tracked using passive acoustic monitoring (PAM) techniques (McDonald *et al.*, 1995; Wilcock, 2012; Soule and Wilcock, 2013; Weirathmueller *et al.*, 2013). Localizing calls allows SLs to be estimated, an important parameter for estimating detection probability and population densities from PAM using distance sampling techniques (Marques *et al.*, 2009; Hildebrand *et al.*, 2015). Successive localizations result in tracks, providing details on animal swimming behaviors and habitat use. However, currently there are no reports of 40-Hz call SL estimates nor localized tracks.

In this article, we describe 40-Hz call parameters, SLs and tracks from two concurrently calling fin whales using an array of PAM recorders deployed in the Gulf of Alaska (GOA). The calls may have been used by the whales to produce convergent tracks with a close-approach (~500 m), but not an extended period of close proximity.

METHODS

In May 2015, three High-frequency Acoustic Recording Packages (HARPs; Wiggins and Hildebrand, 2007) were deployed to the seafloor in the GOA in a equilateral triangle configuration approximately 1 km per side (Table 1). HARPs consist of a low-power, large data storage, high-data-rate recorder, a broadband hydrophone tethered above the instrument package, batteries, acoustic transponder ballast weight release system, electronic equipment pressure housings, and buoyancy in a frame or mooring configuration. Two types of HARPs were used: one single-hydrophone (10 Hz – 100 kHz) system at the north site 1, and two four-hydrophone (10 Hz – 50 kHz) systems (Wiggins *et al.*, 2012) at the southern, downslope sites 2 and 3. Site 1's recording was over four months; whereas, sites 2 and 3 were over three months and had recording errors resulting ~2 s gaps of data every 36 s. Precise instrument location and recorder clock synchrony are required for call localization and tracking. A ship-based global positioning system (GPS) and acoustic transponder survey were used to localize the instruments to within ~10 m, and clock drift rates were measured to be ~10^{-8} s/s. Calibrated hydrophone response is required for accurate SL estimation, so hydrophone electronics were calibrated at Scripps Institution of Oceanography and compared to full-system calibrations from the U.S. Navy's Transducer Evaluation Center, both in San Diego California, and found to have response uncertainties of ± 1-2 dB.

Table 1. Passive acoustic monitoring array site names, locations, depths, recording periods and durations.

Site Name	Latitude (N)	Longitude (W)	Depth (m)	Recording Period	Recording Duration (d)
1	58º 39.335'	148º 05.426'	835	05/01 – 09/06/2015	128
2	58º 38.807'	148º 06.005'	1043	05/01 – 08/07/2015	98
3	58º 38.848'	148º 04.937'	1022	05/01 – 08/08/2015	99

Recordings were processed and analyzed using *Triton* (Wiggins and Hildebrand, 2007) and custom software routines in MATLAB (MathWorks Inc., Natick, MA). Acoustic records were decimated (low-pass filtered and resampled) from 200 kHz and 100 kHz for the two instrument types down to 2 kHz sample rate to allow for more efficient processing and analysis. Using *Triton*, long-term spectral averages (LTSAs) were visually scanned by an analyst (SMW) for bouts of fin whale 40-Hz calls, and call bouts with good signal-to-noise ratio (SNR) were identified for further evaluation. Sound pressure level time series waveform SNR was typically enhanced by applying a Butterworth band-pass filter (BPF) with pass band between 30 – 80 Hz. One call bout was chosen as the focus of this article because it had particularly good SNR. The bout lasted about one hour starting ~18:30 on 20 July 2015 and showed apparently two types of 40-Hz calls, one at higher frequency and intensity than the other (Figure 1).

