Baird's beaked whale echolocation signals

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(Received 27 November 2012; revised 2 April 2013; accepted 23 April 2013)

Echolocation signals from Baird's beaked whales were recorded during visual and acoustic shipboard surveys of cetaceans in the California Current ecosystem and with autonomous, long-term recorders in the Southern California Bight. The preliminary measurement of the visually validated Baird's beaked whale echolocation signals from towed array data were used as a basis for identifying Baird's signals in the autonomous recorder data. Two distinct signal types were found, one being a beaked whale-like frequency modulated (FM) pulse, the other being a dolphin-like broadband click. The median FM inter-pulse interval was 230 ms. Both signal types showed a consistent multi-peak structure in their spectra with peaks at ∼9, 16, 25, and 40 kHz. Depending on signal type, as well as recording aspect and distance to the hydrophone, these peaks varied in relative amplitude. The description of Baird's echolocation signals will allow for studies of their distribution and abundance using towed array data without associated visual sightings and from autonomous seafloor hydrophones. © *2013 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4804316]

PACS number(s): 43.80.Ka [WWA] Pages: 4321–4331

I. INTRODUCTION

Passive acoustic monitoring can be a powerful tool for assessment of cetacean species populations and their distributions. Beaked whales have been shown to produce species-specific echolocation signals (Zimmer *et al.*, 2005; Johnson *et al.*, 2006; Gillespie *et al.*, 2009; McDonald *et al.*, 2009; Baumann-Pickering *et al.*, 2010b; Rankin *et al.*, 2011; Wahlberg *et al.*, 2011; Baumann-Pickering *et al.*, 2013). This characteristic, along with their elusive surface behavior with short surface intervals and prolonged, deep dives (Tyack *et al.*, 2006; Baird *et al.*, 2008), in addition to the difficulty of visual species identification at sea (Jefferson *et al.*, 2008), make beaked whales especially well suited for monitoring with passive acoustics. The most characteristic parameters of their echolocation signals are a gradual increase and decrease of the amplitude in the time series, upswept frequency modulation within a signal (FM pulse), and a preferred, stable inter-pulse interval (IPI; e.g., Johnson *et al.*, 2004, 2006). These characteristics allow beaked whale clicks to be distinguished from other odontocetes.

Baird's beaked whales (*Berardius bairdii*) are the largest of the beaked whale species (up to 12.8 m in length). They are distributed throughout the deep waters of the North Pacific Ocean ranging from waters offshore of Japan east to southern California and Mexico and north to the Bering Sea. They are a deep diving species with recorded dive times of up to 67 min (Jefferson *et al.*, 2008). There has been one previous study documenting the acoustic behavior of Baird's beaked whales (Dawson *et al.*, 1998). This acoustic description provided by Dawson *et al.* (1998) was based on two encounters off the coasts of Oregon and Baja California. Baird's beaked whales were shown to produce whistles, burst pulses, and echolocation clicks. Whistles had fundamental frequencies of 4–8 kHz and 2–3 harmonics present within the recording bandwidth (20 kHz). Clicks showed a multiple peak structure with the largest spectral peak between 22 and 25 kHz, and the second largest spectral peak between 35 and 45 kHz (98 kHz recording bandwidth). One echolocation sequence is reported as having the first eight clicks with spectral peaks from 12 to 16 kHz, much lower than the mean or the last click in the sequence. Mean echolocation click duration was 463 μs (CV = 58%). Dominant frequency and duration were inversely related for all clicks. From their signal description, it is unclear if the typical

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frequency modulation seen in other beaked whale echolocation signals is also one of the species-specific acoustic features for Baird's beaked whales.

The aim of this study was to provide a detailed description of Baird's beaked whale echolocation signals from multiple shipboard towed hydrophone array survey recording sessions that had visual verification to acoustically discriminate them from other beaked whale species, and to compare those findings to similar signals encountered on autonomous, bottom-moored acoustic recorders. We provide a comprehensive description of all on- and off-axis Baird's beaked whale echolocation signals typically received on acoustic towed and seafloor recording systems. This will allow other researchers to determine the presence of Baird's beaked whales in the absence of visual sightings and without knowledge about the relative location and orientation of the animal to the receiver.

II. METHODS

A. Data collection

Acoustic recordings were made in the presence of Baird's beaked whale during a shipboard survey in the California Current ecosystem and autonomously with long-term high-frequency acoustic recording packages (HARPs) at four sites in the Southern California Bight (Fig. 1).

The shipboard survey area included the waters off Washington, Oregon, and California from July to December 2008. Seven acoustic encounters from visually confirmed single-species groups of Baird's beaked whales were analyzed to describe their echolocation signals (Fig. 1; Table I). Visual methods consisted of a team of three experienced visual observers searching with "big-eye" 25 × 150 power binoculars, 7× hand-held binoculars, and unaided eye (Kinzey *et al.*, 2000). All visual sightings were approached for accurate species identification and group size estimation. A hydrophone array was towed 300 m behind the vessel at an average depth of 8–12 m at speeds of 10 kn during daylight hours. The five-element oil-filled hydrophone array consisted of two mid-frequency hydrophones [EDO (New York, NY) ceramic with a sensitivity of −155 dB re 1 V/μPa from 500 Hz to 55 kHz ± 5 dB after 40 dB pre-amplification] and three high frequency hydrophones (Teledyne RESON, Slangerup, Denmark) (Reson TC4013 hydrophones with a sensitivity of −171 dB re 1 V/μPa from 1.5 to 150 kHz ± 3 dB after 40 dB pre-amplification). All hydrophone channels were recorded at a 480 kHz sample rate with 16-bit quantization. Only recordings from the high frequency hydrophones were used to measure echolocation signals herein.

