Swim track kinematics and calling behavior attributed to Bryde's whales on the Navy's Pacific Missile Range Facility

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Time difference of arrival methods for acoustically localizing multiple marine mammals have been applied to recorded data from the Navy's Pacific Missile Range Facility in order to localize and track calls attributed to Bryde's whales. Data were recorded during the months of August–October 2014, and 17 individual tracks were identified. Call characteristics were compared to other Bryde's whale vocalizations from the Pacific Ocean, and locations of the recorded signals were compared to published visual sightings of Bryde's whales in the Hawaiian archipelago. Track kinematic information, such as swim speeds, bearing information, track duration, and directivity, was recorded for the species. The intercall interval was also established for most of the tracks, providing cue rate information for this species that may be useful for future acoustic density estimate calculations.
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I. INTRODUCTION

North Pacific Bryde's whales (*Balaenoptera edeni*) are the only baleen whale that is distributed tropically and subtropically year-round. This population is known to congregate in their low latitude, subtropical breeding areas south of 20°N in January through March, then migrate to mid-latitude (20°N–40°N) feeding grounds in the summer,[1–4] although some whales may remain in lower or higher latitudinal waters year-round.[2,3] This mid-latitude region, from 20°N to 40°N and about 140°E to 160°W, was considered a prime whaling area by Japanese whalers until as recently as 1987.[4] The National Marine Fisheries Services estimates the Bryde's whale Hawaii stock to have a population size of 798, with a coefficient of variation (CV) equal to 0.28.[5] Due to limited prior estimates with higher CVs, there is insufficient data currently available to assess any population trends, although this latest figure was higher than the 459 estimated in 2002.[6] However, the Hawaiian stock is likely part of the greater North Pacific stock, which has been estimated to have a size of between 20 000 and 25 000 animals, based on surveys conducted in the 1980s through early 2000s.[2,7,8] The North Pacific stock boundary extends to about 150°W, although no whales have been sighted between 140°W and 155°W,[2] making that the approximate boundary between the North Pacific and Eastern Tropical Pacific (ETP) stocks.

Bryde's whales are known to make a variety of signal types; some call types are similar between populations, while others appear to be unique. Earlier descriptions of Bryde's acoustic calls all have the majority of energy content above 90 Hz.[9,10] Cummings *et al.*[9] reported calls from the Gulf of California and the Gulf of Mexico with fundamental frequencies of approximately 124 Hz with 0.4 s duration, and Edds *et al.*[10] reported on sounds in the Gulf of California with fundamentals ranging from 90 Hz to 900 Hz with duration varying from 25 ms to 1.4 s.

Lower frequency Bryde's calls were subsequently reported by Oleson *et al.*,[11] who described calls received in the presence of confirmed Bryde's whales in the ETP, southern Caribbean, and Northwest Pacific. In all but a single case, calls had components with frequencies of 60 Hz or less. These calls (labeled Be1–Be8b), had frequencies ranging from 21 Hz to 207 Hz with durations spanning 0.35 s–2.8 s. In addition, Heimlich *et al.*[12] reported acoustic only observations of suspected Bryde's whale calls at several different sites in the ETP, with some call characteristics similar to those reported by Oleson *et al.*, particularly Be1–Be3. Bryde's whale calls have also been reported off the coast of New Zealand;[13] these calls were reported to lack regular repeat intervals, and were described as similar to Oleson's[11] Be3 type call, as well as to down sweep calls reported by Kibblewhite *et al.*[14] for New Zealand.

A recent description of Bryde's whale calls off the coast of Southeast Brazil revealed five additional distinct call types (PS1, LFT, FMT, TM1, and TM2), with frequencies ranging from 9 to 670 Hz and durations spanning 0.8 to 1.5 s. It was noted that LFT, TM1, and TM2 contained universal

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characteristics readily identifiable for the species, with the TM1 call particularly similar to the Be3 call reported by Oleson *et al.*[11]

Passive acoustic monitoring at the Navy's Pacific Missile Range Facility (PMRF) range during the summer and fall of 2014 revealed a low frequency call that matched closely to the universal properties of the burst type pulses of Bryde's calls reported in the literature. Visual confirmation of Bryde's whales has not occurred in conjunction with the recorded signal at PMRF, but the call, shown in the upper left panel of Fig. 2, does not match the characteristics of any other known species in the area.

Automated localizations of acoustic calls attributed to Bryde's whales at PMRF provide a unique insight into both the acoustic and kinematic behavior of these animals in an offshore region that is rarely accessible by human observers. The analysis in this paper builds on initial acoustic detections and localizations described by Martin *et al.*,[15] and are the first reported detections of Bryde's whale calls in the Hawaiian islands region. Processing methods for localizing whales using the time difference of arrival (TDOA) of recorded acoustic signals have been established on the PMRF range.[16] The techniques were initially developed for humpback whales (*Megaptera novaeangliae*), but have since been expanded and used successfully for Bryde's, sei (*Balaenoptera borealis*), fin (*Balaenoptera physalus*), blue (*Balaenoptera musculus*), and minke (*Balaenoptera acutorostrata*) whales. The TDOA method was facilitated with the use of the generalized power-law (GPL) detector[17] and enhanced with a spectral "templating" procedure to characterize individual vocalizations by extracting a fundamental for each vocalization and setting the remainder of the spectrogram to zero. Cross-correlations of the templates allowed for localization of multiple animals concurrently with an incorrect localization rate of 2% or less.[16] Additional software was developed in order to positively associate each whale vocalization with a location. This step was necessary in order to accurately obtain the intercall interval (ICI) of the Bryde's calls, which is an important metric needed for density estimation.