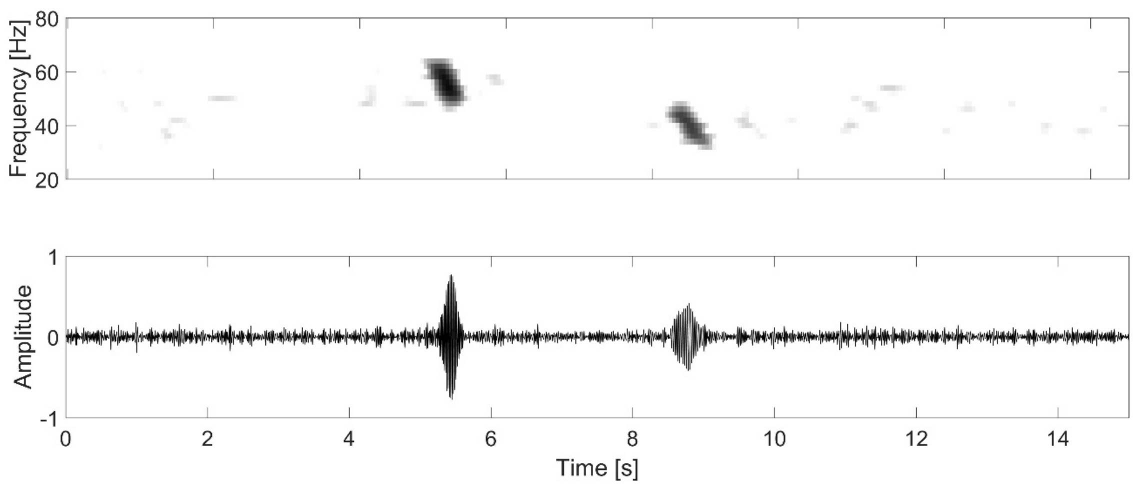

Figure 1. Example of two types (high and low frequency) of 40-Hz calls recorded at site 1 near the beginning of the recording ~18:30. The top panel spectrogram was computed using 1000 samples and Hann window with 90% overlap. The bottom panel shows how the time series amplitude was typically lower for the low frequency call.

To investigate this call bout further, call localization was performed by a least-square best-fit grid search method similar to Wiggins *et al.* (2013) in which measured time difference of arrival (TDOA) between the same call recorded on the three instruments was compared to modeled TDOAs to identify the call location in the model with the best fit. The model space was a three-dimensional 5 km x 5 km x 1.2 km grid with 25 m resolution and homogeneous sound speed of 1475 m s^{-1}. The call depth was constrained to near the sea surface (20 m) as per Stimpert *et al.* (2015). Measured TDOAs were obtained by cross-correlating three-second sound pressure time series windows that were chosen based on analyst manual visual detections of calls from the recordings. Each 40-Hz call detection was labeled either “A” for the calls with higher or “B” for calls with lower frequencies and intensities. Post-localization misidentified calls were reassigned their correct identifier based on probable location and continuity (i.e., along track) with other calls. Some calls could not be localized because of poor SNR or recording errors.

Location and duration between detections along tracks were used to estimate swim speeds. Start and end frequencies and start times of calls were noted from time series waveforms and spectrograms from which inter-call-intervals (ICIs) and median frequencies were calculated. Peak-to-peak (pp) and -3 dB root-mean-squared (rms) received sound pressure levels (Madsen, 2005) were measured in the detection window. Hydrophone sensitivity corrected received levels were used with slant range distance from the hydrophones to the localized whales to estimate their SL using the sonar equation: SL = RL + TL where, transmission loss was estimated using spherical spreading: $TL = 20*\log_{10}(\text{Range [m]})$. Absorption is negligible for fin whale call frequencies and the relatively short propagation distances. Means and standard deviations were calculated for these parameters.

RESULTS

A synthetic spectrogram based on the analyst detections of 105 fin whale 40-Hz calls at site 1 provides an overview of calling behavior during the ~1 h bout (Figure 2a). Noticeable from the spectrogram, whale A called more often, over a longer period, typically with a shorter ICI, and at higher frequency than whale B, as also shown in the call parameter measurements (Table 2).

The asynchronous timing of the whales’ calls do not appear coordinated with one another in a strict call-counter-call sense as the initiation of each call does not seem to be in response to the arrival of a call from the other animal (Figure 2a).