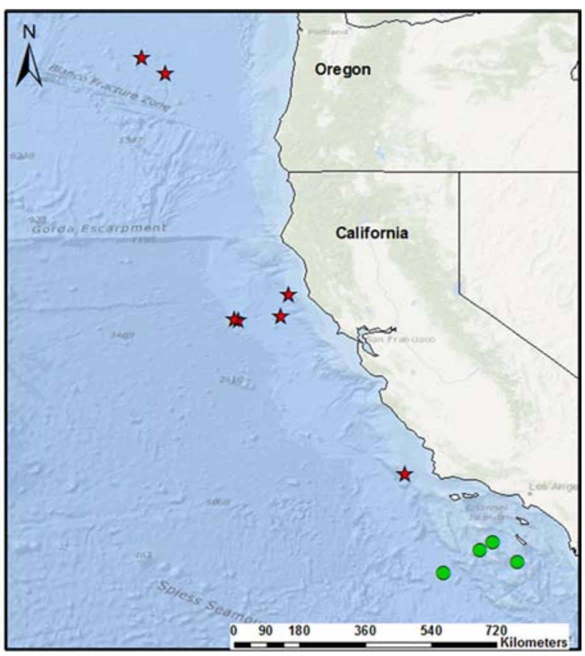

FIG. 1. (Color online) Study area with Baird's beaked whale encounters from Southwest Fisheries Science Center combined visual and acoustic surveys (stars) and acoustic encounters from autonomous HARPs (dots).

TABLE I. Baird's beaked whale acoustic encounters for towed-array data.

Date/time (PDT)[a]	Latitude	Longitude	Signal count
8/7/2008 10:08	44.8176	−127.8176	16
8/18/2008 8:19	44.4265	−127.2366	218
9/6/2008 8:20	38.4498	−124.3977	307
9/6/2008 14:11	38.9673	−124.1912	422
9/18/2008 7:32	38.3456	−125.4387	69
09/18/2008 8:40	38.3653	−125.5226	145
10/04/2008 16:23	34.5631	−121.3396	159

[a]Pacific daylight time (PDT).

HARPs were bottom-mounted at depths between 950 and 1300 m (Fig. 1; Table II), in a seafloor packaged configuration with the hydrophone at about 10 m above the seafloor (Wiggins and Hildebrand, 2007). The recorders were equipped with an omni-directional sensor (ITC-1042, International Transducer Corporation, Santa Barbara, CA), which had an approximately flat (±2 dB) hydrophone sensitivity from 10 Hz to 100 kHz of −200 dB re 1 V/μPa. The sensor was connected to a custom-built preamplifier board and bandpass filter. The preamplifiers were designed to flatten the frequency response of the ambient ocean noise, which provided greater gain at higher frequencies where ambient noise levels are lower and sound attenuation is higher (Wiggins and Hildebrand, 2007). The calibrated system response was corrected for during analysis. All HARPs were set to a sampling frequency of 200 kHz with 16-bit quantization.

B. Signal processing

Signal processing was performed on one channel of the high frequency towed array data using XBAT (Harold Figueroa, http://www.xbat.org) and custom routines in MATLAB (Mathworks, Natick, MA). All echolocation signals collected during shipboard surveys were initially manually detected, and start and ends were roughly marked using XBAT. Precise start and end times of each signal and duration were later computed using the Teager energy algorithm described by Soldevilla *et al.* (2008).

HARP recordings were manually screened for acoustic encounters with Baird's beaked whales using the custom software program *Triton* (Wiggins and Hildebrand, 2007),

TABLE II. Baird's beaked whale acoustic encounters for autonomous HARP data.

Site	Latitude	Longitude	Depth (m)	Date	Start (GMT hh:mm)[a]	End	Signal count
SOCAL 1[b]	32 39.409	−119 28.419	1300	8-Apr-09	18:15	20:45	11 755
SOCAL 2	32 50.587	−119 10.170	950	23-Apr-09	7:30	9:00	12 812
SOCAL 2	32 50.587	−119 10.170	950	4-May-09	13:50	14:10	1576
SOCAL 2	32 50.587	−119 10.170	950	5-May-09	19:40	20:05	1131
SOCAL 1	32 39.409	−119 28.419	1300	6-May-09	13:40	16:40	9221
SOCAL 3	32 22.186	−118 33.885	1300	30-Jul-09	8:10	8:30	2028
SOCAL 4	32 54.913	−120 22.544	1100	23-Apr-10	19:00	1:00	4933
SOCAL 4	32 54.913	−120 22.544	1100	27-Apr-10	11:05	0:00	12 597
SOCAL 4	32 54.913	−120 22.544	1100	13-May-10	8:00	8:05	1459
SOCAL 4	32 54.913	−120 22.544	1100	15-May-10	14:15	14:20	1511

[a]Greenwich Mean Time, hours:minutes.
[b]Southern California (SOCAL).

looking for signals similar to those detected on shipboard survey recordings described below and reported by Dawson *et al.* (1998). Long-term spectral averages (LTSAs) were calculated for visual analysis of the long-term recordings. LTSAs are long-term spectrograms with each time segment consisting of an average of 500 spectra, which were created using the Welch algorithm (Welch, 1967). The averages were formed from the power spectral densities of non-overlapped 10 ms Hann-windowed frames. The resulting long-term spectrograms have a resolution of 100 Hz in frequency and 5 s in time. An individual echolocation click can be detected in averaged spectra when displaying a 1-h LTSA. When echolocation signals were notable in the LTSA, the sequence was inspected more closely. Time series of 5 s lengths gave indications of IPI, time series of 3 ms lengths displayed the shape of the waveform, and spectrograms over 3 ms [Hann window, 60-point discrete Fourier transform (DFT), 98% overlap] were used to evaluate the presence of FM pulses. Start and end times of acoustic encounters were noted if beaked whale-like FM pulses and a specific spectral peak structure were identified. Individual echolocation signals were automatically detected within these manually classified HARP Baird's beaked whale encounters (Soldevilla *et al.*, 2008; Roch *et al.*, 2011).

For both shipboard survey and HARP data, the individual echolocation signals were digitally filtered with a 10-pole Butterworth band-pass filter with a pass-band between 5 kHz and 95 kHz. Since the two data sets were sampled at different rates, each data set was processed with different parameters to make the analyses more comparable (Table III).

TABLE III. Analysis settings for towed array and autonomous HARP data.