The goals of this paper are threefold: to describe the vocalization recorded in Hawaii and compare it with those recorded in other regions of the Pacific Ocean; to describe the acoustic and kinematic metrics for 17 suspected Bryde's whale tracks that occurred during the months of August–October, 2014 in Hawaii; and to discuss these tracks in the ecological and behavioral context of what is known about North Pacific Bryde's whales. The call description, kinematics, and behavior discussed in this paper provide baseline information that could be helpful for future acoustic density estimation of this species.

II. METHODS

The PRMF range is located off the west coast of the island of Kauai in the Hawaiian Islands. Thirty-one time-synchronized hydrophones from the PMRF underwater range have been recorded on a sample basis of approximately two days a month over the past several years at a 96 kHz sampling rate, with additional days of recordings associated with U.S. Navy mid-frequency sonar training events. More recently, long-term opportunistic recordings spanning several weeks have been recorded at a 6 kHz sampling rate. Of these 31 hydrophones, 14 offshore hydrophones were selected for localization purposes, ranging in depth from 3150 meters to 4700 meters, and covering a rectangular-shaped grid ∼11 km to the east/west and 52 km to the north/south. The 14 hydrophones were subdivided into 4 subarrays (A,B,C,D), each containing 5 hydrophones (Fig. 1). The TDOAs are computed between the center hydrophone of each subarray and the nearest four corner hydrophones. The maximum allowable time delay between the center hydrophone and each adjacent hydrophone in the subarray is limited to the direct path propagation time between them. The subarray configuration was originally chosen such that a direct path solution on four hydrophone pairs always exists across the monitored area for the noise conditions present on the PMRF range for humpback whales. It was discovered for Bryde's whales that subarray A contains gaps in spatial coverage, and so subarrays B–D were used for the Bryde's whale analysis. The process for obtaining whale locations can be subdivided into three steps: detection and feature extraction, cross-correlation of those features to obtain TDOAs, and TDOA-based localization. These steps are outlined in detail using humpback whale calls in Helble *et al.*[16] and, therefore, are not repeated in this paper.

A. Modification of TDOA algorithm for Bryde's whale signal

Minor modifications were made to the methods outlined in Sec. II of Helble *et al.*[16] in order to calculate Bryde's whale localizations. The frequency range of the templating process was changed to monitor the 10–50 Hz frequency band instead of the 150–1000 Hz band described in Sec. II A of Helble *et al.* Additionally, single templates were used (rather than using a sequence of templates) during the cross-

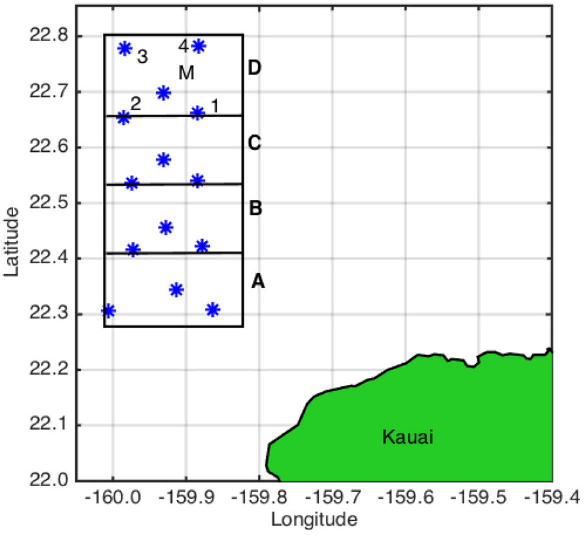

FIG. 1. (Color online) Approximate positions of PMRF hydrophones illustrating subarrays A–D. The center hydrophone is marked on subarray D (M) and the four adjacent hydrophones (marked 1–4).

correlation process described in Sec. II B of Helble *et al.* For humpback whales, vocalizations occur so frequently that cross-correlation of single units produce a high number of false localizations. Bryde's whale calls occur much less frequently, and so single call templates are more appropriate. If multiple vocalizations were utilized, the whale could move a significant distance between vocalizations and the resulting localization would be compromised from the whale's true location. The downside to using fewer vocalizations in the cross-correlation process is that the timing delay errors can become greater than when multiple signals are utilized. However, Helble *et al.* showed that for single tonal humpback calls, the timing delay errors were on the order of 40 ms, resulting in less than a 60 m localization standard deviation. The Bryde's calls recorded on PMRF have more transient structure than the humpback tonal calls tested, and so it is expected that the timing delay errors are no worse than those for the humpback single unit tonals.

