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Steven W. Martin
Brian Matsuyama

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SPAWAR Systems Center Pacific, 53560 Hull St. San Diego, CA 92152

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14. ABSTRACT
Low frequency pulsed signals between 12 and 64 Hz have been detected, localized and tracked automatically using acoustic data recorded at the Pacific Missile Range Facility, Kauai, Hawaii (PMRF). In December 2010 forty-one replacement hydrophones were installed at PMRF with improved low frequency response enabling processing for signals at frequencies under 100 Hz. The automatic processing has provided tracks on the detected pulsed signals which are being attributed to three species of whales: fin, sei and Bryde's whales (Balaenoptera physalus, B. borealis and B. edeni, respectively). Signal types being attributed to fin whales consist of 20 Hz pulses. Down swept signals in this frequency range could be from fin or sei whales (potentially even blue whales). The signals described here as being attributed to Bryde's whales consist of burst type pulses on the order of 2.5 s in duration, with onset frequencies around 33 Hz, with apparent 4 Hz amplitude modulation, and a delayed accompanying 21 Hz tonal component with limited frequency sweep. These pulses are similar to reports which identify the signals as being from visually confirmed Bryde's whales during the calls (Edds et al. 1993 and Oleson et al. 2003) and attributed to Bryde's whales based upon similarities to published calls (McDonald 2006, Kibblewhite et al. 1966, Heimlich et al. 2005). Bryde's whales are the only baleen whales believed to inhabit Hawaiian waters year round. To date, burst type pulses have been confirmed for seven separate encounters of suspected Bryde's whales: one in August 2013, one in August 2014 and five late October 2014. These encounters are providing information on the acoustic behaviors such as swim patterns, speeds and call rates. In six of the seven encounters the whales appear to be traveling with fairly constant headings from 224 to 297 degrees true crossing the range area over distances ranging from 12 to 27 km over time periods of 1.5 to 6 h with estimated swim speeds up to 12 km/h. Two of these encounters on 27 October 2014 overlapped temporally indicating

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two whales traveling on nearly parallel headings separated by approximately 12 km. The longest duration encounter was over 19 h on 25-26 August 2014 and showed an animal exhibiting varied headings and speeds, termed 'irregular speeds and headings' while staying on the range area. The late October 2014 data was from a long term recording over a six day period vice one day recordings being collected twice a month. Five of the seven encounters occurred during the first two days of this 6 day recording illustrating the value of long term recordings for better understanding low density species such as these suspected Bryde's whales in Hawaii.

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Suspected Bryde's whales acoustically detected, localized and tracked using recorded data from the Pacific Missile Range Facility, Hawaii

S. W. Martin[1] and B. Matsuyama[2]

[1]National Marine Mammal Foundation, 2430 Shelter Island Drive Suite 200, San Diego, CA
[2]SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, CA

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SUMMARY

Low frequency pulsed signals between 12 and 64 Hz have been detected, localized and tracked automatically using acoustic data recorded at the Pacific Missile Range Facility, Kauai, Hawaii (PMRF). In December 2010 forty-one replacement hydrophones were installed at PMRF with improved low frequency response enabling processing for signals at frequencies under 100 Hz. The automatic processing has provided tracks on the detected pulsed signals which are being attributed to three species of whales: fin, sei and Bryde's whales (*Balaenoptera physalus, B. borealis and B. edeni,* respectively). Signal types being attributed to fin whales consist of 20 Hz pulses. Down swept signals in this frequency range could be from fin or sei whales (potentially even blue whales). The signals described here as being attributed to Bryde's whales consist of burst type pulses on the order of 2.5 s in duration, with onset frequencies around 33 Hz, with apparent 4 Hz amplitude modulation, and a delayed accompanying 21 Hz tonal component with limited frequency sweep. These pulses are similar to reports which identify the signals as being from visually confirmed Bryde's whales during the calls (Edds et al. 1993 and Oleson et al. 2003) and attributed to Bryde's whales based upon similarities to published calls (McDonald 2006, Kibblewhite et al. 1966, Heimlich et al. 2005). Bryde's whales are the only baleen whales believed to inhabit Hawaiian waters year round. To date, burst type pulses have been confirmed for seven separate encounters of suspected Bryde's whales: one in August 2013, one in August 2014 and five late October 2014. These encounters are providing information on the acoustic behaviors such as swim patterns, speeds and call rates. In six of the seven encounters the whales appear to be traveling with fairly constant headings from 224 to 297 degrees true crossing the range area over distances ranging from 12 to 27 km over time periods of 1.5 to 6 h with estimated swim speeds up to 12 km/h. Two of these encounters on 27 October 2014 overlapped temporally indicating two whales traveling on nearly parallel headings separated by approximately 12 km. The longest duration encounter was over 19 h on 25-26 August 2014 and showed an animal exhibiting varied headings and speeds, termed 'irregular speeds and headings' while staying on the range area. The late October 2014 data was from a long term recording over a six day period vice one day recordings being collected twice a month. Five of the seven encounters occurred during the first two days of this 6 day recording illustrating the value of long term recordings for better understanding low density species such as these suspected Bryde's whales in Hawaii.

INTRODUCTION

The National Marine Fisheries Services estimates the Bryde's whale (*Balaenoptera edeni*) Hawaii stock (Caretta et al. 2013) to have a population size of 798 individuals (CV=0.28). Due to limited prior estimates with higher CV's there is insufficient data currently available to assess any population trends.

Limited information is available on this species; the following is based upon information taken from the NOAA NMFS Protected Species website (NOAA Fisheries Office of protected resources web site). The Balaenoptera genus includes eight extant species: blue (*Balaenoptera musculus*), fin (*B. physalus*), sei (*B. borealis*), minke (*B. acutorostrata*, *B. bonaerensis*), and bryde's (*B. brydei, B. omura and B. edeni*) whales. The Bryde's taxonomy is poorly characterized and the scientific name *B. edeni* is commonly used to refer to the species in the Bryde's whale complex which currently consists of *B. brydei*, *B. edeni*, and *B. omura*. Byde's whales resemble sei whales, with a major distinction being three longitudinal ridges located on the animals' rostrum in front of the blowholes versus the sei's single ridge. Bryde's whales are distributed worldwide in areas of warm temperate, subtropical and tropical waters. They feed upon plankton, crustaceans, and schooling fish (e.g. anchovies, herring, mackerel, pilchards and sardines). Bryde's whales have been sighted individually, in pairs, and with occasional loose aggregations of up to twenty animals around feeding areas. Field biologists often characterize them as having erratic and strange behavior compared to other baleen whales due to their irregular surface intervals and their unexpected heading changes. Bryde's whales are reported to regularly dive for about 5 to 15 min (max 20 min) after 4 to 7 blows at the surface and are capable of reaching depths of up to 300 m. Bryde's whales commonly swim at 2 to 7 km/h.