Parameter	Towed array	HARP
Sampling rate (kHz)	480	200
Signal-to-noise cutoff (dB)	10	5
n-points FFT	1024	512
Frequency resolution (Hz)	470	390
Duration cutoff (μs)	<150 and >600	n.a.[a]
−10 dB bandwidth cutoff (kHz)	>60	n.a.
IPI/ICI cutoff (ms)	n.a.	<50 and >700

[a]Not applicable (n.a.).

Signals with a low signal-to-noise ratio were discarded. Based on a higher noise floor in towed array data, the signal-to-noise cutoff had to be chosen with a higher threshold than the autonomous recorder to prevent false detections. Spectra of each detected signal were calculated with Hann-windowed data centered on the signal (Table III). Peak frequency was determined as the spectral frequency with the highest magnitude. To reduce false detections of random, impulsive noise of the recording system and echosounder pings in the shipboard data, most false detections were successfully eliminated by deleting extreme outliers in duration and −10 dB bandwidth. Cutoff values for these outliers were chosen based on distribution graphs (Table III). The waveform, spectra, and spectrograms of all remaining signals from the towed array data were then viewed by an experienced acoustician in order to eliminate any further false detection of echosounders or impulsive noise. No such eliminations were required for the HARP data because of the large number of recorded echolocation signals and lower false detection rate based on the quieter seafloor environment. Signal duration was derived from the detector output. FM pulses with corresponding IPIs were differentiated from broadband clicks with inter-click intervals (ICIs). These intervals were calculated from the start of an echolocation signal to the start of the previous one. For HARP data, extreme outliers on both sides of the distribution of IPIs or ICIs (Table III) were discarded, as they likely occurred either during periods with signals of low received levels or were made by multiple animals during the same evaluation period, during burst sequences, or during approach of prey. IPI or ICI was not measured for shipboard data because only a few sequences had a high enough signal-to-noise ratio over many signals before weak signals were omitted; therefore, most values did not accurately represent the true IPI/ICI within a sequence. All detected echolocation signals, independent of distance and orientation of the recorded animal with respect to the recorder, were included in the analysis. The frequency-related signal parameters peak frequency, center frequency, and bandwidth were processed using methods from Au (1993). To calculate sweep rate, spectrograms over 1.2 ms of data centered on the signal were computed with 0.3 ms Hann windows and 98% overlap. Sweeps were traced by selecting the frequency bins with maximum spectrum level for each frame. The beginning and ending of a sweep was defined by the −8 dB level from the maximum spectrum level of the traced sweep. The −8 dB criteria was chosen empirically to balance the trade-off between increasing the sample size of signals with a high enough received level while keeping a relevant portion of the FM pulse intact. A line of best fit through the sweep was calculated, resulting in a sweep rate. In towed array and HARP data, all values with negative sweep rate were discarded.

A Gaussian mixture model (GMM) with five mixtures was fitted to the HARP peak frequency histogram of ten individual acoustic encounters as well as all data pooled to describe distinct peaks in the distribution and compare to the towed array distribution. Four subsets of echolocation signals were generated based on these mixtures, using the crossing point of two mixtures as a splitting value and combining signals defined by mixtures four and five into the fourth subset based on similarity of signal parameters. Mean spectra and statistical values (median, 10th, and 90th percentile) were calculated for all measured signal parameters of each subset. FM sweep rates (kHz/ms) were calculated for manually selected FM pulses with definitive sweeps from all subsets in the towed-array data and all signals of the subset 1 HARP data without exception.

III. RESULTS

Two distinct signal types were found, one being a beaked whale-like frequency modulated (FM) pulse, the other a dolphin-like broadband click. The data were split into four subsets based on the fit of a GMM with five mixtures to the HARP peak frequency distribution (Fig. 2). Subset splits were made at 12.3, 20.3, and 30.2 kHz. The GMMs calculated for the ten individual HARP encounters show that these subset splits were consistent across encounters with some variability in peak frequency and variation in relative use (Fig. 3). The two signal types were used in varying degrees within the subsets in both array and HARP recordings.

A. Towed hydrophone array recordings

High-quality recordings from seven single-species encounters with Baird's beaked whale during the ship-based survey were used for description and characterization of echolocation signals (Table I; Fig. 1). A total of 1336

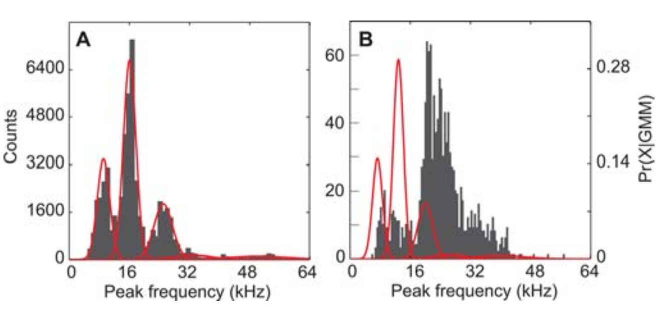

FIG. 2. (Color online) Peak frequency distribution of echolocation signals for HARP (A) and towed array data (B). GMM with five mixtures (line) fitted to the HARP peak frequency histogram. Echolocation signals within the first three mixtures were assigned to subsets 1–3, respectively, and those within the last two to subset 4.