B. Assignment and validation of tracks

The automated localization software described in Helble *et al.*[16] has strict criteria for determining a localization: the call must be templated on all five hydrophones, and the cross-correlation score between all four hydrophone pairs (center hydrophone and each of the four supporting hydrophones) must be greater than 0.4. Over 95% of the calls emitted by the Bryde's whale within the range adhere to these criteria, but for the purpose of measuring ICIs every call emitted by the whale must be included. Additional software was thus developed for the purposes of accurately measuring the ICIs of each whale track. First, the initial localizations produced by the localization software were manually grouped together into tracks (labeled A–K in Fig. 3). Localizations that were within 5 km of each other on similar trajectories and with gaps less than two hours were deemed to collectively make up a track. The tracks were presumed to be from a single vocalizing Bryde's whale, and, while there is no way to independently verify this assumption, it is likely true due to the relative isolation of each track in space and/or time. A second software package was developed to ensure that all calls along the track were included. First, each localized call along the track was identified on the center hydrophone in the subarray for which the call occurred. Next, each unassigned call received on the center hydrophone was assumed to be a missed call along the track. The approximate geographical location of the missed call was estimated by assuming a constant velocity trajectory between the previous known call along the track and the next known call along the track. The expected time delays for the unassigned call were then computed between all hydrophone pairs, with a user defined tolerance. If cross-correlation delays were computed between hydrophone pairs within the user defined tolerance, the call was included in the track. The user can also set the number of hydrophone pair matches required for the unassigned call to be included, relaxing the initial four hydrophone pair solution requirement to three pairs. In practice, relaxing the timing delay tolerance to 170 ms and requiring a match on three hydrophone pairs was sufficient to include any missed calls. This bootstrap method is beneficial because the localization parameters can be relaxed along the whale's apparent trajectory, without relaxing the localization requirements across the entire array, minimizing false localizations. For the final step, manual analysis of the raw spectrograms was utilized to ensure all vocalizations in the acoustic record were correctly assigned to a track. To do so, RAVEN Pro 1.5 software[18] was used to display the spectrograms of the audio channels of the four center hydrophones in the array. Color coded boxes were automatically placed on the spectrograms of the raw data corresponding to the start and end time of each vocalization within a track, with each track assigned a unique color. In almost all cases the localization software identified each vocalization correctly without double assigning vocalizations or missing vocalizations. Occasionally, a vocalization was unassigned by the software and thus assigned manually by the analyst. In most cases an unassigned call was easily assigned to the correct whale track by noting the time of arrival pattern of the call on multiple spectrogram channels. This pattern could then be matched with the pattern of nearby calls that were automatically assigned to a track. For a few cases, it was difficult to choose the correct track for an unassigned vocalizations, and for these tracks the ICI was not computed.

C. Track kinematic extraction

The process of extracting the whale track kinematics (bearings, velocities, directivity, etc.) can be problematic because unlike a physical tag the sampling of the track is limited to the calling rate of the whale. Additionally, there is some (although likely minimal) localization error and bias between the recorded location and the true location of the call. In the extreme example, a whale could vocalize twice—once at the beginning of a track and again at the end of the track. In such a scenario, only one bearing and velocity could be calculated, and the directivity index [the straight line distance (SLD) traveled divided by the total distance traveled (TDT)] would always be equal to one. There is no way to know the animal's movements between calls, and, therefore, the kinematics presented in this paper are the *minimum* known movements of the animal. In general, the ICIs of the calling animals are similar for the 17 tracks analyzed, allowing for comparison of kinematics between animals, but it is important to note these sampling differences when comparing track kinematics.

Curve fitting tools were utilized in order to minimize the effects of sampling differences and localization uncertainty. Each track was parameterized such that latitude is a function of time and longitude is a function of time. Both the latitude and longitude coordinates were fitted separately with a cubic smoothing spline interpolation with adjustable tolerances. The tolerance selected was a tradeoff between the data misfit and the smoothness of the curve as represented by the integral of the curvature (second derivative squared). Tracks were fitted so that no unphysical velocities (>35 kph per 100 m traveled) were allowed between data points along the track. This was accomplished while keeping the along-track errors (distance from fitted curve to location of measured vocalization) to within 100 m. The continuous representation of the fitted track is a convenient means to derive along track sample points that are equally spaced in time for the purpose of computing and comparing track kinematics.

III. RESULTS

A. Call description and comparison

An example acoustic signal attributed to the Bryde's whale can be seen in the upper left panel of Fig. 2, shown as received at the center hydrophone in subarray B at the whale's closest point of approach (∼2 km from overhead) in 4.5 km water depth. The received signal's fundamental frequency is at 21 Hz, and the signal peak frequency, as observed on the seafloor-mounted hydrophones, is ∼33 Hz. It is important to note that the hydrophones are high-pass filtered at 50 Hz, and so levels <50 Hz are artificially depressed. Given the roll-off at lower frequencies, the 21 Hz component is likely higher than the observed peak level at 33 Hz. Secondary peaks reminiscent of pulse repetition rate harmonics (amplitude modulated sidebands at rates of ∼4 Hz) are present at multiple frequencies (e.g., 12, 29, and 37 Hz).