Gaps in calling, where calls are separated by greater time intervals, occur at regular intervals throughout the call sequence for both whales (non-shaded regions Figure 2a); these may be associated with surfacing for breathing. Whale A typically called at ~2 -10 Hz lower frequency in the beginning and end of a call sequence bounded by calling gaps; whereas, this behavior was not as apparent for whale B. Also, whale A typically had a high rate of calling (~4 calls/minute) after a gap compared to the remainder of a calling sequence (~2 calls/minute), but whale B calling interval was more consistent.

Both the pp and rms SL were about 10 dB higher and less variable for whale A than whale B (Figure 2b; Table 3). SLs versus calling frequency show SLs increase with increasing call frequency for both whales (Figure 3).

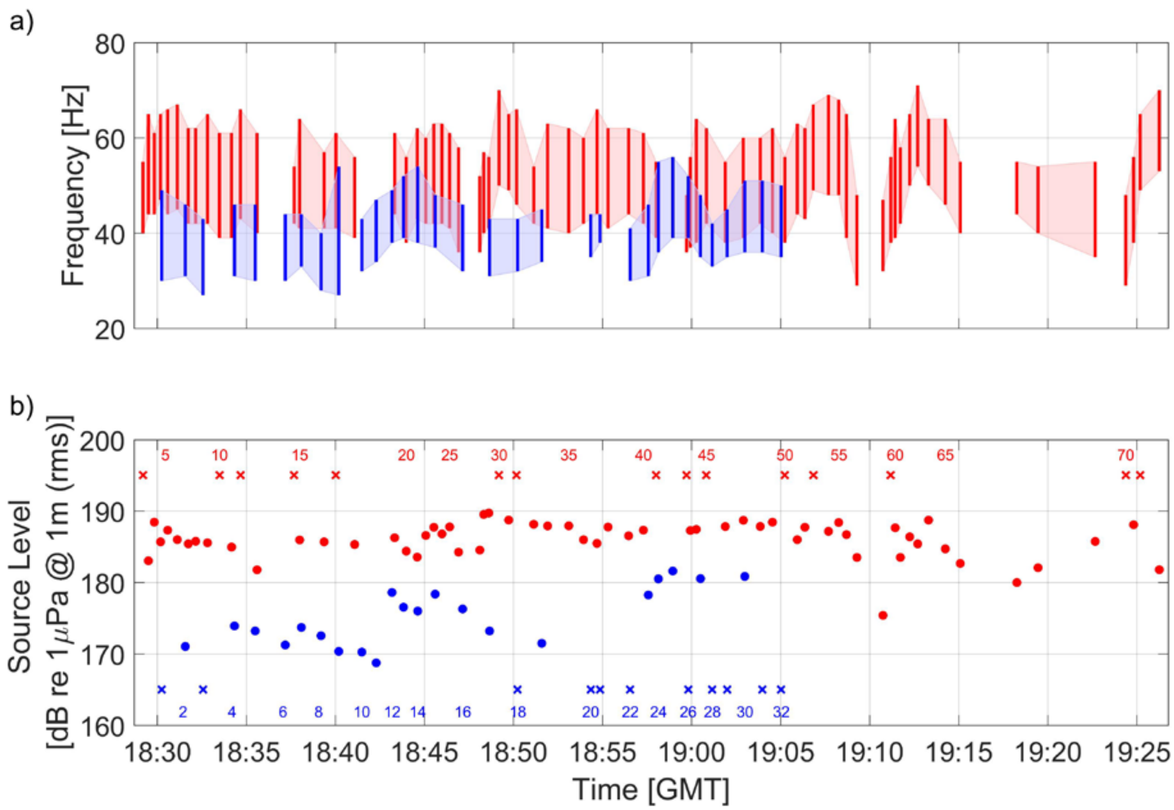

Figure 2. Two concurrent 40-Hz fin whale calling sequences. a) Synthetic spectrogram of fin whale calls generated using start and end frequencies of analyst detected calls. Red calls for whale A, blue calls for whale B, and shaded presumed dive sequence with gaps for breathing. b) Estimated call sound pressure source levels. Numbers represent call sequence, dots "•" are for localized calls, and "x" indicate calls not localized due to low signal-to-noise ratio or recording errors.

