Received: 11 March 2019 | Accepted: 10 January 2020

DOI: 10.1111/mms.12680

NOTE

Marine Mammal Science

Fin whale 40-Hz calling behavior studied with an acoustic tracking array

Sean M. Wiggins | John A. Hildebrand

Scripps Institution of Oceanography, La Jolla, California

Correspondence
Sean M. Wiggins, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0205.
Email: swiggins@ucsd.edu

Funding information
U.S. Pacific Fleet, Environmental Readiness Directorate Chip Johnson, Grant/Award Number: CESU N62473-17-2-0014

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, that are known by their primary frequencies as "20-Hz" and "40-Hz" calls (Širović, Williams, Kerosky, Wiggins, & Hildebrand, 2013; Watkins, 1981). The 20-Hz calls may have reduced bandwidth of ~1 Hz and also may include higher frequency components at 135–140 Hz (Castellote, Clark, & Lammers, 2012). The 20-Hz calls are the most commonly reported fin whale sound, and may 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). The 40-Hz call occurs in irregular sequences and is more common during the summer, but its social context is not well understood (Širović et al., 2013; Watkins, 1981).

Fin whale dive behavior has been described as two types: short dives of 2–6 min and longer dives of 6–14 min or longer (Goldbogen et al., 2006; Stimpert et al., 2015; Watkins, 1981). Both the 40-Hz call, and single 20-Hz calls, are produced more often during long dives (Stimpert et al., 2015; Watkins, 1981), 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. Typically, calls are not produced when fin whales are at the surface, leading to longer time 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, Hildebrand, & Wiggins, 2007; Weirathmueller, Wilcock, & Soule, 2013), allowing the call to be detected at long distances (10s of km) and to be localized and tracked using passive acoustic monitoring (PAM) techniques (McDonald, Hildebrand, & Webb, 1995; Soule & Wilcock, 2013; Varga, Wiggins, & Hildebrand, 2018; Weirathmueller et al., 2013; Wilcock, 2012). Call localization allows SLs to be estimated, an important parameter for estimating detection probability and population densities from PAM using distance sampling techniques (Hildebrand et al., 2015; Marques, Thomas, Ward, DiMarzio, & Tyack, 2009), and 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.

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

In May 2015, three autonomous high-frequency acoustic recording packages (HARPs; Wiggins & Hildebrand, 2007) were deployed to the seafloor in the GOA in an 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, McDonald, & Hildebrand, 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. 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^{-2} parts per million, and all times are presented relative to Greenwich Mean Time. 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 frequency response uncertainties of ±1–2 dB. Hydrophone sensitivities were −159 and −153 dB re V/μPa for the four-hydrophone and single-hydrophone systems, respectively.

Recordings were processed and analyzed using *Triton* (Wiggins & 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 were visually scanned by an analyst (S.M.W.) for sequences of fin whale 40-Hz calls, and call sequences 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 and 80 Hz. One sequence of calls, chosen as the focus of this study, had particularly high SNR. The sequence lasted about 1 hr starting ~18:30 on July 20, 2015 and showed two types of 40-Hz calls, one at higher frequency and intensity than the other (Figure 1).

To investigate this sequence of calls further, call localization was performed by a least-square best-fit grid search method similar to Wiggins et al. (2013) in which a set of three measured time difference of arrivals (TDOAs) between the same call recorded on the three instruments were minimized with modeled TDOAs to identify the call location in the model. The model space was a three-dimensional 5 km × 5 km × 1.2 km grid with 25 m resolution and homogeneous sound speed of 1,475 m/s based on temperature profiles taken during HARP deployments. Call depth was constrained to near the sea surface (20 m) as per Stimpert *et al*. (2015). Sets of measured TDOAs were obtained by cross-correlating three-second sound pressure time series windows that were chosen based on the analyst's manual visual detection of calls from the recordings. Successive call localizations with small differences in range from previous localizations typically heading the same general direction constituted individual tracks. Some calls could not be localized because of poor SNR or recording errors that resulted in gaps in the tracks.

TABLE 1 Passive acoustic monitoring array configuration.