Early descriptions of Bryde's whale calls (Cummings et al. 1986 and Edds et al. 1993) characterized their signals having frequencies over 90 Hz. Cummings et al. (1986) reported calls from the Gulf of Mexico with frequencies of approximately 124 Hz, with 0.4 s durations, and estimated source levels of 152-174 dB re micro Pascal (uPa). It is interesting to note that the spectrum shown in the paper also shows a secondary peak at approximately 25 Hz which appears less than 5 dB below the level of the 124 Hz peak signal reported, however it is uncertain if this was produced from the whale. Edds et al. (1993) reported on sounds from both on a captive juvenile which stranded off the Gulf Coast of Florida and free-ranging Bryde's whales in the Gulf of California, however the lowest frequencies reported for pulsed sounds was 90 Hz.

More recent descriptions of lower frequency Bryde's whale calls have been reported by Oleson et al. (2003) for calls received in the presence of Bryde's whales sighted in the Eastern Tropical Pacific. One hundred four calls over 21.7 h were utilized to identify six call types (Be1 through Be6). The most abundant type, with 37 calls, was termed Be1 (Figure 1 upper) which had a mean duration of 2.7 s. The Be1 call was a complex two-part signal with an upper frequency component of approximately 37 Hz and a delayed accompanying lower-frequency component of approximately 21 Hz. The average call interval reported was 1.25 min (0.2 to 4.4 min). Oleson et al. (2003) also reported a Be3 type call (N=18) with a mean duration of 1.7 s and a frequency of 25.6 Hz (Figure 1 lower) and a mean call interval of 2.28 min (0.45-8.65 min).

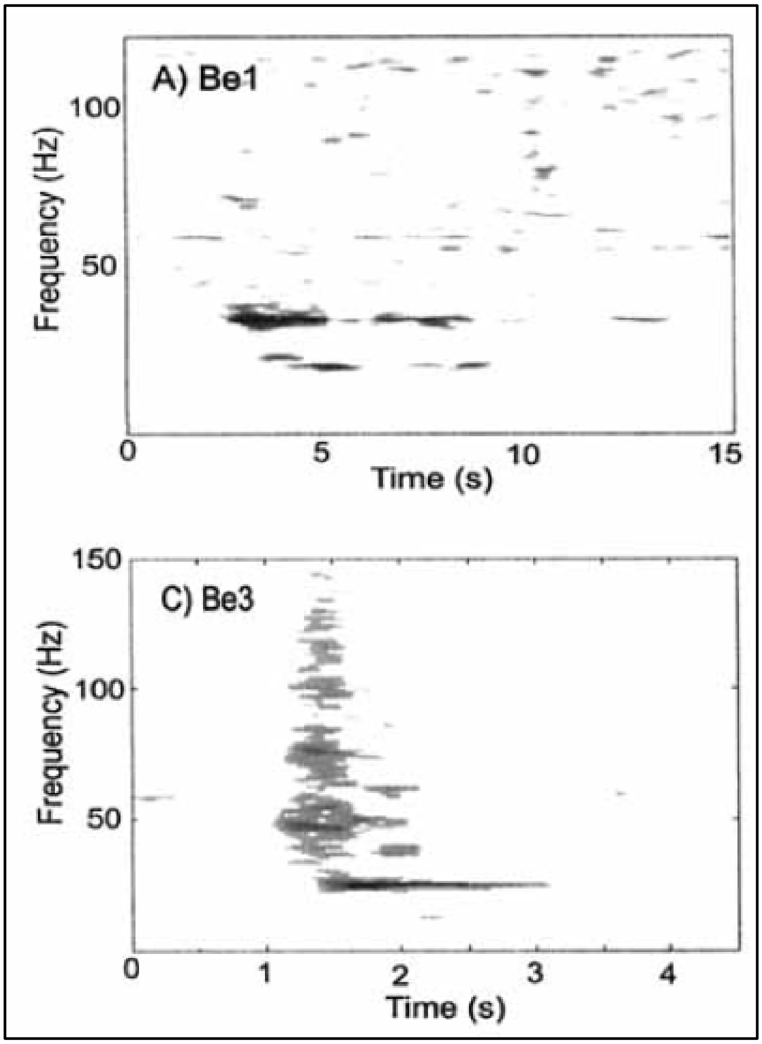

Figure 1 - Spectrogram of Be1 and Be3 Bryde's calls from the Eastern Tropical Pacific from Oleson et al. (2003).

Calls from baleen whales off New Zealand have been reported by McDonald (2006). One of the two call types identified as being from Bryde's whales consisted of an impulsive broadband sound at the start of each call and included a down swept frequency component from 25 to 22 Hz (Figure 2). The calls were reported to have irregular repeat intervals and to be similar to Oleson et al.'s (2003) Be3 calls as well as down swept calls reported for New Zealand (Figure 3) by Kibblewhite et al. (1966).

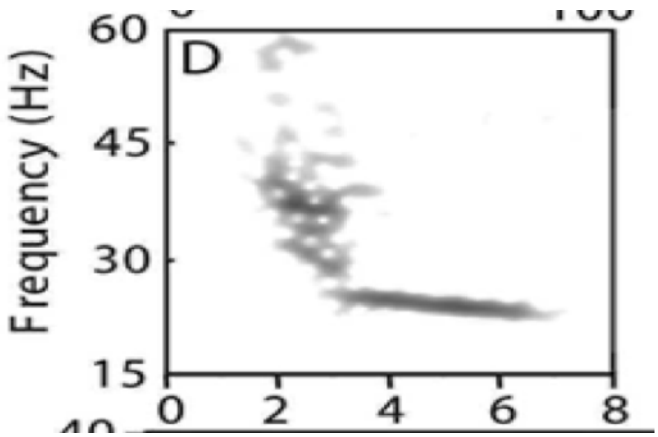

Figure 2 – Spectrogram of a broadband impulsive call identified as being from a Bryde's whale in New Zealand [extracted from McDonald (2006), horizontal axis is in seconds].