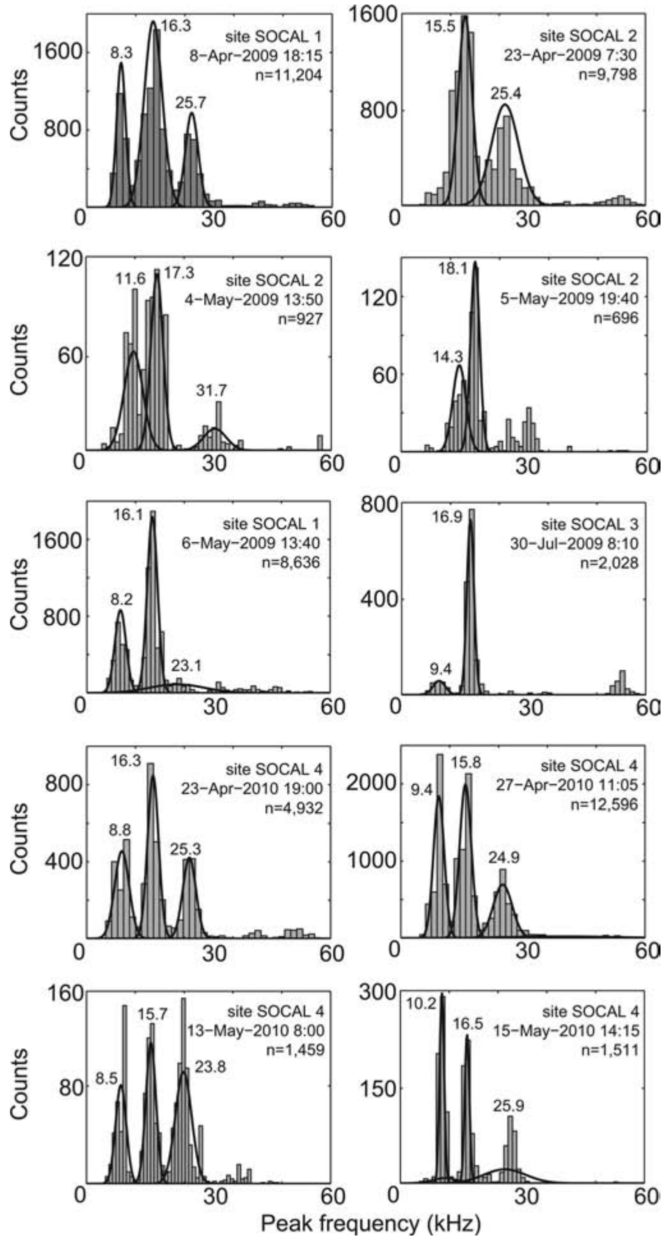

FIG. 3. Peak frequency distribution of echolocation signals in ten individual HARP encounters (site, date, time, and *n* number of echolocation signals given). GMM with five mixtures fitted (line) to the peak frequency histogram, probability of fit was omitted, and only dominant fits are shown to simplify graphs.

echolocation signals were measured. Concatenated spectrograms of echolocation signals over all subsets show peak frequency ranges from approximately 8 to 41 kHz, there is often multi-peak structure evident, and most of the energy in all of the signals is between 5 and 55 kHz [Fig. 4(A)].

The median peak frequencies for the four subsets were at approximately 9 kHz, 19 kHz, 24 kHz, and 35 kHz (Table IV), representing 10%, 16%, 57%, and 16%, respectively, of all measured signals ($n1 = 131$, $n2 = 220$, $n3 = 766$, $n4 = 219$; Fig. 4; Table IV). Definitive FM sweeps were identified in 18% of subset 1 (sweep rate median = 15.1 kHz/ms), 15% of subset 2 (median = 16.1 kHz/ms), 6% of subset 3 (median = 26.1 kHz/ms), and 15% of subset 4 (42.0 kHz/ms). Median sweep rates for each subset increased with increasing peak frequency (Table IV). Due to the high level of variation