Site name	Latitude (N)	Longitude (W)	Depth (m)	Recording period	Recording duration (d)
1	58°39.335′	148°05.426′	835	January 5–September 6, 2015	128
2	58°38.807′	148°06.005′	1,043	January 5–August 7, 2015	98
3	58°38.848′	148°04.937′	1,022	January 5–August 8, 2015	99

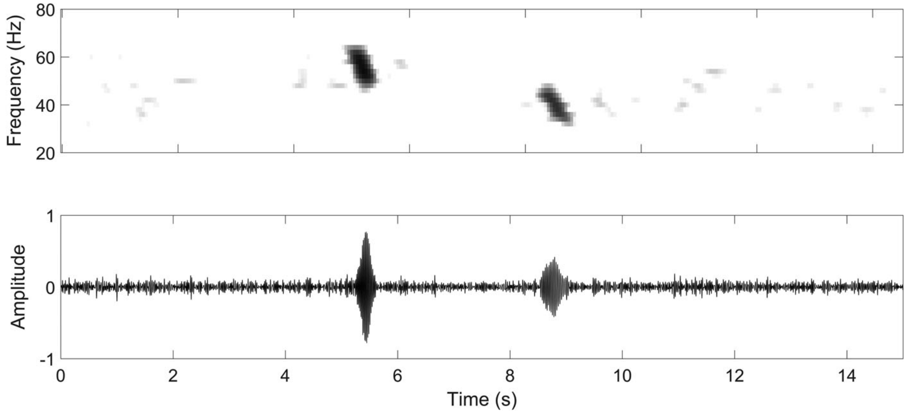

FIGURE 1 Spectrogram and amplitude time series of two types of fin whale 40-Hz calls. High and low frequency 40-Hz calls recorded at site 1 near the beginning of the recording ~18:30. The top panel spectrogram was computed using 1,000 samples and Hann window with 90% overlap. The bottom panel shows how the time series amplitude was typically lower for the low frequency call.

Call localization error analysis was conducted by applying a small error or perturbation to one of the three modeled TDOAs at each grid point, solving for locations based on the perturbed TDOAs, and differencing the new locations from the original unperturbed model to provide an error estimate at each grid point. This was repeated for the other two TDOAs of each set of three, and using both positive and negative perturbations for a total of six different sets of error maps. The six error maps were averaged to provide an error estimate at each grid point for a given magnitude of perturbation. While recorder location and synchronicity uncertainties were found to be low, errors associated with selecting cross-correlation peaks may be possible such that being off by one peak in the cross-correlation would result in a 25 ms TDOA error (i.e., 1/40 Hz). Using a perturbation of 25 ms in the error analysis provides a location uncertainty map with concentric rings of constant location uncertainty centered on the array but skewed slightly toward the south because of ~200 m depth difference between the north recorder and the two southern recorders. At 500 m range from the center of the array, the location uncertainty for 25 ms error is 30 m, at 1,500 m range the error is 100 m, and at 2,500 m range the error is 300 m. It is noted that much larger errors than estimated here for our deep-water array, especially along lines connecting recorders (i.e., end-fire directions), would be obtained using the error analysis for a similar array geometry but with the instrument depths reduced to continental shelf depths ~100–200 m.

Distances and times between adjacent localizations within a track were used to estimate swim speeds. Start and end frequencies and start times of individual calls were picked from spectrograms and time series waveforms, respectively. Intercall-intervals (ICIs) were calculated from differencing successive call start times and call median frequencies were calculated as halfway between start and end frequency for each call. Peak-to-peak (pp) and − 3 dB root-mean-squared (rms) received sound pressure levels (Madsen, 2005) were measured in the detection window. Received levels (RLs), corrected for hydrophone sensitivity, were used with slant range distance from the hydrophones to the localized whales to estimate SL using the sonar equation: SL = RL + TL where, transmission loss (TL) was estimated using spherical spreading: TL = $20*\log_{10}$[Range (m)] without accounting for absorption due to the low frequency character of the calls (Urick, 1983). Means and standard deviations were calculated for call start, end, median, and bandwidth frequencies in addition to ICI, swim speed and, pp and rms apparent SL.

Estimated whale call locations over approximately one hour show two different converging, but passing, tracks about 4–5 km long with one whale (A) traveling from the south to the north along a slightly serpentine path and another whale (B) traveling from the north to the southeast along a less curved path (Figure 2).