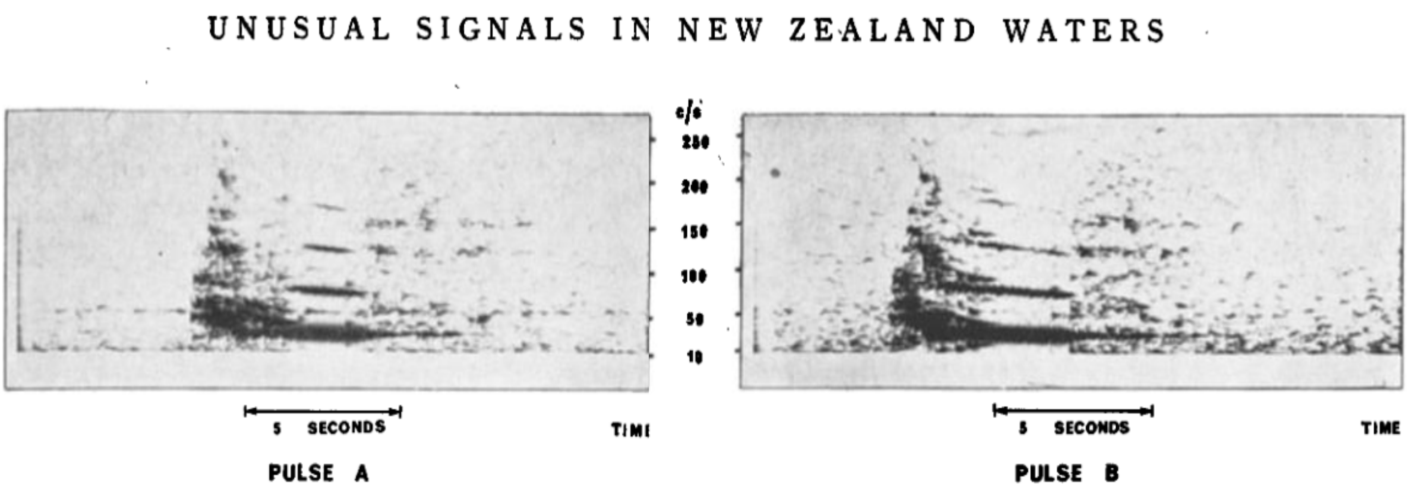

Figure 3 – Spectrograms for two pulsed calls reported by Kibblewhite et al. (1966) in New Zealand waters.

The pulsed calls reported by Kibblewhite et al. for New Zealand were identified as '5 second' pulses with the onsets described as having higher frequency components then continuing with a single frequency component. The calls were attributed to being biologic in origin due to the motion of the sources of up to 6 knots (11.1 km/h) with typical speeds of 2 to 3 knots (3.7 – 5.5 km/h). Some tracks were reported as 'a rather aimless movement', while others 'implied a deliberate passage across the area'.

Acoustic only observations of suspected Bryde's whale calls have also been reported by Heimlich et al. (2005) from recordings at several different sites in the Eastern Tropical Pacific. The calls were short duration (means under 3 s), low-frequency (< 80 Hz), and characterized as possessing predominant and secondary tonal components. The sounds were grouped into five categories: harmonic tonal, swept and non-swept alternating tonal, and low and high burst-tonal. Over 1100 sounds were characterized and compared to those reported by Oleson et al. (2003).

The majority of call types were found to be similar to the Be1 type in Oleson et al. 2003), however they included both swept and non-swept alternating tonal. The calls referred to as low burst tonal were reported to have onset burst frequency mean of 29.8 Hz (24.1 -36.1 Hz) and a delayed lower frequency component of 18.5 Hz (16.8 – 26.7 Hz). These signals were also reported to have non-harmonically related tones present and inter-call-intervals of 5.8 min (SD 4.2, 1.7-33.8 min). Call intervals were also shown to have large variations.

METHODS

The PMRF underwater hydrophone range contains hundreds of hydrophones for supporting US Navy undersea warfare training. The majority of these hydrophones are high-pass filtered at approximately 10 kHz as they were designed for tracking high frequency underwater pingers. Prior to December 2010 none of the PMRF hydrophones had adequate response to process for signals under 100 Hz in frequency. In December of 2010 forty-one Barking Sands Underwater Range Expansion replacement hydrophones (BSURE-R) were installed. These hydrophones have improved low frequency response with a high pass filter specified as -3 dB at 50 Hz with roll-off characteristics that enable detection of signals down to approximately 12 Hz. The BSURE-R hydrophones are located in waters approximately 18 to 75 km north/north-west of the Napali coast of Kauai, Hawaii ranging in depth from approximately 1.5 km to nearly 5km (31 of the phones are in water depths of over 4 km). Figure 7 provides a plan view of the area with approximate locations of the BSURE-R 41 hydrophones shown with their hydrophone numbers. These BSURE-R hydrophones enable low frequency call detection for species such as fin, sei and Bryde's whales.

Acoustic recordings from subsets of PMRF hydrophones have been obtained over the past decade for various purposes. In January of 2011 eighteen of the forty one BSURE-R hydrophones replaced older BSURE hydrophones in the ongoing recordings of a subset of 31 PMRF hydrophones. The recordings were being made on a two days a month sample basis as well as multiple days before, during and after US Navy training events. In August of 2012 the recordings were expanded to 62 hydrophones (including the remaining 32 BSURE-R hydrophones) to support localization of whale calls. In August of 2014 recordings also include long duration recordings to sample near continuously when feasible operationally. These long duration recordings provide all 41 of the new BSURE-R hydrophones sampled at 6 kHz (vice standard 96 kHz) with the emphasis on localizing whales with vocalizations under the 3 kHz Nyquist rate.

Recorded acoustic data is processed with automatic detection algorithms for monitoring various species of cetaceans [i.e. beaked whale (*Ziphiidae family*) foraging clicks, sperm whale (*Physter microcephalus*) clicks, humpback whale (*Megaptera novaeangliae*) songs, minke whale (*Balaenoptera acutorostrata*) boings and low frequency (< 65 Hz) calls from fin, sei and Bryde's whales]. Low frequency automatic detections are not tuned for specific species, rather the process detects pulsed (>0.37 s in duration) signals in the frequency band. The low frequency automatic detection algorithm works simultaneously with other marine mammal species auto-detection algorithms at the 96 kHz sample. Individual frequency bins are normalized using standard alpha-beta filtering techniques. Detection criteria for the low frequency signals are: frequencies in the processing band (under 65 Hz); have a start frequency equal to or greater than the end frequency; have a duration of at least 0.37 s; and have a nominal 12 dB signal to noise ratio.

Automatic detections are processed with model-based localization algorithms to generate localizations (Martin et al. 2015). Localizations are then processed with a custom Matlab routine that associate the localizations to create tracks for individual whales. The tracking routine utilizes documented inter-call-intervals and swim dynamics for each species for setting thresholds of various tracking parameters. The tracking routine provides the tracked individuals' call-intervals and speed between calls. A variety of parameter settings are required for the tracking routine (e.g. number of elements required to establish a track, number of hydrophones required for each element of a track, maximum delay between calls before a new track is established). Typical parameter settings for tracking Bryde's whales are at least 12 localizations (elements) to create a track, at least 8 hydrophones utilized in generating each localization solution, and a maximum time between calls of 30 min.

Once tracks for low frequency calls are obtained, individual calls are then extracted from the hydrophone acoustic data to investigate the details of the call types to identify the species producing the calls. Call types typically detected include '20 Hz pulses' from fin whales as well as low frequency down sweeps attributed to fin and sei whales. The down sweeps are difficult to attribute to a single species based upon the description by Rankin and Barlow (2007) of down sweeps attributed to sei whales sighted in Hawaiian waters being very similar to those reported for fin whales.