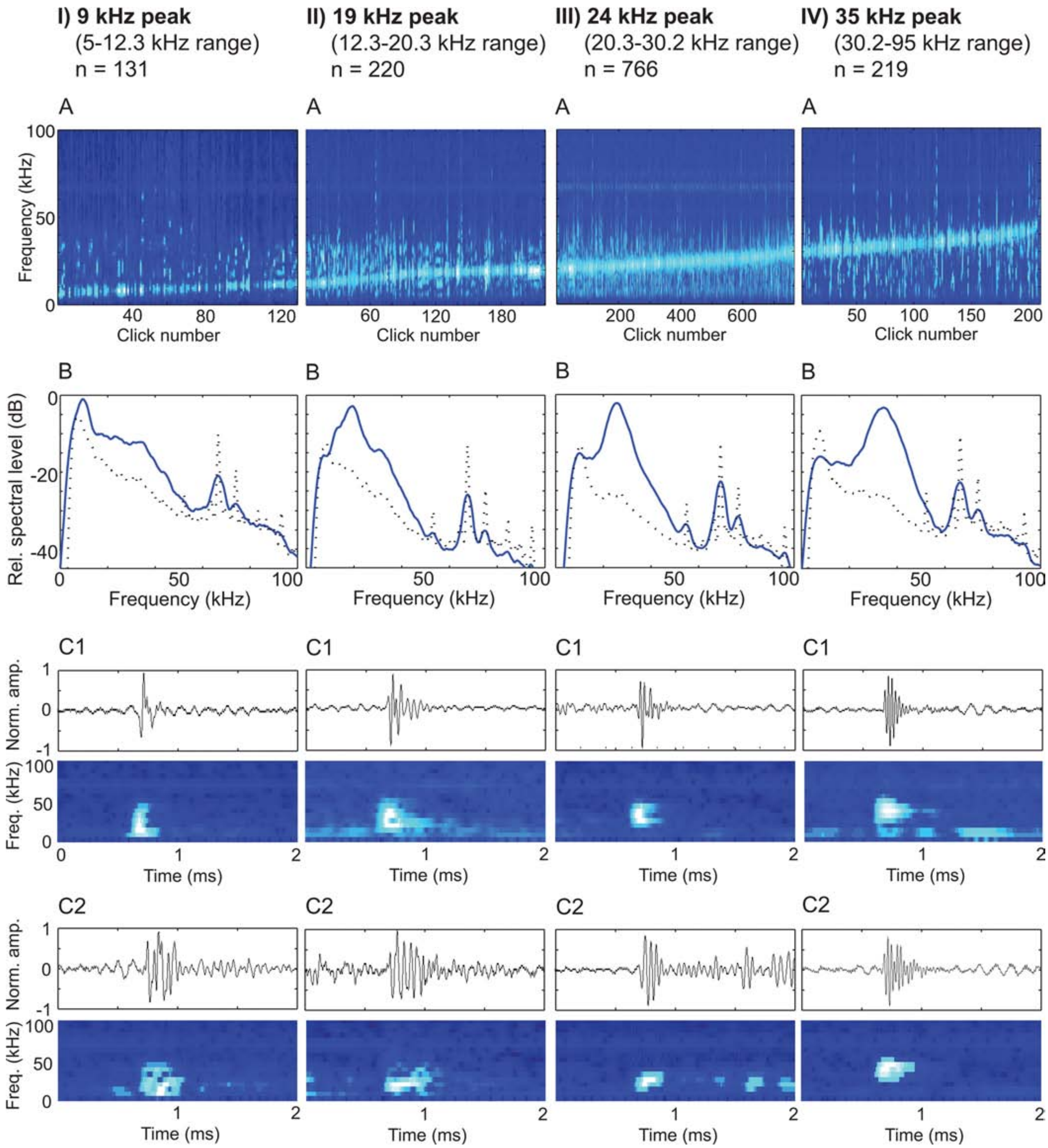

FIG. 4. (Color online) Description of echolocation signals extracted from towed array recordings split into four subsets (I–IV). (A) Concatenated spectrograms with signals sorted by peak frequency. (B) Spectra with mean signal (solid line) and mean noise before signal (dashed line). (C) Two signal examples with waveform (normalized amplitude, top) and spectrogram [144 points discrete Fourier transform (DFT), 98% overlap, bottom].

in signals recorded on the towed array, the proportion of FM sweeps identified in each subset likely is not an accurate representation of signal type composition for the subset.

B. HARP recordings

Ten acoustic encounters with Baird's beaked whales from four HARP sites in the Southern California Bight were included in the analysis (Fig. 1; Table II) resulting in a total duration of encounters of almost 23 h and 53 756 detected echolocation signals. The median peak frequencies for the four subsets were at approximately 9 kHz, 16 kHz, 25 kHz, and 43 kHz (Table IV), representing 24%, 49%, 20%, and 7%, respectively, of all measured signals ($n1 = 12\,889$, $n2 = 26\,445$, $n3 = 10\,913$, $n4 = 3509$; Fig. 5; Table IV).

TABLE IV. Signal characteristics for four subsets of Baird's beaked whale signals with splits based on multi-modal peak frequency distribution in HARP data for both towed array and autonomous HARP data. Number (n) of echolocation signals in subset, median, and 10%–90% percentiles of distribution in subset are presented.

Subset limits (kHz)	Subset 1 5–12.3		Subset 2 12.3–20.3		Subset 3 20.3–30.2		Subset 4 30.2–95	
	131		220		766		219	
Towed array n	Median	(10%–90%)	Median	(10%–90%)	Median	(10%–%–90%)	Median	(10%–90%)
Peak frequency (kHz)	9.4	(7.8–11.7)	18.8	(13.4–20.2)	23.9	(21.1–28.1)	35.2	(31.4–41.3)
Center frequency (kHz)	18.5	(12.8–26.9)	19.7	(17.4–24.4)	23.5	(20.1–27.3)	33.2	(27.7–37.9)
−3 dB bw. (kHz)	6.0	(4.7–7.5)	5.6	(4.2–9.8)	5.6	(4.2–8.4)	7.0	(4.7–9.8)
−10 dB bw. (kHz)	10.3	(7.0–21.1)	10.8	(6.8–23.9)	10.3	(7.0–16.4)	12.7	(8.4–22.5)
Duration (μs)	258	(174–436)	321	(175–477)	305	(179–483)	237	(165–397)
IPI (ms)	—	—	—	—	—	—	—	—
Sweep rate (kHz/ms)[a]	7.1	(5.25–20.6)	13.4	(5.0 – 22.3)	14.3	(7.1–20.9)	30.8	(25.9–43.1)
	12889		26445		10913		3509	
HARP n	Median	(10%–90%)	Median	(10%–90%)	Median	(10%–90%)	Median	(10%–90%)
Peak frequency (kHz)	9.0	(7.0–10.9)	16.0	(13.7–18.0)	25.0	(21.9–27.7)	42.6	(31.6–55.1)
Center frequency (kHz)	17.2	(12.3–27.5)	19.0	(15.2–28.0)	23.4	(19.4–30.7)	35.6	(28.3–45.6)
−3 dB bw. (kHz)	3.5	(2.7–5.1)	4.7	(3.1–7.8)	5.5	(3.1–8.2)	5.9	(3.1–12.9)
−10 dB bw. (kHz)	5.9	(3.9–11.7)	9.0	(5.1–18.4)	10.9	(5.9–19.9)	13.3	(5.9–35.5)
Duration (μs)	570	(290–960)	485	(275–845)	485	(275–820)	475	(250–870)
IPI (ms)	233	(97–454)	225	(96–425)	234	(115– 440)	239	(82–480)
Sweep rate (kHz/ms)	30.0	(3.6–84.4)		—	—	—	—	—

[a]Towed array sweep rates are only presented for the portion of measured signals that showed a clearly defined sweep upon manual examination: 18%, 15%, 6%, and 15%, respectively, for subsets.

Subset 1 consisted almost exclusively of FM pulses, with the majority of their energy at the lower frequency end and beginning of their sweep (Fig. 5, I/C1 and C2). Subset 2 had both FM pulses and clicks in approximately equal numbers (Fig. 5, II/C1 and C2). Subset 3 was again comprised of FM pulses and clicks with a larger emphasis on FM pulses (Fig. 5, III/C1 and C2). The last subset contained predominantly clicks (Fig. 5, IV/C1 and C2). Comparing concatenated spectrograms and mean spectra of all subsets (Fig. 5, I–IV/B), it is apparent that the peak structure shown in the peak frequency distribution (Figs. 2 and 3) is valid in all subsets, only emphasis is given to either one of these peaks per subset, particularly strong in subset 2 and least pronounced in subset 4. The echolocation clicks, for the most part, contained the multi-peak energy distribution with stronger peaks around 16 and 43 kHz (Fig. 5, II/C2 and IV/C1). There were, however, few clicks that did not show this bimodality (Fig. 5, III and IV/C2). The main frequency content of all FM pulses was consistently between 5 and 35 kHz with the peak energy varying between subsets. FM pulses with high-received levels showed a harmonic-like frequency structure (Fig. 5, I-III/C1 and I/C2). Having described the properties of these subsets and signals, the peak structure and different signal types become evident looking at LTSAs, which additionally demonstrate the variability in use of these different signals within and across acoustic encounters (Fig. 6). The most prevalent IPI independent of all subtypes was about 230 ms (Fig. 5, I–IV/D; Table IV). These were calculated on a subset basis indicating that signals of the same subset were produced within one echolocation bout, instead of alternating between signals of different subsets within a single bout. The use of signals from a certain subset within a bout is also evident when individual echolocation sequences are reviewed (Fig. 7).