The closest approach distance between the callers was about 500 m at ~18:57, toward the end of whale B's calling period, and while estimated localization uncertainties are ~150–200 m for this region of the model, the

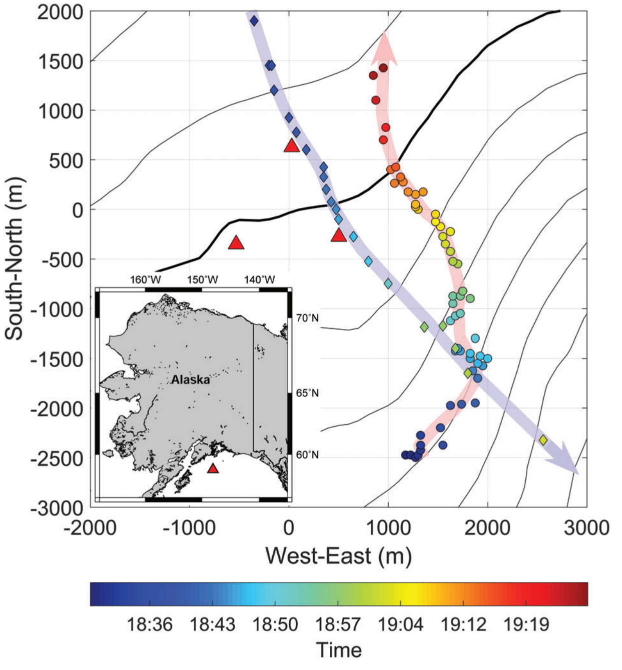

FIGURE 2 Map of two fin whale tracks from 40-Hz call localizations in the Gulf of Alaska on July 20, 2015. The origin (0, 0) is at 58°38.997′N, 148°05.456′W. Red triangles are passive acoustic recorder locations, circles are locations for whale A traveling south to north (light red track), and diamonds are locations for whale B traveling north to southeast (light blue track). The color of the whale locations corresponds to the time scale at the bottom going from cool to warm colors as time progresses. Tracks were calculated by applying a running average to sequential whale localizations and interpolating at 10 m increments in the south–north direction. Black bathymetric contour lines are spaced 100 m apart in depth with the thick black line at 1,000 m and depth increasing to the southeast (bathymetry from: Lim, Eakins, & Wigley, 2011); however, bathymetry accuracy appears to be low based on the acoustic-GPS localization depths of the seafloor instruments (Table 1). Inset shows the array location as a red triangle in the northern Gulf of Alaska.

TABLE 2 Measured call and swimming parameters for localized 40-Hz calls from whales A and B.

	Whale A	Whale B
Number of localizations	58	21
Peak-to-peak SL (dB re 1 μPa @ 1 m)	198.6 (± 2.4)[a]	188.9 (± 3.5)
Root-mean-square SL (dB re 1 μPa @ 1 m)	188.4 (± 2.5)	177.5 (± 4.0)
Swim speed (m/s)	2.7 (± 2.3)[b]	3.1 (± 1.6)

[a]Values in parentheses are standard deviations.
[b]Two swim speed outliers >12 m/s were omitted for whale A.

continuity of the tracks suggest the whale localizations are reasonable. After passing, both whales continued swimming and calling, and do not appear to have paused to remain in close proximity for any extended period. Calls from whale A were detected for more than 25 min after calls from whale B were detected; however, this may be because whale B was beyond the detection range of the acoustic array. Using the localizations, both pp and rms SL estimates were about 10 dB higher and less variable for whale A than whale B, and both whales' mean swim speeds were around 3 m/s, with whale B approximately 15% faster than whale A (Table 2).

A synthetic spectrogram based on the analyst's detections of 105 fin whale 40-Hz calls at site 1 provides an overview of calling behavior during the ~1 hr sequence of calls (Figure 3a). A synthetic spectrogram was used instead of a standard spectrogram to better show the temporal-spectral differences and patterns of individual calls from the two whales. 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, also as shown in the call parameter measurements (Table 3).

The 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 3a), as described for blue whale D-calls (McDonald, Calambokidis, Teranishi, & Hildebrand, 2001).

TABLE 3 Measured 40-Hz call parameters for whales A and B.