In August of 2013 an unexpected low frequency track was detected (fin and sei are typically only present in Hawaiian waters seasonally approximately November to April). Upon subsequent investigation of the call types being tracked, a burst type call was identified with similar characteristics as those described for Bryde's whales (Kibblewhite 1966; Oleson 2003; McDonald 2006; Heimlich 2005). Given that Bryde's whales' range includes this area year round and the similarity of the signals to the type termed Be1 in Oleson et al. (2003) for Bryde's whales, these localizations are believed to be from a Bryde's whale. Six additional encounters totaling over 400 localized calls have been detected in recorded data to date (table 1).

Acoustic Encounters of Bryde's whale at PMRF

Table 1 provides dates of the seven encounters to date where signals have been verified as suspected Bryde's whale burst signals (vice 20 Hz pulses from fin and the down swept signals from fin and sei). Also included in the table are the encounter durations, distances traveled, estimated average speeds, number of calls automatically localized and tracked, and the call intervals of the auto-detected and localized calls. The 6 August 2013 encounter is the only encounter which has been manually verified (to date) for actual number of calls being tracked which impacts other parameters in table 1. The 6 August 2013 data set was also re-processed at a 6 dB detection threshold above background (vice 12 dB default value) for automatically detecting more of the calls emitted, although with more duplicate calls generated. This manual verification process could be applied to the other encounters; however it requires additional analysis which has not been performed to date. The two encounters on October 27, 2014 overlapped in time, showing two individuals present and traveling on nearly the same headings and separated by approximately 12km.

TABLE 1. Automatic detection, localization, and tracking results for Bryde's whales.

Year/date	GMT	Encounter duration (h)	Course (deg T)	Distance traveled (km)	Estimated speed (km/h)	# calls tracked	Call interval (sec) mean (SD), min-max
2014 Oct 29	17:17-19:07	1.83	260	12.7	6.9	19	417.6 (350.6), 126-1351
2014 Oct 29	3:30-6:42	3.2	230.7	23.5	7.3	42	274.9 (61.9), 181-480.7
2014 Oct 28	4:52-11:01	6.15	224.5	27	4.4	82	351.4 (177.5), 209-1282
2014 Oct 27 # 2	22:39-01:10	2.52	241.2	24	9.5	30	338.8 (170.5), 175-816
2014 Oct 27 # 1	21:50-23:55	2.08	236.6	14.2	6.8	26	366.3 (242), 195-2155
2014 Aug 25	21:52-16:42	19	Varied	~ 90	3.2– 20	188	366 (241), 195-2159
*2013 Aug 6	20:54-23:35	2.68	297	34.5	12.2	32	198.8 (82.7), 21-358

* This data set was unique in that detailed manual analysis was involved, whereas all other entries are based upon automatic track information only.

Encounter 6 August 2013 Details

A recording was made for the period of time from 6 August 2013 16:29 GMT to 7 August 2013 00:18 GMT. This is the first observation of the signals being attributed (Martin and Matsuyama 2014) to Bryde's whales which was automatically detected, localized and tracked from 20:54 to 23:35 GMT over a 2.68 h period moving across the range, east to west on a heading of 297 deg T at an average speed of approximately 12.2 km/h over 34.5 km (Figure 4). This fits with the 'deliberate passage across the area' description provided by Kibblewhite et al. (1966) and could also be described simply as ‘traveling’. This encounter data is unique in that it was re-processed at a lower detection threshold of 6 dB compared to the standard detection threshold of 12 dB utilized for all other encounters presented herein. The lower threshold allowed localization of calls farther outside of the hydrophone array albeit at less accuracy and precision, however more of the localizations were actually duplicates. The duplicate localizations typically resulted from localizing the same call using a different set of hydrophones. Figure 4 shows over 40 localizations while detailed manual analysis of this entire encounter showed that only 32 were unique localizations over this time period. The tracking routine also has a capability to automatically reject duplicate track elements by establishing minimum call intervals. The manually corrected localization/track data for this encounter had a mean call interval of 198.8 s (SD 82.7 s, range from 21 to 358 s). Water depth in the area is nominally 4.5 km.

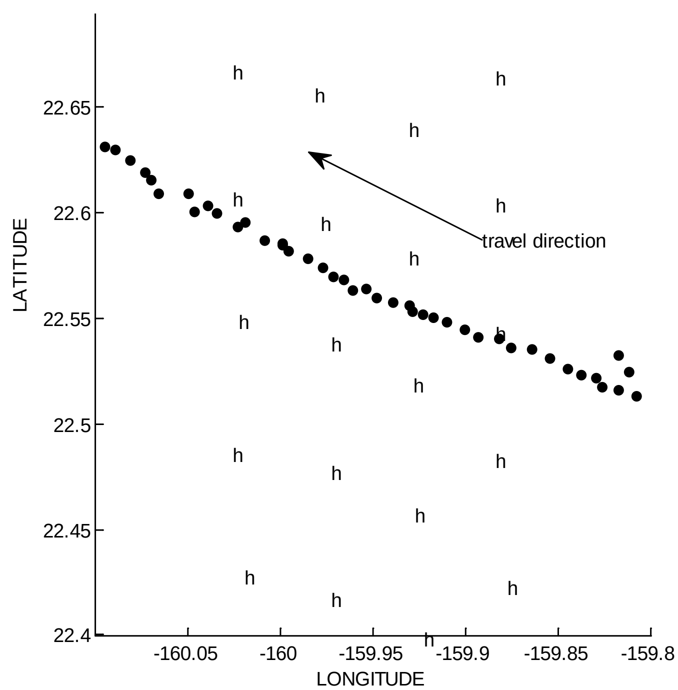

Figure 4 – Encounter track for 6 August 2013 processed at a 6 dB threshold showing a Bryde’s whale traveling on a fairly constant heading of 297 deg T across the PMRF offshore range. The ‘h’ symbols on the figure correspond to the approximate hydrophone positions.

Figure 5 provides a screen capture of adobe audition generated spectral data for the call received at approximately 21:30 on 6 August 2013 on the hydrophone located at approximately 22.55 deg latitude and -159.87 deg longitude. At this time the animal was nearly directly overhead (in x-y only) of the hydrophone in approximately 4.5 km water depth. The data had been down sampled to 6 kHz from the recorded 96 kHz sample rate. The upper plot is a spectrogram from DC to 140 Hz (vertical axis) over a 15 s time window (horizontal axis) using 4k FFTs with 50 % overlap and hanning windows. The lower plot shows the spectrum of the call centered at approximately 2:08 with the vertical axis showing signal level from 0 to -96 dB relative to full scale and the horizontal axis showing frequency in Hz on a log scale from DC to 140 Hz (generated using a 16 k FFT and a blackman-harris window).