Burst pulses were commonly detected in HARP acoustic encounters. These varied from short bursts to extensive burst sequences of up to 15 s (Fig. 8). All signals in burst sequences were of the FM pulse type, even during very fast bursts. Slow burst periods had IPIs of 30–60 ms while fast bursts had IPIs ranging from 5 to 10 ms. Over the almost 23 h of Baird's beaked whale acoustic encounters, only very few whistles were detected concurrent with echolocation activity (Fig. 9). Whistle fundamental frequencies were between 4 and 12 kHz with up to three harmonics, with the first harmonic most energetic. Whistles were complex, had frequency-modulated as well as constant frequency components, multiple inflection points, as well as frequency steps and durations between 2 and 4 s.

IV. DISCUSSION

Baird's beaked whales use two distinctly different echolocation signals: an FM pulse and a broadband click. The different functions of these signals is unknown, but they consistently occurred both in all array and all HARP acoustic encounters, although the proportional use of each type varied among encounters. Given the autonomous HARP recording without visual confirmation, there may be the possibility of

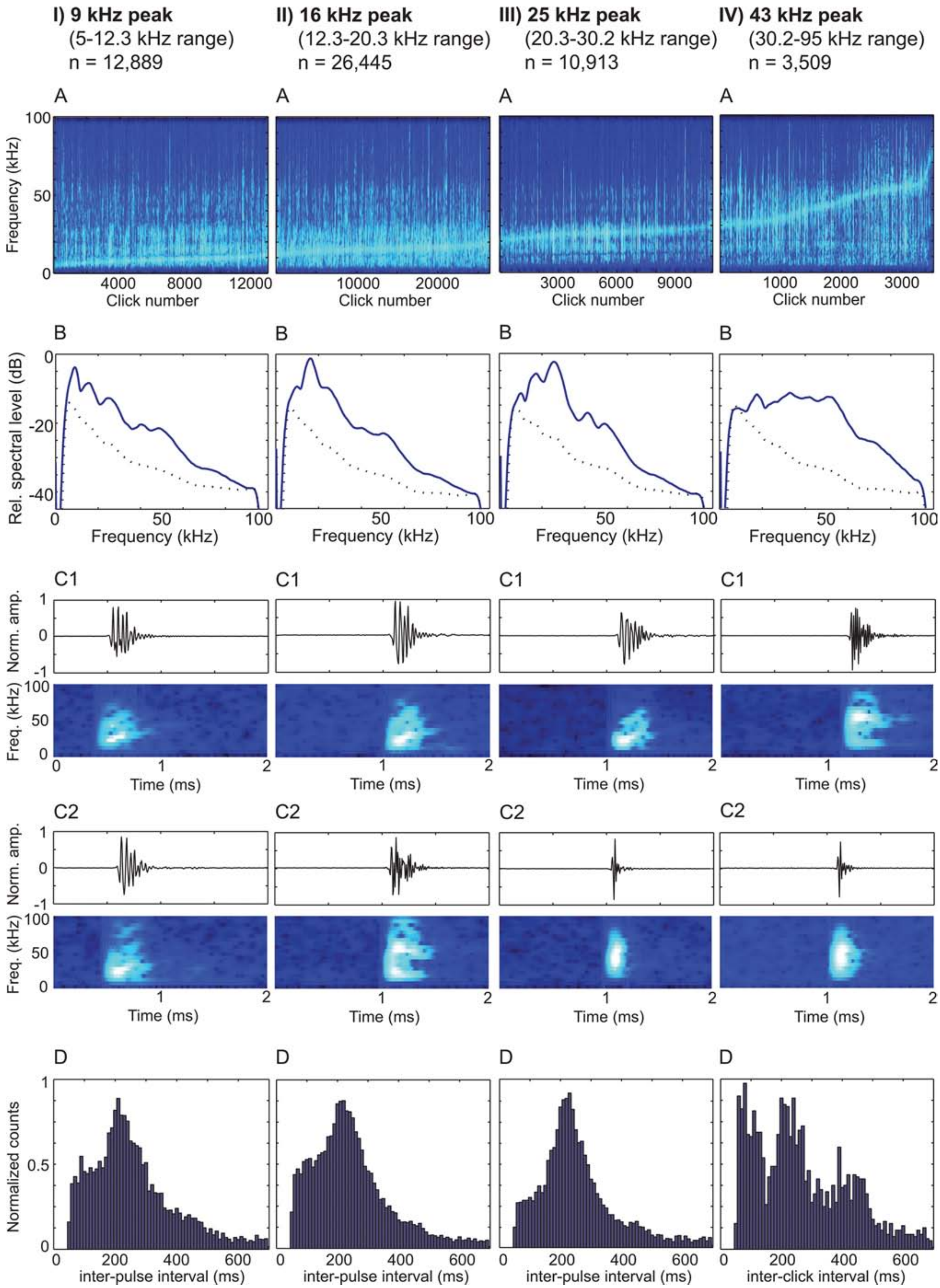

FIG. 5. (Color online) Description of echolocation signals extracted from HARP recordings split into four subsets (I–IV). (A) Concatenated spectrograms with signals sorted by peak frequency. (B) Spectra with mean signal (solid line) and mean noise before signal (dashed line). (C) Two signal examples with waveform (normalized amplitude, top) and spectrogram (60 points DFT, 98% overlap, bottom). (D) Histogram of inter-pulse/inter-click interval.