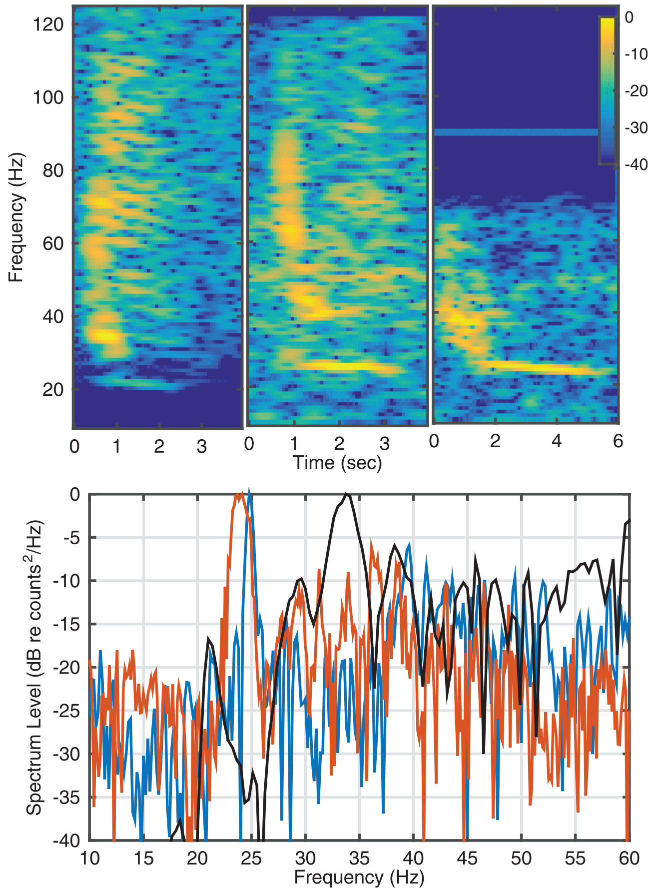

FIG. 2. Example spectrogram of the Bryde's whale signal recorded at PMRF (upper left), compared with the Be3 call recorded in the Eastern Tropical Pacific (Ref. 11) (upper middle), and call recorded off the coast of New Zealand (Ref. 13) (upper right). The colorbar indicates relative decibel (dB) levels normalized to the peak frequency of each call. The PMRF call was recorded with a 6 kHz sampling rate, and the spectrogram was created using a 2048 point fast Fourier transform (FFT) with a Hanning window and 87.5% overlap. The Be3 call and the New Zealand call were resampled to 6 kHz so that the same FFT settings could be used for all three calls. The spectrum of each call is plotted in the lower panel, in black, blue, and red, respectively. The lower plot shows the spectrum of the call (black line) using a 16 000 point FFT and Hanning window. The PMRF signal was recorded with a high-pass filter at 50 Hz, as evidenced by significant roll-off in the signal. The original sampling rate for the New Zealand call was 160 Hz, and so no frequency content is available above 80 Hz. Audio files for all three signals are available for download (Ref. 23).

The recorded signal at PMRF was compared against all other known Bryde's whale calls, and was found to match most closely with the Be3 calls recorded from the ETP,[11] and calls recorded in the south Pacific off New Zealand.[13] A spectrogram of the Be3 call can be seen in the upper middle plot of Fig. 2, and the spectrum can be seen in the lower panel (blue line). The Be3 call had a mean duration of 1.7 s and a peak frequency of 25.6 Hz. The South Pacific call is shown in the upper right panel of Fig. 2, with the accompanying spectrum shown in the lower plot (red line). This call consisted of an impulsive broadband sound at the start of each call and a down sweep frequency from 25 to 22 Hz.

B. Track kinematics

A total of 17 tracks attributed to Bryde's whales can be seen in Fig. 3. The shading of the tracks indicates the number of hours since midnight for each listed date. The tracks are labeled with a letter (A–K), and tracks that occurred with overlapping time are marked with the same letter and a number to indicate the overlap (i.e., tracks B1 and B2 transited with overlapping time through the range). A total of 7 days contained tracks out of the 17.7 days monitored between Aug 25, 2014 and Oct 28, 2014. Tracks were present for 47.17 h of the total 424.8 h of monitored time. The clustering of tracks in time suggests the whales were traveling in groups, with individual calling whales spaced 5–20 km apart. There are two events that indicate encounters between two calling Bryde's whales: tracks B1 and B2 intersected each other in the southern portion of the range, and tracks G2 and G3 intersected each other in the northern region. A single track emerged from the intersection of G2 and G3 transiting westward, but the track is not plotted since it is unclear to which whale the track should be attributed. Nearly all tracks (except for the cessation of either G2 or G3) appeared to persist for the entire duration of time it took for the whale to transit across the range, and faint calling recorded on the hydrophones as the animal transited into and out of the array boundaries suggests that the whales vocalized for extended periods of time.

Track kinematics for the 17 tracks displayed in Fig. 3 are given in Table I. The number of calls that make up the track (N_{calls}), the elapsed time of the track (E_{time}), the TDT, SLD, directivity index (SLD/TDT), 10th percentile (v_{min}), mean (v_{mean}), and 90th percentile (v_{max}) velocities, and ICIs (ICI_{mean} and ICI_{median}) are given for each of the tracks.

All of the tracks had directivity indices of 0.95 and higher except for track A, indicating that the whales followed very straight trajectories. Velocities varied between 0.15 kph and over 15 kph, with the average velocity of all 17 tracks equal to 5.93 kph. The velocities versus elapsed track