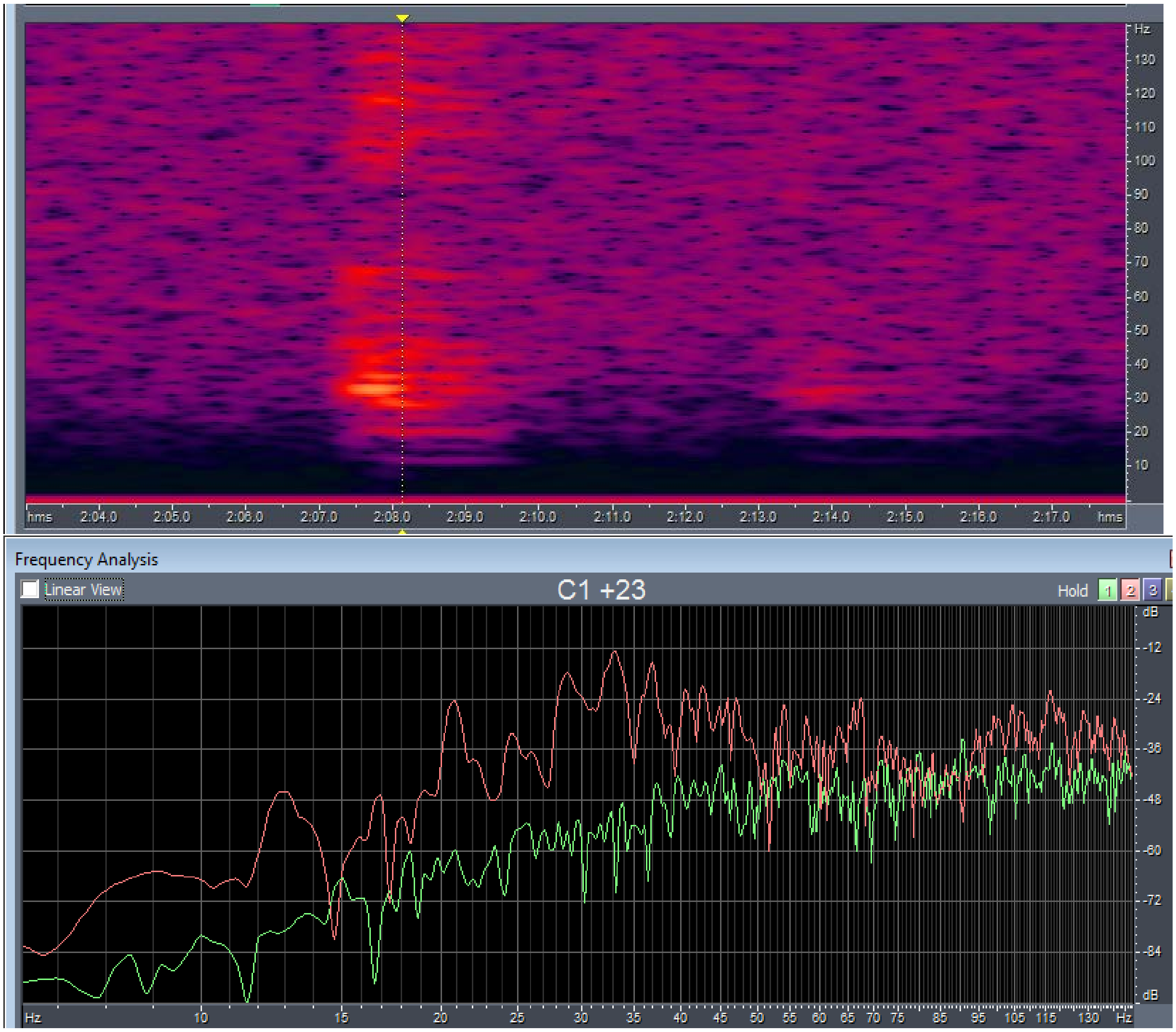

Figure 5 – Spectrogram (top) and spectra (lower) for a low frequency burst call attributed to a Bryde's whale close to the latitude and longitude of the bottom mounted hydrophone. The spectrogram shows the direct path arrival near 2:07.2 and a bottom-surface multipath arrival 5.8 s later at 2:13. The spectrum in the lower plot shows the ambient noise for data centered at 2:04 (green line) and the direct path arrival's spectrum for data centered at 2:08 (red line).

The spectrogram in the upper plot of Figure 5 shows the complex nature of the burst pulses' direct arrival at 2:07.2 on the time axis with duration of 2.3 s. The strongest component as observed on the hydrophone mounted near the seafloor is around 33 Hz with other components both higher in frequency (grouped in various bands to over 140 Hz) and lower in frequency components delayed from the onset of the call. A bottom-surface multipath arrival delayed approximately 5.8 s from the direct path is evident in the spectrogram at 2:13 on the time axis which provides confirmation that the animal generating this signal is located nearby (i.e. the multipath arrival is delayed by a path of approximately twice the water depth).

The spectrum in the lower plot of Figure 5 shows a sample of the noise background (centered at 2:04 around 3 seconds before the call arrives) as the green line. Decreasing amplitudes with decreasing frequency are observed believed to be primarily due to the 50 Hz high-pass filter. The spectrum for data centered on the direct path arrival signal at approximately 2:08 is shown (red line) represents spectral data for the call which is similar to other calls detected, localized and tracked for all encounters reported in this report. As received by the hydrophone located near the seafloor, the signal's peak frequency is 33 Hz and 12 dB down from full scale with nearby frequency peaks at 29 and 37 Hz characteristic of a 4 Hz amplitude modulation (AM) rate. Note that additional peaks at 21, 17, and 13 Hz also appear to have the 4 Hz separation characteristic. The component at 21 Hz is 24 dB down from full scale, but when considering the high-pass filtering of the data this component could potentially be near the same level as the 33 Hz component. The 13 Hz component is visible but at a level of 45 dB below full scale and 21 dB below the level of the 21 Hz component.

Encounter 25 August 2014 Details

Figure 6 presents the automated generated track on 25 August 2014 attributed to a Bryde's whale, inter-call-intervals (ICIs), and the estimated speed between tracked localizations. The left plot of Figure 6 is a latitude – longitude plot showing the approximate location of the BSURE-R hydrophones (h symbols) and a track for a Bryde's whale (black dots) over a 19 h period The animal's track exhibited 'a rather aimless movement' as described by Kibblewhite et al. (1966), a more descriptive term for this behavior could be 'irregular movement' with varied speeds and headings resulting in the animal staying on the range area for a relatively long time period. The animal exhibited rapid changes in headings, including a circular maneuver, and large speed variations from 0.9 to 5.5 m/s (approximately 3 to 20 km/h). This behavior is contrasted with the animal 'traveling' across the range on 6 August 2013. The upper right plot in Figure 6 shows automatically generated ICIs plotted against the localization number. The middle right plot shows the ICI's (corrected to remove duplicate call localizations) plotted against time. The lower right plot provides the estimated speed in m/s between track points. The auto-corrected estimated ICI for this encounter has a mean of 366 s (SD 241 s). The acoustic signal details for these calls indicate a burst signal type very similar to that shown in Figure 5, with details of the calls shown in table 1.