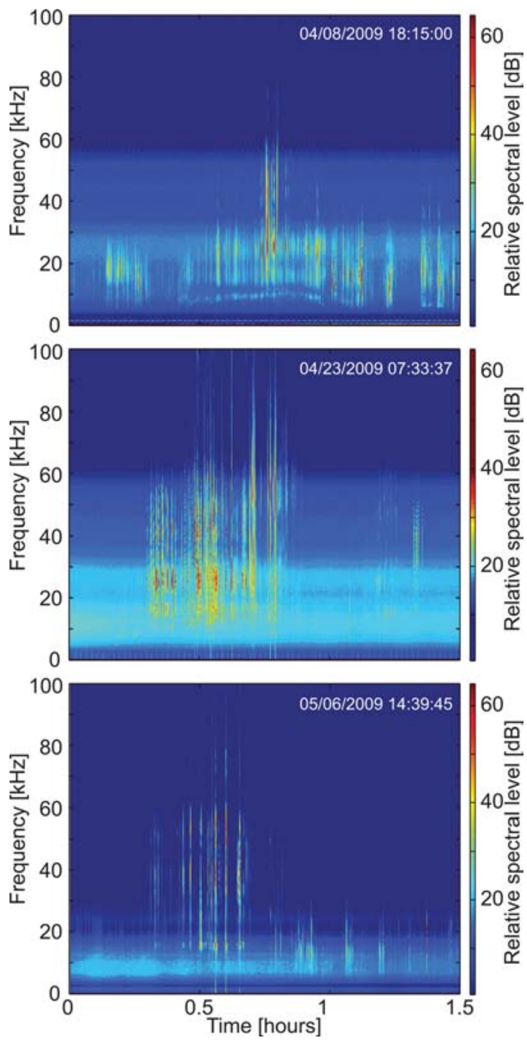

FIG. 6. (Color online) Long-term spectral average (LTSA) of three representative acoustic encounters of Baird's beaked whale on HARP recordings. Different signal types were notable in the LTSA with variable proportions of FM pulses versus clicks in each encounter. Distinct banding pattern was apparent in all three examples.

mixed species recordings, indicated by these two signal types. However, all 24 Baird's beaked whale sightings reported in Southwest Fisheries Science Center cruise reports from the California Current and Eastern Tropical Pacific ship-based surveys were single species. During the Southern California Behavioral Response Study in 2011 there was one sighting of common dolphins within 0.5 nmi of a Baird's beaked whale sighting (observation T.M.Y.). Echolocation click and whistle parameters of dolphin species in the Southern California region are well described (e.g., Oswald *et al.*, 2003; Soldevilla *et al.*, 2008) and have distinctly different signal parameters to those described for Baird's beaked whales. While a mixed species acoustic encounter on the HARP can never be ruled out, it likely would have been noticed and eliminated during analysis.

The spectral and temporal characteristics of Baird's beaked whale echolocation signals are distinct from those of known signals of other beaked whale species, which have an overlapping geographic distribution: Cuvier's (*Ziphius cavirostris*), Blainville's (*Mesoplodon densirostris*), and Stejneger's (*Mesoplodon stejnegeri*) beaked whales (Fig. 10; Zimmer *et al.*, 2005; Johnson *et al.*, 2006; Baumann-Pickering *et al.*, 2013). Baird's beaked whale signals have a lower median spectral content than other species, and their median IPI (approximately 0.23 s) is slower than in Stejneger's (0.08 s) and faster than in Cuvier's (0.43 s) and Blainville's (0.37 s) beaked whales.

The main discriminatory features of Baird's beaked whale echolocation signals are the use of FM pulses lower in frequency than any other currently described beaked whale FM pulses, common use of dolphin-like clicks, consistent spectral peaks independent of signal type, and a species-specific IPI. The distribution of signals making up each subset and the distribution of signal types within each subset likely are highly dependent on a number of factors, for example, the behavioral state of the animals, the number of animals acoustically active, the orientation of the animal's head relative to

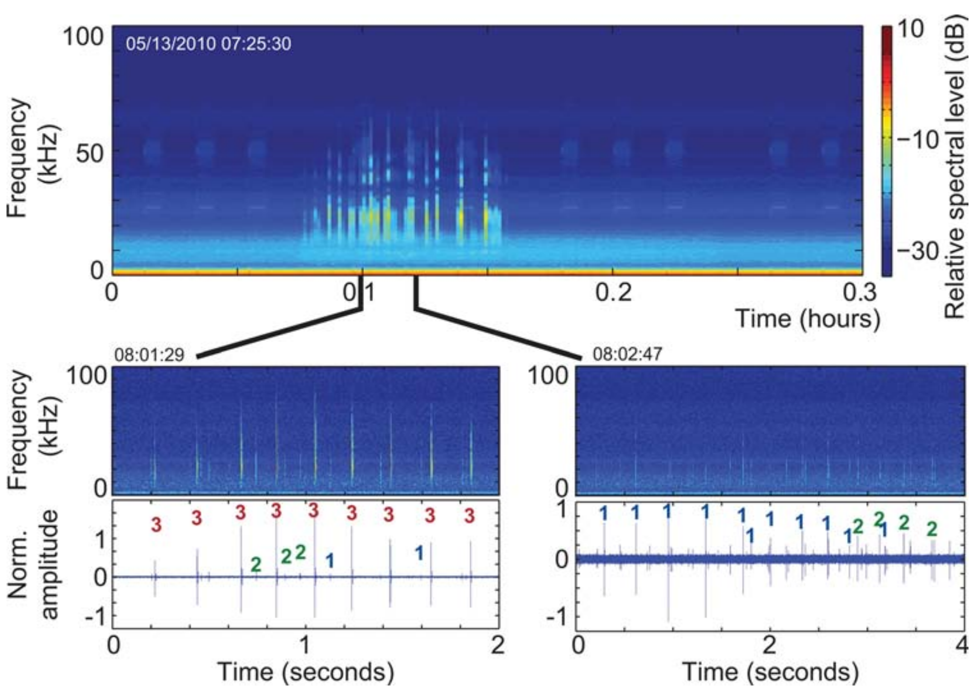

FIG. 7. (Color online) Example acoustic encounter showing an LTSA (top) and two echolocation sequences (bottom, spectrogram and time series) within the same encounter. Echolocation clicks associated with a certain subset are indicated by subset numbers (1–3).