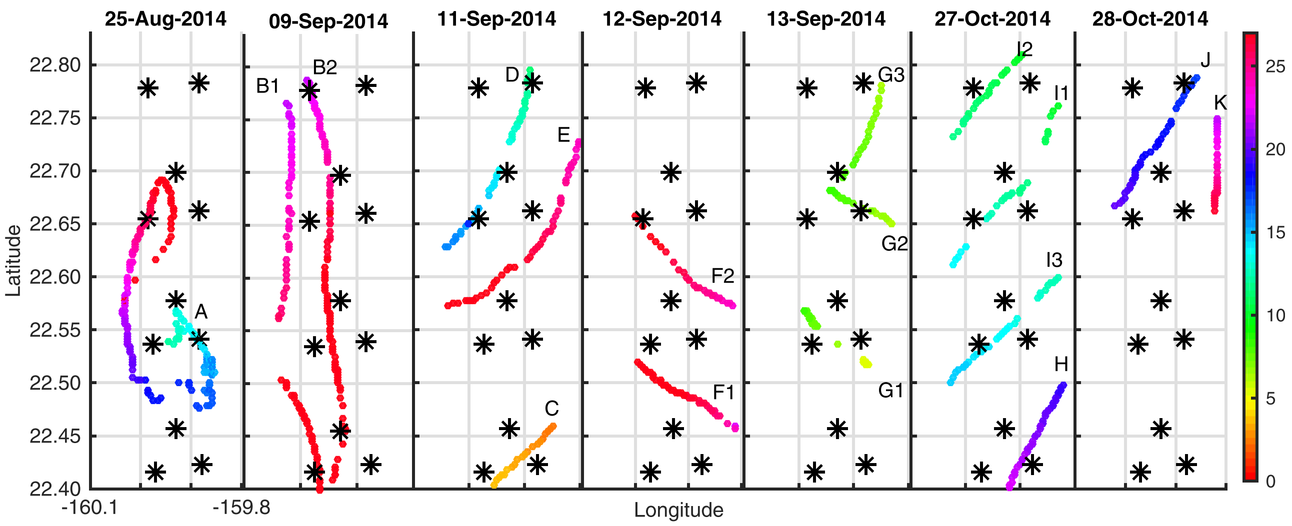

FIG. 3. (Color online) Bryde's tracks formed from TDOA acoustic localizations on the Navy's Pacific Missile Range Facility. Individual tracks are labeled A–K, tracks with the same letter represent tracks that occurred at the same time. The letter position indicates the beginning of the track. The shading gradient represents the time elapsed since midnight local time for each subplot.

times for tracks A, B1, B2, F1, G2, H, and J are displayed in Fig. 4. The tracks are grouped into subplots of similar track duration so that the details of the track velocities can be seen. Some tracks maintained nearly constant velocities, such as track B2, while others' velocities varied widely over the duration of the track, such as tracks A and J. The markers on the plot indicate each time the whale emitted a vocalization, and show that the whales generally increased the time between calls during periods of fast transit or periods of rapid acceleration or deceleration. The apparent gap of acoustic calls in track B1 was due to the animal transiting just outside the range before transiting back in. Calls for track B1 were manually tabulated while the whale was outside of the range for the purpose of obtaining the ICI, but localizations were not obtained for B1 outside of the range boundaries.

C. ICI

The ICI for each track was computed using the methods outlined in Sec. II B. ICIs were not included for tracks G1 and I2 because each call could not be confidently assigned to the correct whale. The mean and median ICIs for each track can be seen in Table I. The upper plot in Fig. 5 shows the 10th percentile, 90th percentile, mean, and median ICI for each track. The lower plot shows a histogram of the aggregated ICIs in 30 s bin increments for all the tracks for a total of 746 calls. The tallest bin (mode) is between 240 and 270 s, containing 163 calls. Further reducing the bin

TABLE I. Track kinematic information for tracks shown in Fig. 3. N_{calls} represents the number of calls that make up the track, E_{time} is the elapsed time of the track (in hours), SLD is the straight line distance between the first call and last call (in km), TDT is the total distance traveled along the track (in km), D_{index} is the ratio of SLD to TDT, $v_{\min}$ is the 10th percentile velocity measurement for the track (in kph), $v_{\max}$ is the 90th percentile velocity measurement for the track (in kph), v_{mean} is the mean velocity measurement for the track (in kph), bearing is the average bearing for the track (in degrees), and ICI_{mean} and $\text{ICI}_{\text{median}}$ are the mean and median ICIs for the track, respectively.

Track	Start time (local)	N_{calls}	E_{time}	SLD	TDT	D_{index}	$v_{\min}$	$v_{\max}$	v_{mean}	Bearing	ICI_{mean}	$\text{ICI}_{\text{median}}$
A	8/25/14 11:52 a.m.	179	17.98	10.06	70.87	0.142	0.15	15.26	3.94	309.26	363.73	295.48
B1	9/9/14 9:42 p.m.	99	7.51	41.23	43.31	0.952	4.90	6.80	5.78	171.44	278.99	266.67
B2	9/9/14 9:50 p.m.	110	10.86	42.60	43.94	0.970	3.65	4.46	4.07	173.39	381.28	300.68
C	9/11/14 2:12 a.m.	20	1.59	12.84	12.87	0.997	3.74	12.31	8.20	243.09	300.55	293.29
D	9/11/14 11:20 a.m.	44	4.66	24.17	24.82	0.974	4.52	6.21	5.32	217.21	382.02	288.22
E	9/11/14 11:38 p.m.	46	4.81	29.62	31.04	0.954	5.84	7.82	6.45	233.60	384.54	364.41
F1	9/12/14 10:09 p.m.	45	6.40	20.23	20.30	0.996	0.38	5.00	4.44	292.69	523.88	306.95
F2	9/12/14 11:36 p.m.	27	4.12	21.24	21.43	0.991	3.67	6.71	5.20	302.40	570.26	475.65
G1	9/13/14 5:11 a.m.	52	2.99	13.45	13.55	0.993	0.22	5.26	4.43	298.91	—	—
G2	9/13/14 5:38 a.m.	25	2.76	12.32	12.48	0.986	0.52	6.22	4.57	291.73	414.76	308.74
G3	9/13/14 6:17 a.m.	20	1.67	12.06	12.28	0.982	5.45	10.14	7.41	213.51	316.86	281.52
I1	10/27/14 9:50 a.m.	31	4.04	3.03	3.04	0.997	6.88	7.54	7.19	229.73	308.18	282.27
I2	10/27/14 9:53 a.m.	25	1.91	15.58	15.64	0.996	7.07	10.32	8.19	231.83	—	—
I3	10/27/14 12:16 p.m.	30	2.46	14.16	14.26	0.993	6.75	15.84	10.59	242.36	247.45	313.70
H	10/27/14 7:03 p.m.	38	3.07	14.56	14.61	0.997	4.41	5.39	4.78	223.61	298.32	240.31
J	10/28/14 5:10 p.m.	38	2.76	21.55	22.00	0.979	3.14	14.12	8.22	227.82	268.45	263.88
K	10/28/14 9:36 p.m.	43	4.73	9.71	9.74	0.996	1.39	2.69	2.00	183.02	405.67	310.82