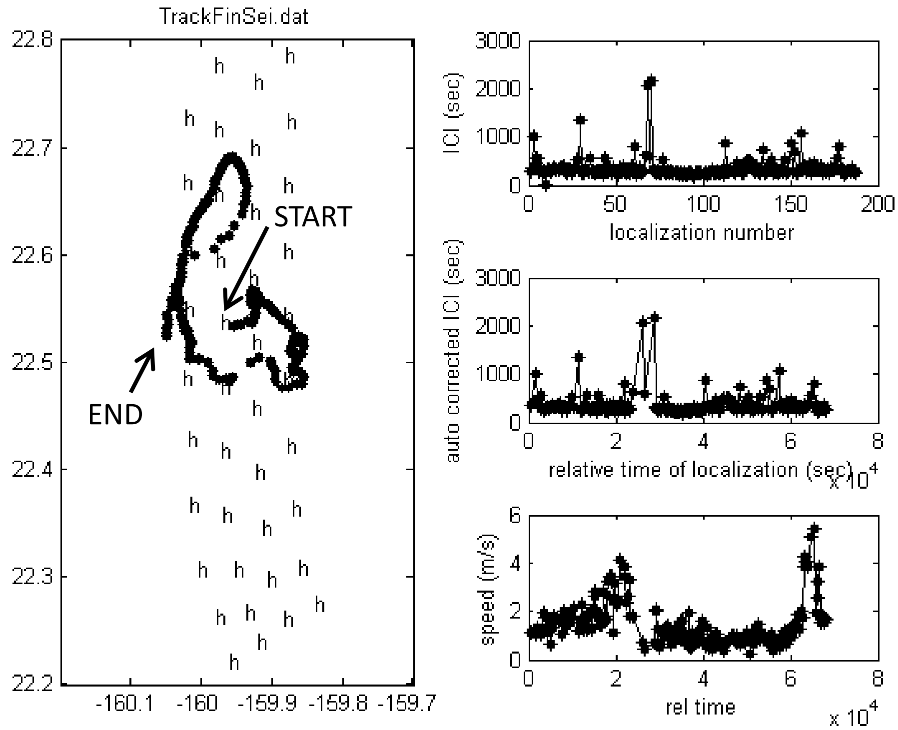

Figure 6 – Encounter for 19 h on 25-26 August 2014 showing: Left- latitude-longitude plot of the Bryde's whale track with the h symbols indicating the approximate hydrophone locations. Upper right – inter-call-intervals (ICI) plotted against the tracked localization numbers showing at least one duplicate localization (ICI value near zero); Middle right – corrected ICI's plotted against time (corrected to automatically remove duplicate localizations); Lower right – estimated speed in m/s between corrected track elements plotted against time.

Five encounters 27-29 October 2014 Details

A long term recording was started at 18:02 GMT on 27 October 2014 and ran near continuously for over 6 days, ending at 16:59 GMT on 2 November 2014 (there was an 11 min gap between 23:08 and 23:19 on 27 October). A total of 9209 low frequency detections were made at the 12 dB threshold setting and 2026 of these utilized to generate 225 localizations for an average of nine hydrophones in each localization solution. During this six day recording interval, five encounters with Bryde's whales occurred during the first two days while none occurred over the last four days. This demonstrates the importance of long term recording when dealing with low density species such as Bryde's. Short term recording strategies could potentially miss many encounters. Figure 7 provides the automatically generated tracks for all five Bryde's whales over the two day period 27-29 October 2014.

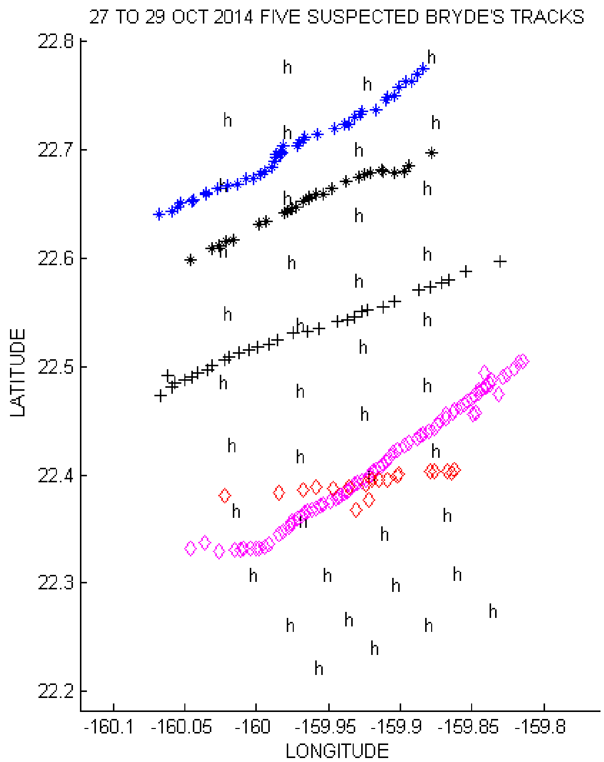

Figure 7 provides the automatically generated tracks for five Bryde's whales over the two day period 27-29 October 2014. Two tracks (black asterisk and plus symbols) are for animals which overlapped in time (the 27 October encounters). The 28 October animal's track is indicated by magenta diamond symbols to the south and the 29 October animal's tracks correspond to the red diamond and blue asterisk symbols (tracks to the south and north respectively). These animals are all exhibiting traveling type behavior headed in the same general direction (headings vary from 224 to 297 deg T) with speeds ranging from 4.4 to 9.5 km/h.

Two of these encounters overlap by 71 min as indicated in Table 1 (27 October 2014 #1 and # 2 encounters). Both animals were traveling on nearly the same headings with slightly converging paths (separations approximately 13.5 km initially and ending at 10.5 km). Figure 8 is a screen capture of the graphical user interface (GUI) for a two h period beginning 27 October at 22:30 which shows the paths of the two Bryde's whales over this period. The GUI provides the analyst situational awareness and allows them to rapidly temporally review PAM results for multiple species, as well as overlaying other auxiliary data (e.g. ship tracks, satellite tagged animal locations, visual sighting locations).