	Whale A	Whale B
Number of detections	73	32
Call sequence duration (mm:ss)	54:04	34:47
Median frequency (Hz)	51.1 (± 4.8)[a]	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)
Intercall-interval (ICI) (s)	39.0 (± 17.6)[b]	59.7 (± 7.4)[b]

[a]Values in parentheses are standard deviations.
[b]Six and four ICI outliers >100 s were omitted for whales A and B, respectively.

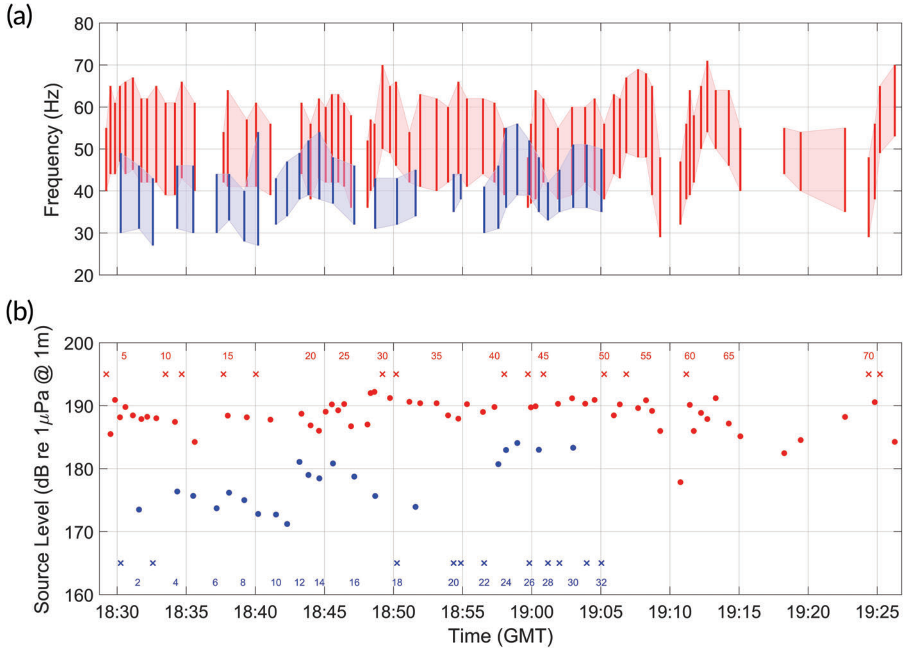

FIGURE 3 Two concurrent 40-Hz fin whale calling sequences. (a) Synthetic spectrogram of fin whale calls generated using analyst-detected call times and start and end frequencies. Red calls for whale A, blue calls for whale B, and shaded presumed dive sequence with gaps for breathing. (b) Estimated call sound pressure source levels. Numbers represent the call sequence, dots "●" are for localized calls, and "x" indicate calls not localized due to low signal-to-noise ratio or recording errors.

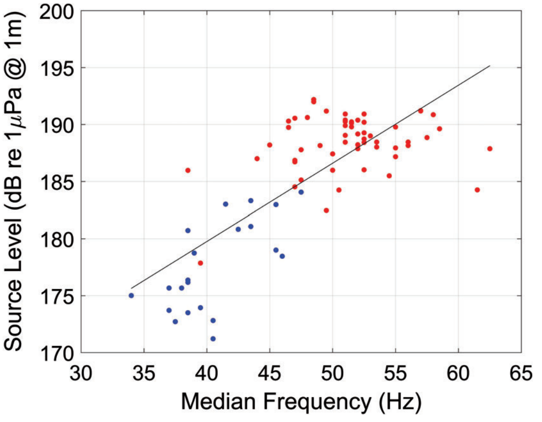

FIGURE 4 40-Hz fin whale call source sound pressure level from localizations and corresponding call median frequency. Red dots are for whale A, and blue dots are for whale B. The black line is a linear least-squares fit: SL = 0.69 × median frequency + 150 dB re 1 μPa @ 1 m (rms), and R^2 = 0.59.