Table 2. Measured 40-Hz call parameters for whales A and B. Number of detections, bout duration, call average median, starting, and ending frequency, call bandwidth and inter-call-interval (ICI). Values in parentheses (± #) are standard deviations. * denotes six and four ICI outliers >100 s were omitted for whales A and B, respectively.

	Whale A	Whale B
Number of Detections	73	32
Bout Duration (MM:SS)	54:04	34:47
Median Frequency (Hz)	51.1 (±4.8)	40.2 (±3.4)
Starting Frequency (Hz)	60.5 (±5.4)	47.1 (±4.3)
Ending Frequency (Hz)	41.7 (±4.7)	33.5 (±3.5)
Call Bandwidth (Hz)	18.7 (±3.2)	13.5 (±3.8)
Inter-call-interval (ICI) (s)	39.0 (±17.6) *	59.7 (±17.4) *

Table 3. Measured call and swimming parameters for localized 40-Hz calls from whales A and B. Number of localizations, mean peak-to-peak and root-mean-squared source sound pressure levels and swim speed. Values in parentheses (± #) are standard deviations. * denotes two swim speed outliers >12 m s^{-1} were omitted for whale A.

	Whale A	Whale B
Number of localizations	58	21
Peak-to-Peak SL (dB re 1 µPa @ 1 m)	196.2 (±2.4)	186.4 (±3.5)
Root-Mean-Square SL (dB re 1 µPa @ 1 m)	186.0 (±2.5)	175.1 (±4.0)
Swim Speed (m s^{-1})	2.7 (±2.3) *	3.1 (±1.6)