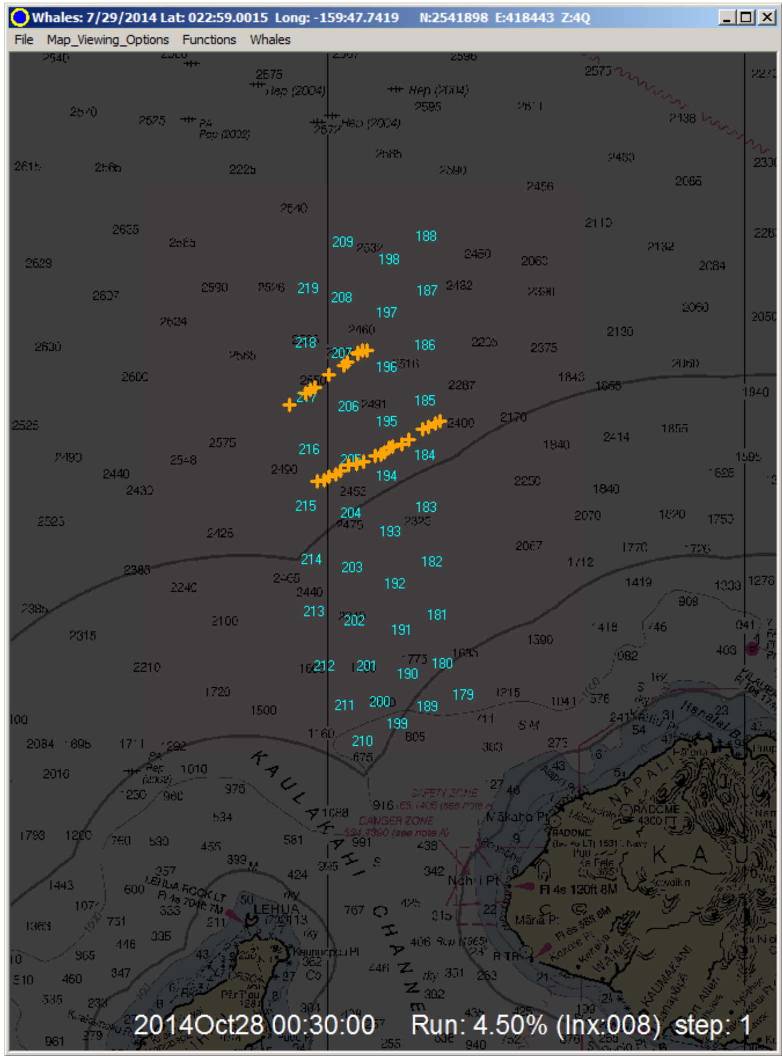

Figure 8 – Graphical user interface screen capture showing study area north-west of Kauai, Hawaii overlaid with approximate hydrophone locations designated with numbers from 179 to 219. Automatic localizations for two suspected Bryde's whales (orange plus symbols) shown for a 2 h period ending 28 October 2014 00:30 GMT on similar headings with slightly converging paths.

At 23:58 on 27 October 2014 the northern animal is approximately 700 m horizontally away from the bottom mounted hydrophone number 217 (upper left in Figure 8). The predicted multipath delay between the direct arrival and the bottom-surface (b-s) multipath should be approximately 6 s assuming the animal is near the surface in 4.5 km of water and a nominal speed of sound of 1.5 km/s (path length difference approximately twice the water depth). Similarly for the southern animal, being approximately 11 km distant from hydrophone number 217 at this time the predicted multipath delay will be on the order of 3 s. The actual delays measured from spectrograms during the manual validation of call types showed values of 6.15 s and 3.25 s respectively giving a quick confidence check on the localization process results.

Verification of call types

Recorded acoustic data was manually examined for a close approach to a hydrophone's x-y location for each encounter to confirm the calls burst nature which is attributed to Bryde's whales. Ten-minutes of hydrophone data was utilized to verify the burst nature of the calls and document: the date and time; hydrophone number; measures of the distances and headings from the whale positions to the hydrophones; measured multipath delays of the bottom-surface multipath from the direct path arrival; details for how many calls from the tracked animal were present in the ten-minute files; and measured signal characteristics of the burst pulses (Table 2). Signal characteristics include the frequency of apparent major energy, estimated amplitude modulation (AM) rate and the frequency of the lower frequency delayed component (nominally 21 Hz).

Table 2 – Signal parameters verified from close approaches to hydrophones for each encounter

Year date	GMT	phone #	Horizontal distance to phone (m)	Bearing to phone (deg T)	Multipath delay (s)	Times of calls in 10 min file (s) Signal frequency characteristics
2014 Oct 29	18:25	192	400	137	5.9	107/233/345/510 33 Hz, 3.7 Hz AM, 20.5 Hz lf
2014 Oct 29	06:06	218	82	133	6.4	323/554 33 Hz, 4 Hz AM, 21 Hz lf weaker calls not localized
2014 Oct 28	08:17	192	71	337	6.0	142/452 33.4 Hz, ~3.4 Hz AM, 21.5Hz lf weak ~20 Hz calls
2014 Oct 27(2)	23:58	205	1704	273	5.6	67/547 ~34 Hz, ~4 Hz AM, ~21 Hz lf weak ~ 20 Hz calls
2014 Oct 27(1)	23:58	217	706	313	6.3	63/156/195/294/396/415/505 34.5 Hz, ~5 Hz AM,21 Hz lf
2014 Aug 26	3:02	183	657	196	5.8	281/563 33 Hz, ~4 Hz AM,~22 Hz lf sweep
2013 Aug 6	21:30	184	164	84	5.9	127/315/348/553 ~33 Hz,~3.7 Hz AM, ~21.3 Hz lf

All of the encounters were confirmed to have signals similar in nature (e.g. burst pulses with similar characteristics as indicated in Table 2 and shown in Figure 5). The multipath delays measured are all consistent with animals estimated distances from the hydrophones when considering each hydrophones actual depth and assumption that the whale's depth is near the surface. The variable nature of the inter-call-intervals is evident in the last column of table 2 showing from 2 to 7 calls received from the tracked individuals in the ten-minute data file.

The August 2013 and August 2014 encounters had no other apparent low frequency signals present in the files which were investigated manually. However, the data from the end of October 2014 had very weak low frequency down sweeps suspected to be from fin or sei whales, some very low level 20 Hz pulses (suspected from distant fin whales) and some low level burst calls which were not localized (suspected from other Bryde's whales located well outside the hydrophone array).

DISCUSSION

Comparison of PMRF low frequency burst type calls to reported Bryde's whale calls

The calls from PMRF can be described as complex single pulse burst sounds with dominant observed energy of approximately 33 Hz with a delayed ~ 21 Hz low frequency tonal component. One must keep in mind that the electronics system response for these PMRF hydrophones includes a 50 Hz high pass filter which artificially attenuates signals as they decrease in frequency under 50 Hz. Due to the electronic filter influence the ~ 21 Hz low frequency components of these signals could potentially be comparable to the levels of the 33 Hz broadband onset component.

The PMRF burst type signals are similar to the most abundant Bryde's call type reported (Be1 with N=37) by Oleson et al. (2003) which were recorded in the presence of Bryde's whales in the Eastern Tropical Pacific. These calls were described as a complex two-part, frequency modulated call which begins with an upper-frequency component at approximately 37 Hz. While the upper tone continues, a lower frequency down swept tone begins (23 Hz with ~ 4 Hz of sweep). The call durations averaged 2.7 s. This is similar to the PMRF pulsed signals which start at ~33 Hz with a delayed component at ~21 Hz and durations around 2.4 s although limited sweep in the 21 Hz component has been observed. This PMRF data for seven suspected Bryde's whale encounters captures at least 400 separate calls with representation from nominally 8 different hydrophones for each call which provides a rich data set for further characterization of the calls. Visual verification for the species producing these calls at PMRF would be beneficial but will take time to obtain (aerial observers represent a good approach for rapidly traveling the large distances to areas where calls can be localized in near real-time for verification).