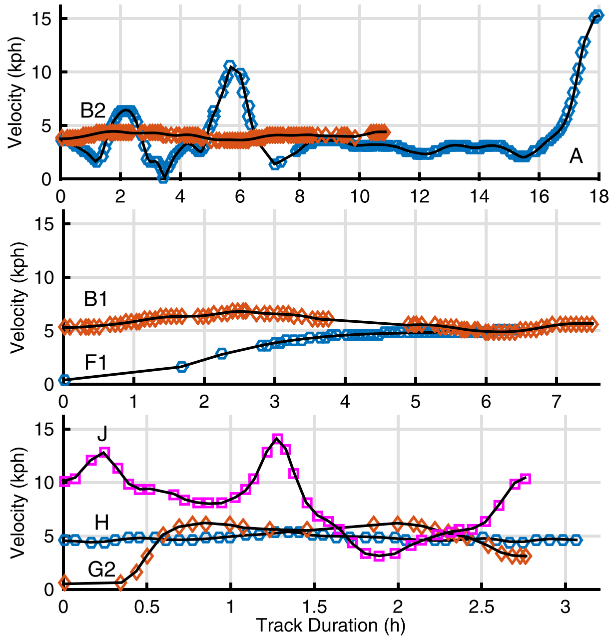

FIG. 4. (Color online) Velocities for 7 of the 17 tracks shown in Fig. 3. Markers indicate emission time of acoustic call by the whale. Tracks are grouped by similar track duration for scaling purposes. The apparent gap in track B1 is due to the whale transiting off-range, and so exact position and speed is unknown during this period.

size to one second bin width reveals the highest peak to be ~270 s.

An analysis of the calling behavior of tracks occurring at the same time does not reveal an exact call and countercall pattern, i.e., a whale does not necessarily respond with a call as soon as a call is heard from a conspecific. However, for all tracks occurring at the same time (B1-B2, F1-F2, G1-G2-G3), there are time periods along the tracks where the ICIs become very synchronous for several hours at a time. For example, in the case of B1 and B2, the ICIs are nearly identical for the first portion of the track before B1 veers off-range. While off-range, the two ICIs drift apart slightly before falling back in synch as the whale returns to the range. The ICIs from B1 and B2 then stay at nearly identical rates until B1 stops calling, at which point the ICI from B2 immediately increases for the remainder of the track (see Fig. 6).

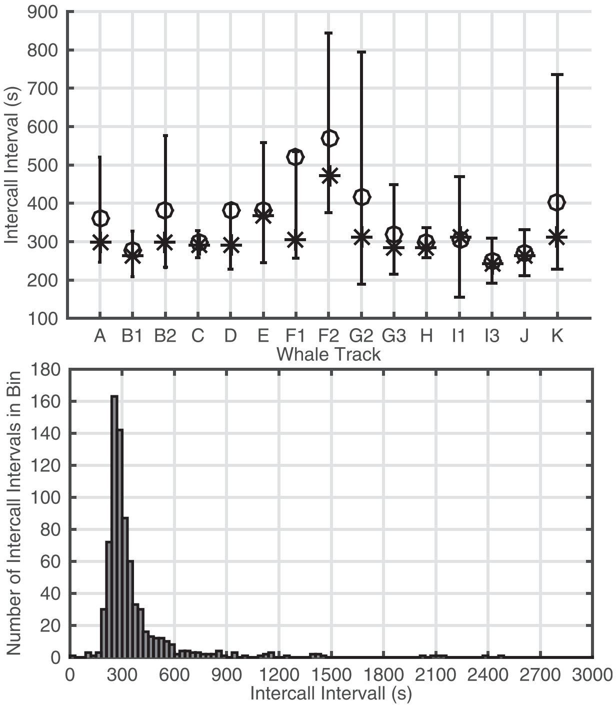

FIG. 5. ICIs for each Bryde's track (upper plot) showing the mean (circle) and median (asterisk) values. Error bars represent the 10th and 90th percentile ICI for each track. The histogram (lower plot) shows the aggregated ICIs for all 746 calls, the tallest bin is between 240 and 270 s, with 163 calls. The mean and median for all aggregated ICIs is 363 s and 290 s, respectively.