Gaps in calling, where calls are separated by longer time intervals than their mean ICIs, occur throughout the call sequence for both whales (nonshaded regions Figure 3a); these may be associated with surfacing for breathing and appear as call location gaps along the tracks, especially for whale A (Figure 2). Whale A often called at 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 often had a high rate of calls after a gap compared to the remainder of a calling sequence, but whale B call interval was less variable. SLs versus median call frequency show SLs increase with increasing median call frequency for both whales (Tables 2 and 3; Figure 4).

Fin whales producing 20-Hz calls have been previously tracked (e.g., McDonald et al., 1995; Soule & Wilcock, 2013; Varga et al., 2018; Weirathmueller et al., 2013) and the animals were generally moving during the period of call production. This is the first published 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, rather as a loosely coordinated call sequence, and not as a single call and a single response. 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 shown that only male 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 these behaviors.

While a simplification relating sound frequency to size (i.e., high frequency = small) could be invoked (e.g., Morton, 1977), it may be that both the tracked whales were similar in size. Whale A produced higher frequency calls (51.1 ± 4.8 Hz), but at higher source level (188.4 ± 2.5 dB re 1 μPa @ 1 m [rms]) than those of whale B (40.2 ± 3.4 Hz and 177.5 ± 4.0 dB re 1 μPa @ 1 m [rms]). As Aroyan et al. (2000) modeled, for the same lung volume, baleen whale SL goes up with increasing frequency. Applying a constant lung volume assumption to these whales and given the differences in call frequencies, the SL difference would be only 4.2 dB which is less than the observed difference 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, to account for the higher SL. 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 in both frequency and SL (Figure 3, whale A).

While much has been learned over the past few decades about marine mammals from single, independent, long-term, PAM records, more can be learned about these animals from their movement and calling behaviors using PAM tracking arrays. This technology can reveal details of acoustic interactions that are unavailable via visual observation techniques. Furthermore, details of swimming behavior, call rates, and SLs can be used with distance sampling techniques to provide better estimates of their population densities.

ACKNOWLEDGMENTS

We thank Ryan Griswold of the Scripps Whale Acoustic Lab for instrument preparation, deployment, and recovery, Erin O'Neill for processing and archiving the acoustic recordings, and Bruce Thayre for assistance with data analysis and computer software and hardware support. We also thank the captain and crew of the Alaska Maritime National Wildlife Refuge R/V *Tiglax* for assistance with instrument deployment and recovery. Chip Johnson of the U.S. Pacific Fleet, Environmental Readiness Directorate provided support for this work under Cooperative Ecosystems Study Unit Cooperative Agreement N62473-17-2-0014. Mark McDonald and Chris Clark provided helpful comments on the manuscript.

ORCID

Sean M. Wiggins https://orcid.org/0000-0002-9686-035X

REFERENCES

Aroyan, J., McDonald, M. A., Webb, S. C., Hildebrand, J., CLark, D., & Laitman, J. T. (2000). Acoustic models of sound production and propagation. In W. W. L. Au, A. N. Popper, & R. R. Fay (Eds.), *Hearing by whales and dolphins*. New York, NY: Springer.

Castellote, M., Clark, C. W., & Lammers, M. O. (2012). Fin whale (*Balaenoptera physalus*) population identity in the western Mediterranean Sea. *Marine Mammal Science*, *28*, 325–344.

Croll, D. A., Clark, C. W., Acevedo, A., Tershy, B., Flores, S., Gedamke, J., & Urban, J. (2002). Only male fin whales sing loud songs. *Nature*, *417*, 809.

Edds-Walton, P. L. (1997). Acoustic communication signals of mysticete whales. *Bioacoustics*, *8*(1–2), 47–60.

Goldbogen, J. A., Calambokidis, J., Shadwick, R. E., Oleson, E. M., McDonald, M. A., & Hildebrand, J. A. (2006). Kinematics of foraging dives and lunge-feeding in fin whales. *Journal of Experimental Biology*, *209*, 1231–1244.

Hildebrand, J. A., Baumann-Pickering, S., Frasier, K. E., Trickey, J. S., Merkens, K. P., Wiggins, S. M., … Marques, T. A. (2015). Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico. *Scientific Reports*, *5*, 16343.

Lim, E., Eakins, B. W., & Wigley, R. (2011). *Coastal relief model of southern Alaska: Procedures, data sources and analysis*. NOAA Technical Memorandum NESDIS, NGDC-43.