The signals from PMRF were observed to have low frequency (~ 4 Hz) AM like components in the spectrum around the 33 Hz component. However, AM rates (or pulse repetition rates) this low in frequency had not been documented for Bryde's whales. These low frequency AM rates are more easily identifiable in spectrums of the calls (vice spectrograms or time series). It would be instructive to see if other regions Bryde's calls exhibit similar low frequency AM structure and if so at what frequency.

The spectrogram presented for the Be3 signal in Oleson et al. (2003) was observed to be similar in shape to those being observed for the PMRF burst signals, however the frequencies are different from those reported (Oleson et al. report the Be3 having a 25.6 Hz component with some of the calls showing harmonics). This compared to the PMRF signals' onset frequencies around 33 Hz with delayed component at 21 Hz. The spectrogram presented by McDonald (2006) attributed to Bryde's whales is described as having an impulsive broadband sound at the start of each call with a downward sweep from 25 to 22 Hz (Figure 2). The onset component at around 37 Hz shows more burst characteristics than the signal from Oleson et al. (2003) in Figure 1. McDonald also reported irregular repeat intervals for this type of call.

The case for PMRF calls being from Bryde's whales

Fin and potentially sei whales are observed seasonally at PMRF between approximately October and April. Fin whales are widely reported to generate 20 Hz pulses which are also observed in PMRF data and attributed to fin whales. Down sweep calls are observed seasonally at PMRF with start frequencies up to 64 Hz (our current processing band limit) and end frequencies below 20 Hz. Rankin and Barlow (2007) reported on sei calls in Hawaii from November 2002 where one call type swept from 100 Hz to 44 Hz with durations of 1.0 s and a second call type swept from 39 Hz to 21 Hz over 1.3 s. These sounds reported by Rankin and Barlow (2007) are similar to sounds attributed to fin whales in Hawaii. Thus, with low frequency down sweeps it is uncertain if they should be attributed to fin or sei whales. Tracks for low frequency calls in August at PMRF have, to date, consisted solely of these burst type calls which are quite different from 20 Hz pulses and down sweeps reported (and also being observed in PMRF data) for fin and sei whales. Call intervals being observed for these burst type calls are of similar ranges and irregularity as reported in literature for Bryde's whales. The 'traveling' and 'irregular movement' behaviors observed in August fit with reported information for Bryde's whales. The irregular surfacing interval reported may be related to the irregular call intervals. These facts coupled with the call characteristics being similar to reported calls for Bryde's whales suggest these calls and tracks are from Bryde's whales and we are cautiously reporting them as Bryde's whale calls and tracks.

Localizing and tracking

Localizing and tracking whale vocalizations at PMRF allows insights into the acoustic behavior of the whales. Swim speeds and directions of individuals provide information related to the behavioral state of the animals which is not readily available from single sensor data collections. The majority of these Bryde's whales encounters estimated speeds fit with the commonly reported speeds for Bryde's of 2 to 7 km/hr. Two of these encounters show swim speeds estimated as 9.5 and 12.2 km/h for over two h in each case suggesting higher common swim speeds at least for on the order of 2 h. The August 2014 'irregular movement' animal had a rapid speed estimated as high as 5.5 m/s (near 20 km/h) which, while high, are reasonable for the species burst speeds. To date, six tracks of animals traveling late summer and early fall have been on a south-southwest or westerly course; it will be interesting to see if these Bryde's tracks have temporal relationships with potential suggestions of large scale movements of the species in the area. In addition, the 5 animals detected in the two day period (27-29 October 2014) could indicate loose aggregations of animals traveling together. The one period in which two Bryde's were tracked simultaneously showed nearly parallel headings separated by approximately 12km. These details are only available when utilizing methods which allow localization of the animals.

Localization enables estimation of source levels by back propagating calls to estimated whale position when calibrated hydrophone information is available. Generic calibration is available for the PMRF BSURE-R hydrophones with a reported response down to 50 Hz; however, calibration data is not available under approximately 1 kHz. Thus, assumptions must be made re the response at 50 Hz and the roll-off characteristics to estimate source levels at these frequencies. The first encounter on 5 August 2013 was analyzed for an estimated source level using a 9 dB attenuation of the 33 Hz component of the call attributed to the high-pass filter. Generic hydrophone calibration utilized for the 5 August 2013 encounter coupled with the estimated 9 dB loss from the filter, resulted in an estimated source level of 167 dB re 1uPa (SD 6 dB). This is similar to the few reports with Bryde's calls source levels, although the reported source levels were for higher frequency call types (i.e. 124 Hz in Edds et al. 1993).

Long term recordings at PMRF

The use of long term recordings of PMRF acoustic data is enabling better understanding of baleen whale species utilization of the range area. Previous sample recordings (typically one day done twice a month) between January 2011 and August 2014 have to date only revealed two suspected Bryde's whale encounters. Long term recordings of 48 hydrophones at a sample rate of 6 kHz allows nearly five weeks of data to fit onto a single 2TB hard disk drive compared to 45 h of data for 62 hydrophones at the native 96 kHz sample rate. While the reduced sample rate precludes analysis of most odontocete's sounds emitted (e.g. whistles and echolocation) it will improve knowledge for the baleen whales as when animals are present and vocal they can be localized.

The six day long term recording which began on 27 October 2014 revealed five suspected Bryde's whales transiting the range in the first two days with no subsequent activity detected in the remaining 4 days of data. This more than doubled the total encounters processed to date, although more sample data is still being analyzed. The Bryde's whale estimated population for the Hawaiian stock is in the area of 500 to 700 individuals indicating a low density species. Temporally sampling data for low density species likely misses a majority of the animals. Without the 27 October 2014 long term recording the five Bryde's encounters would not have been observed. Given these long term recordings were first started late August 2014, their value is already being shown after obtaining and beginning analysis for the first three months of available recordings (late August to mid November 2014).

CONCLUSIONS

The calls reported here were similar to reported calls for Bryde's in other regions and it is reasonable to assume the calls are produced by Bryde's whales. This analysis of PMRF hydrophone data attributed to Bryde's whales has, to date, revealed 7 acoustic encounters of over 37 h duration showing them using the PMRF underwater acoustic range area for 'traveling' and 'irregular movement' behaviors. These encounters are providing new information not only for their usage of the PMRF range but for Bryde's in general (e.g. over 400 calls tracked, estimated swim speeds when traveling from 4.4 to 12.2 km/h, amplitude modulation components of the calls indicating pulse repetition rates likely related to the source generation mechanism). The range of estimated swim speeds may indicate different behaviors of the animals while traveling (i.e. potentially a 'fast travel' behavior for the animal with average speed of 12.2 km/h).

The utility of long term recordings at PMRF, which began late August 2014, has already provided value in enabling encountering the five suspected Bryde's whales late October 2014. Five animal tracks over a two day period followed by no tracks for the following 4 days reflects the low density of the species and need for more continuous type monitoring to understand how often they frequent the area.

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