IV. DISCUSSION

The 17 acoustically derived tracks presented here represent some of the first continuous Bryde's whale tracks to be developed. Two Bryde's whales were recently tagged using satellite tags in the western North Pacific,[3] providing insight into longer-term movements of this species that had previously only been described using marks made by whalers.[2] These marks could only be "recovered" when the whales were caught, thus, only providing start and end locations over periods ranging from months up to 34 yr,[2] with no intermediary information on distribution or movement. The satellite tag tracks of Murase *et al.*[3] demonstrated unexpected behavior, with both whales moving southward to the subtropics in the summer, rather than remaining in the higher latitude feeding ground as expected. The tracks presented here offer similarly new and interesting results.

Many of the Bryde's whales appeared to be traveling together, remaining in vocal contact as they transited the range separated by several kilometers. In addition, the tracks appear on the range in a clustered nature—with several

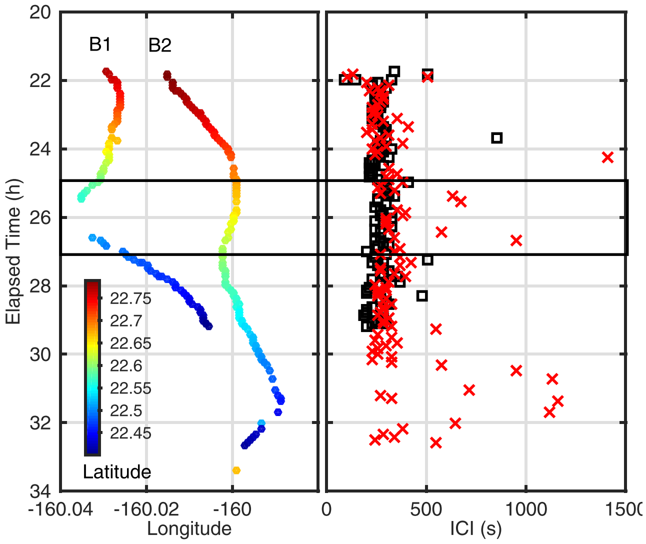

FIG. 6. (Color online) Bryde's tracks B1 and B2 shown as a function of longitude and elapsed time (left), and the corresponding ICI for tracks B1 (square) and B2 (×) as a function of elapsed time (right). Latitude is indicated by the shading of the tracks. Elapsed time is shown in hours since midnight on 9 September 2014. The boxed region indicates the time period where track B1 left the range, during this same time period, the ICI for track B2 becomes less coordinated with B1. The ICI for track B2 also becomes erratic after B1 ceases calling.

whales transiting through the range over the course of a few days, followed by several days of inactivity. In most scenarios, tracks that occurred at the same time were parallel in nature, suggesting the whales may have used vocalizations to maintain spacing. However, there are a few scenarios where whale tracks appeared parallel in nature with this same spacing structure even though one whale may have completely transited through the range before the lagging whale entered the range, such as tracks D and E.

The synchronization of the tracks' ICIs, combined with the synchronization of track speeds as described in Sec. III B, indicates the vocalizations are likely used as a means of maintaining travel cohesion and spacing with conspecifics, suggesting the whales may be traveling in groups. The synchronization of ICIs in concurrent parallel tracks such as those shown for whales B1 and B2 further supports this hypothesis. In contrast, the ICIs described by Oleson *et al.*[11] showed considerable variability by call type and also within a call type. The Be1 and Be3 calls (most similar to the calls recorded at PMRF) had mean ICIs of 75 s and 137 s, respectively, and with ranges of 12–264 s for Be1 and 27–519 s for Be3. Oleson *et al.*[11] also noted that the Be1 call appeared to occur in the presence of other calling whales also producing the Be1 call, and suggested a possible call and countercall behavior.

The acoustically tracked Bryde's whales in Hawaii traveled at mean speeds of 2–11 kph, with an overall mean of 5.9 kph. The satellite of Murase *et al.*[3] tracked whales traveling at mean speeds of 2.9 and 5.5 kph, which they found comparable to travel speeds of other baleen whale species, ranging from 1 to 5.4 kph. The Bryde's whales at PMRF were therefore traveling at generally faster speeds than most other baleen whales, and demonstrated occasional bursts of speed up to 10–15 kph (Fig. 4). It may be that over longer distances and time frames, as would be sampled by a satellite tag, these mean speeds would decrease, and that these snapshots of behavior represent periods of highly directed travel. More acoustic data from PMRF need to be analyzed to look for seasonal behavior and habitat use patterns; the fast travel speeds and parallel tracks between multiple individuals may be a common occurrence at PMRF or may be atypical behavior. Similarly, Track A's meandering track was anomalous when compared with the other tracks, and it is unclear what drives this differing behavior. Additional data should be collected earlier in the summer to study whether this change in track behavior could vary depending on the season.