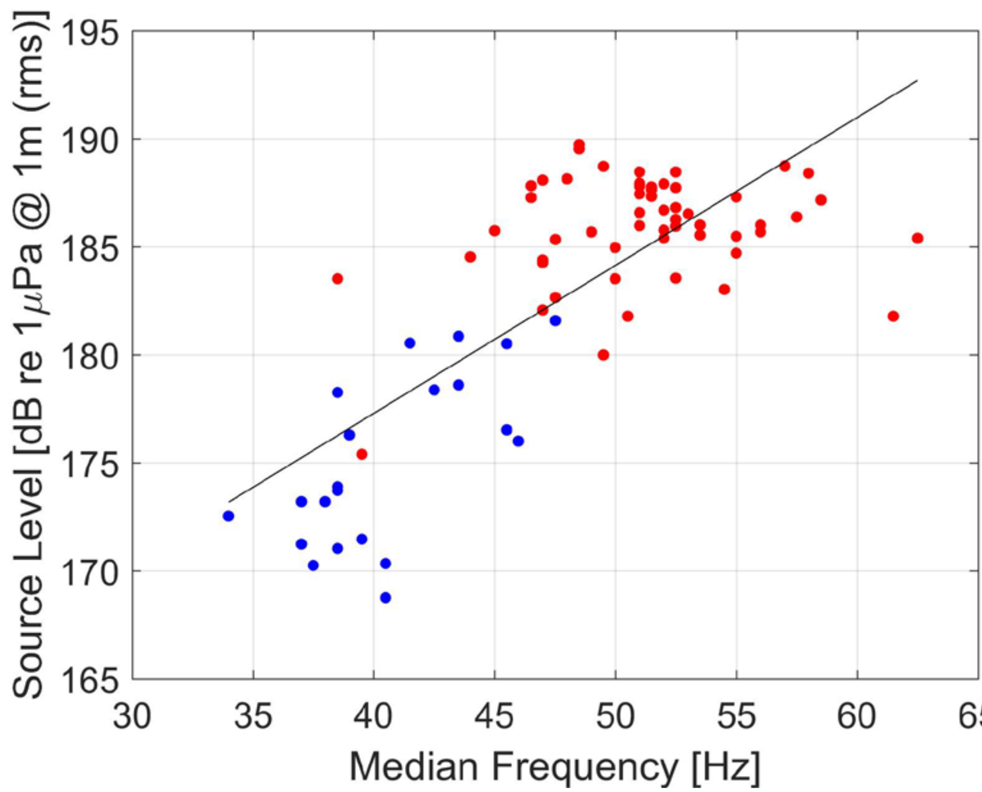

Figure 3. 40-Hz fin whale call source sound pressure level from localizations and corresponding call median frequency. Red dots are for whale A, and blue dots are for whale B. The black line is a linear least-squares fit: SL = 0.69 x Median Frequency + 150 dB re 1 μPa @ 1 m (rms), and $R^2 = 0.59$.

Whale call locations over the one-hour sequence show two different converging, but passing, tracks about 4 – 5 km long with whale A traveling from the south to the north along a slightly serpentine path and whale B traveling from the north to the southeast along a less curved path (Figure 4). Gaps in calling (Figure 2a) appear as call location gaps along the tracks, especially for whale A.

The closest approach distance between the callers was about 500 m at ~18:57, toward the end of whale B's calling period when its SLs were highest (Figure 2b). After passing, both whales continued swimming and calling, and do not appear to have paused to remain in close proximity for any extended period. Whale A continued calling for a substantially longer period than whale

B; however, this likely may be because whale B was beyond the detection range of the acoustic array. Also, whale B had approximately 15% faster mean swim speed than whale A (Table 3).