Madsen, P. T. (2005). Marine mammals and noise: Problems with root mean square sound pressure levels for transients. *Journal of the Acoustical Society of America*, *117*, 3952–3957.

Marques, T. A., Thomas, L., Ward, J., DiMarzio, N., & Tyack, P. L. (2009). Estimating cetacean population density using fixed passive acoustic sensors: An example with Blainville's beaked whales. *Journal of the Acoustical Society of America*, *125*, 1982–1994.

McDonald, M. A., Calambokidis, J., Teranishi, A. M., & Hildebrand, J. A. (2001). The acoustic calls of blue whales off California with gender data. *Journal of the Acoustical Society of America*, *109*, 1728–1735.

McDonald, M. A., Hildebrand, J. A., & Webb, S. C. (1995). Blue and fin whales observed on a seafloor array in the Northeast Pacific. *Journal of the Acoustical Society of America*, *98*(2 PART 1), 712–721.

Morton, E. S. (1977). On the occurrence and significance of motivation-structural rules in some bird and mammal sounds. *American Naturalist*, *111*(981), 855–869.

Reilly, S. B., Bannister, J. L., Best, P. B., Brown, M., Brownell R. L., Jr., Butterworth, D. S., … Zerbini, A. N. (2013). *Balaenoptera physalus*. *The IUCN Red List of Threatened Species 2013*, e.T2478A44210520.

Širović, A., Hildebrand, J. A., & Wiggins, S. M. (2007). Blue and fin whale call source levels and propagation range in the Southern Ocean. *Journal of the Acoustical Society of America*, *122*, 1208–1215.

Širović, A., Williams, L., Kerosky, S., Wiggins, S., & Hildebrand, J. (2013). Temporal separation of two fin whale call types across the eastern North Pacific. *Marine Biology*, *160*, 47–57.

Soule, D. C., & Wilcock, W. S. D. (2013). Fin whale tracks recorded by a seismic network on the Juan de Fuca Ridge, Northeast Pacific Ocean. *Journal of the Acoustical Society of America*, *133*, 1751–1761.

Stimpert, A. K., DeRuiter, S. L., Falcone, E. A., Joseph, J., Douglas, A. B., Moretti, D. J., … Goldbogen, J. A. (2015). Sound production and associated behavior of tagged fin whales (*Balaenoptera physalus*) in the Southern California Bight. *Animal Biotelemetry*, *3*(1), 23.

Urick, R. J. (1983). *Principles of underwater sound* (3rd. ed.). New York, NY: McGraw-Hill.

Varga, L. M., Wiggins, S. M., & Hildebrand, J. A. (2018). Behavior of singing fin whales *Balaenoptera physalus* tracked acoustically offshore of Southern California. *Endanger Species Research*, *35*, 113–124.

Watkins, W. A. (1981). Activities and underwater sounds of fin whales. *Scientific Reports of the Whales Research Institute, Tokyo*, *33*, 83–217.

Weirathmueller, M. J., Wilcock, W. S., & Soule, D. C. (2013). Source levels of fin whale 20 Hz pulses measured in the Northeast Pacific Ocean. *Journal of the Acoustical Society of America*, *133*, 741–749.

Wiggins, S. M., & Hildebrand, J. A. (2007, April). *High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring*. Paper presented at the International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables & Related Technologies 2007, Tokyo, Japan.

Wiggins, S. M., Frasier, K. E., Elizabeth Henderson, E., & Hildebrand, J. A. (2013). Tracking dolphin whistles using an autonomous acoustic recorder array. *Journal of the Acoustical Society of America*, *133*, 3813–3818.

Wiggins, S. M., McDonald, M. A., & Hildebrand, J. A. (2012). Beaked whale and dolphin tracking using a multichannel autonomous acoustic recorder. *Journal of the Acoustical Society of America*, *131*, 156–163.

Wilcock, W. S. D. (2012). Tracking fin whales in the northeast Pacific Ocean with a seafloor seismic network. *Journal of the Acoustical Society of America*, *132*, 2408–2419.

How to cite this article: Wiggins SM, Hildebrand JA. Fin whale 40-Hz calling behavior studied with an acoustic tracking array. *Mar Mam Sci*. 2020;1–8. https://doi.org/10.1111/mms.12680