Most North Pacific Bryde's whale sighting data have come from Japanese whaling data, or research cruises that have been focused on the western half of the North Pacific.[1,2,4,8] However, even in more recent studies that have focused on waters around the Hawaiian archipelago, Bryde's whales have largely only been observed in deeper offshore waters.[6] In 2007, a single Bryde's whale was observed within 70 km of Oahu;[19] this represents one of the first published sightings of a North Pacific Bryde's whale found relatively nearshore and is also one of the easternmost sightings of a whale from this population. National Marine Fisheries vessel surveys were conducted around the Hawaiian archipelago in 2002 and only found Bryde's whales in deep offshore waters. However, this survey was repeated in 2010 in the same months and along the same survey track, and far more whales were observed near the main Hawaiian islands and in nearshore waters. Figure 7 summarizes these sightings in the Hawaiian archipelago, including the locations of the acoustic-based tracks on the PMRF range. The tracks presented in this paper all occurred within 100 km of Kauai and at 160°W are also near the eastern boundary of the western North Pacific Bryde's whale population. This pattern of more Bryde's whale sightings closer to shore and further east in the last decade may be indicative of an overall shift in distribution for North Pacific Bryde's whales, or could simply represent a shift in prey distribution relative to climate forcing. Additional passive acoustic monitoring at PMRF and future visual and passive acoustic surveys may help to shed light on whether these patterns persist in the future.

The vocalization that was utilized to track the suspected Bryde's whales at PMRF most closely resembled that of the ETP Bryde's whale Be3 call[11] and a Bryde's whale recorded off New Zealand in the South Pacific.[13] Whales in the ETP region are considered a separate stock than those in Hawaiian waters. While Bryde's whales in the South Pacific are presumably from a different stock than the western North Pacific and ETP stocks, not enough is known about their behavior at lower latitudes to know whether whales migrate across the equator. However, the similarities in these three calls from different Pacific Ocean regions could suggest that some sharing of vocalizations may be occurring between regions, which may be indicative of more cross-population communication or movement than has been previously described. Conversely, the similarities of the TM1 call recorded off the coast of Brazil[20] to those in the ETP, New Zealand, and Hawaiian waters may suggest the stocks are indeed separate, and universal call characteristics have remained relatively stable despite stock isolation.

The ETP and New Zealand calls have the most similar fundamental frequencies at 25.6 and 22–25 Hz, respectively, and were recorded within a few years of each other.[11,13] The recording from PMRF has a much lower fundamental frequency at 21 Hz, which could indicate a lowering in the fundamental frequency of this call over time. McDonald *et al.*[21]

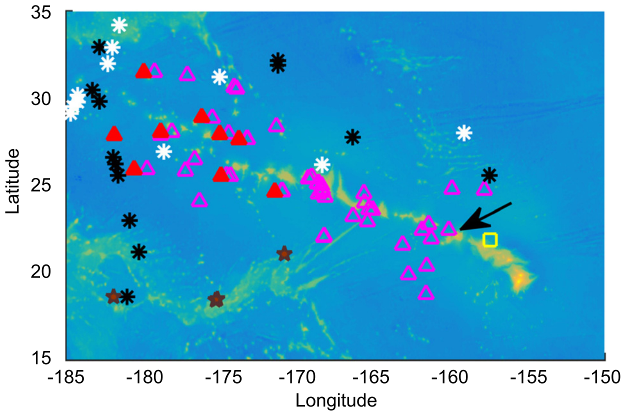

FIG. 7. (Color online) Bryde's visual sightings in the Hawaiian archipelago from surveys published in Refs. 4 (stars), 7 (dark asterisks), 8 (light asterisks), 24 (open triangles), 6 (closed triangles), 19 (squares), and the PMRF acoustic detections (arrow).

found a decrease in tonal frequencies of blue whale vocalizations globally since the 1960s, possibly due to concurrently increasing levels of ambient noise in the ocean[22] or due to post-whaling increases in population sizes. Testing this hypothesis is outside the scope of this paper, but these efforts may lay the groundwork for future studies in that direction. Continued passive acoustic monitoring at PMRF, as well as at other locations throughout the Pacific Ocean (including the ETP and off New Zealand), is necessary to track the stability of these calls over time.

These tracks provide the first evidence of Bryde's whales utilizing the waters of PMRF. However, in order to derive density estimates from these types of tracks, both the fraction of the population that is capable of being vocally active and the fraction of time those whales produce sounds would need to be known. These numbers could be obtained from either acoustic tags or from ship or air-based observations in combination with acoustic recordings. In the meantime, track counting could prove useful for obtaining minimum density estimates at PMRF—the number of transiting tracks reveals the absolute minimum number of whales that are present. This metric could prove to be stable when looking for changes in populations over time.

V. CONCLUSIONS

A new call type attributed to Bryde's whales has been recorded and described in the offshore region of Kauai on the Navy's Pacific Missile Range Facility. The call type is similar to those described for Bryde's whales in other regions, but the spectral characteristics and the ICI are notably different. Long calling bouts in combination with the call's repetitious nature allow for swim kinematics to be calculated for the whales. Of the 17 tracks analyzed, 16 appear to be very directional transit tracks with average speeds varying between 2 and 10.5 kph. The clustered pattern of the tracks suggests the whales are traveling in widely spaced groups and may use vocalizations to maintain group cohesion and spacing. The proportion of calling whales within the population is unknown on the PMRF range, but the vocally active whales produced sounds continuously as they cross the range with most ICIs occurring every 4.5 min. The swim kinematics and calling behaviors outlined in this paper could prove useful for future acoustic density studies. The calls described in this paper likely represent the first acoustic recording of Bryde's whales in the North Pacific, and the tracks are some of the closest inshore and furthest east locations of North Pacific Bryde's whales that have been made.

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