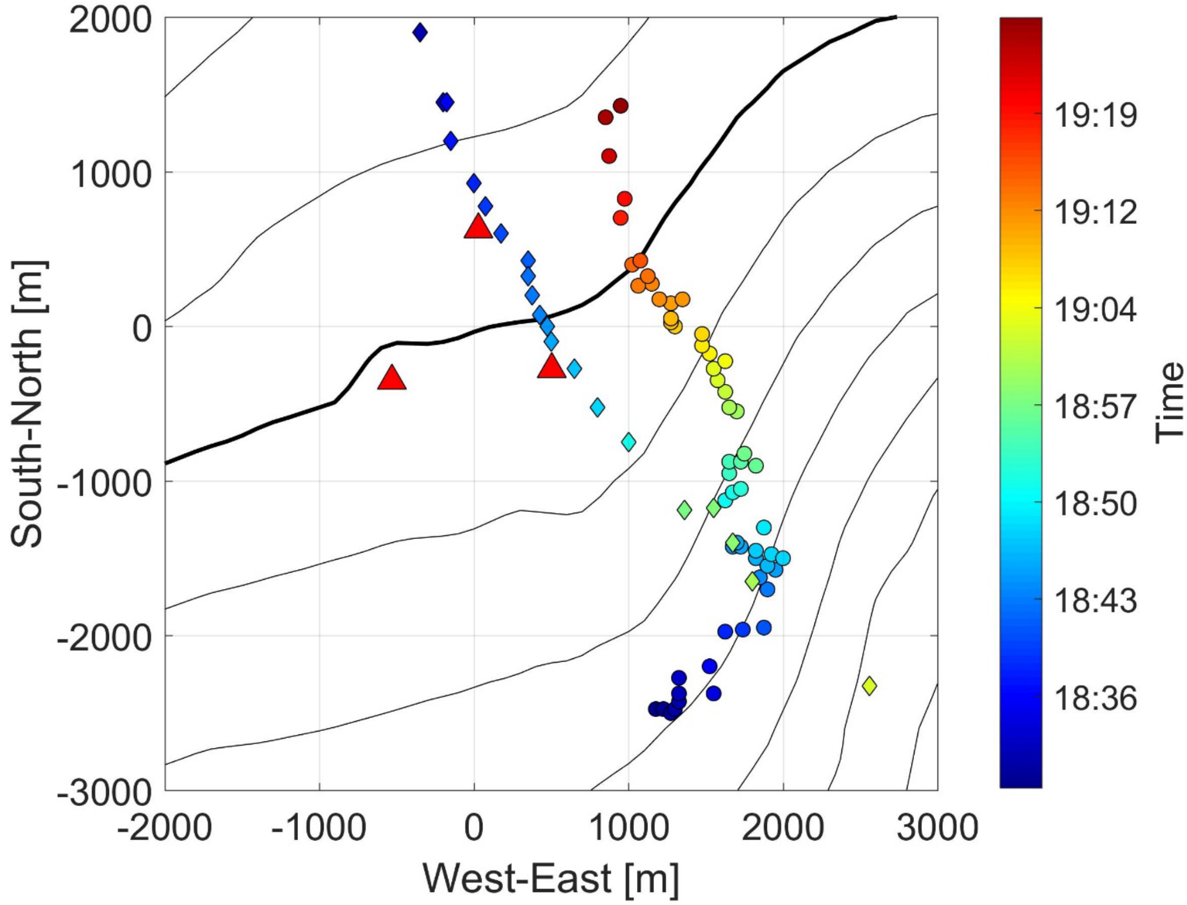

Figure 4. Map of two fin whale tracks from 40-Hz call localizations in the Gulf of Alaska on 20 July 2015. The origin (0,0) is at 58º 38.997'N, 148º 05.456'W. Red triangles are passive acoustic recorder locations, circles are locations for whale A traveling south to north, and diamonds are locations for whale B traveling north to southeast. Color of whale locations corresponds to time scale on right going from cool to warm colors as time progresses. Black bathymetric contour lines are spaced 100 m apart in depth with the thick black line at 1000 m and depth increasing to the southeast (bathymetry from: Lim *et al.*, 2011).

DISCUSSION AND CONCLUSIONS

Fin whales producing 20-Hz calls have been previously tracked (e.g. McDonald *et al.*, 1995) and the animals were generally moving during the period of call production. This is the first report of tracked 40-Hz fin whale calls, and again the animals were shown to be moving while producing calls. As suggested previously (Watkins 1981), more animals than one were simultaneously engaged in 40-Hz call production, but not in a strict call-counter-call sense. The pair of 40-Hz calling fin whales had converging tracks that passed within ~500 m of each other, but the animals did not pause from swimming to remain in close proximity. It has been suggested that only males fin whales produce 20-Hz calls (Croll et al. 2002), but no information is available to determine whether 40-Hz calls are made by one or both sexes. Metrics for each animal's calling frequencies, SLs and swim speeds were somewhat different suggesting individual differences in behavior.

While an over-simplification relating sound frequency to size (i.e., high frequency = small) could be invoked, it may be that both the tracked whales were similar in size and chose different SLs. Whale A produced higher frequency calls (51.1 ±4.8 Hz), but at higher source level (186.0 ±2.5 dB re 1 µPa @ 1 m (rms)) than those of whale B (40.2 ±3.4 Hz and 175.1 ±4.0 dB re 1 µPa @ 1 m (rms)). As Aroyan *et al.* (2000) outlined, for the same lung volume, baleen whale SL goes up with increasing frequency. Applying a constant lung volume assumption to these whales, given the differences in call frequencies the SL difference would be only 4.2 dB, less than the observed value of 10.9 dB. The two tracked whales could be choosing different SLs similarly to choosing different call frequencies. Alternatively, if total lung volume was different for each caller, then whale A would need an additional 6.7 dB increased lung volume, or about twice as much volume as the lower frequency whale B. Additionally, it is possible the calling depth may play a role in call frequency and source level, given that calls adjacent to surfacing for breathing appear to be lower than mid-sequence calling in both frequency and source level for Whale A than Whale B suggesting Whale A may vary more in calling depth around breathing than Whale B.

While much has been learned over the past few decades about marine mammals from single, independent, long-term, PAM records, much more can be learned about how these animals interact, their behaviors, and how they utilize their habitat from multiple-sensor PAM tracking arrays. Details of swimming behavior, call rates, and SLs can be used with distance sampling techniques to provide a better estimate of population densities by taking into account a more complete repertoire of calls.

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