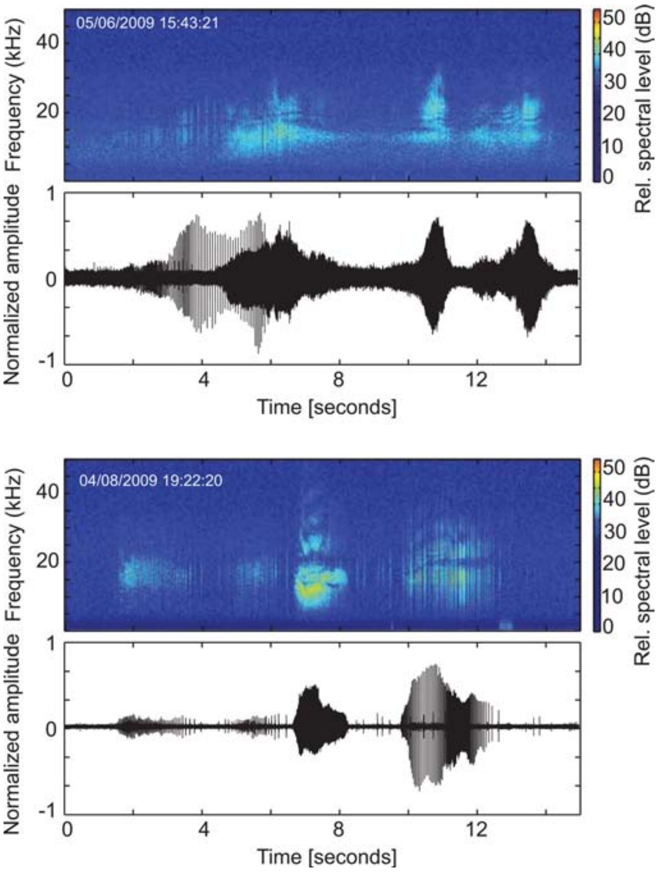

FIG. 8. (Color online) Two example burst pulse sequences of up to 15 s duration from HARP recordings. All signals were of the FM pulse type. Interpulse intervals ranged from slow 30–60 ms to fast 5–10 ms.

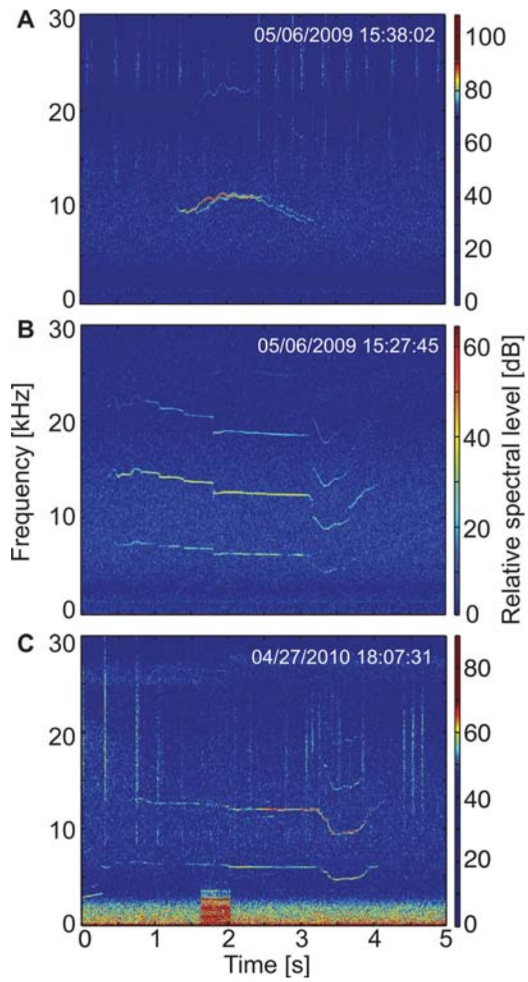

FIG. 9. (Color online) Whistles of Baird's beaked whales with fundamental frequencies between 4 and 12 kHz and up to three harmonics from HARP recordings.

the hydrophone, and their distance to it. Peak frequency of directional echolocation clicks have been shown in tank studies to vary according to their angle of orientation (Au, 1993; Au *et al*., 2012a,b) and higher frequencies are known to attenuate faster over distance (Urick, 1983); however, the purpose of this analysis was to describe all signals from this free-ranging species in its natural habitat as they would be recorded by passive acoustic monitoring systems such as towed hydrophone arrays or bottom-mounted recorders.

There is variability of echolocation measures both within and between recording instrument types. Some of the variability between recordings likely can be explained by source and receiver geometry, sound propagation path differences, and to some degree by hydrophone variability (Baumann-Pickering *et al*., 2010a). The only signal measure that differed substantially between the two recording instruments for all four subset categories was signal duration. Duration was over 150 μs less for towed-array measures in all subsets. Part of this discrepancy likely occurred due to signals greater than 600 μs having been eliminated from the towed-array analysis, due to increased false detections of impulsive noise and echosounder pulses. They were not eliminated from the HARP analysis (as also is evidenced in the percentile range values). Using a median opposed to mean calculation should have accounted for most of those few outliers. The more important aspect, however, probably was the very different signal-to-noise ratio between the two recording situations, with a much quieter environment at the seafloor and with a stationary hydrophone, HARP recordings resulted in longer signal durations.

Reported sweep rate values within and across recording instruments differed greatly. Median values ranged from 7 to 31 kHz/ms and 10th–90th percentile values ranged from 4 to 84 kHz/ms. For towed array data, sweep rate was only calculated for a small sample of definitive sweeps for each subset (18%, 15%, 6%, and 15%, respectively). For HARP data, sweep rate was calculated for subset 1, as this was, unlike all other subsets, almost exclusively comprised of FM pulses. Sweep rate is inherently difficult to measure because it depends on a clear and consistent frequency increase over time, which may only be a clean sweep for on-axis pulses and might be distorted for off-axis pulses. With our method, sweep rate is calculated based on the frequency and amplitude distribution in the spectrogram of all recorded signals. However, very few signals in an echolocation sequence are on-axis and show an ideal sweep. Therefore, the sweep calculation is sensitive to any distortion in the signal due to the arrival path and is also sensitive to the received geometry of the signal.

Another noteworthy difference in signal measures between towed-array and HARP data was in the median peak frequency and peak frequency range values reported for

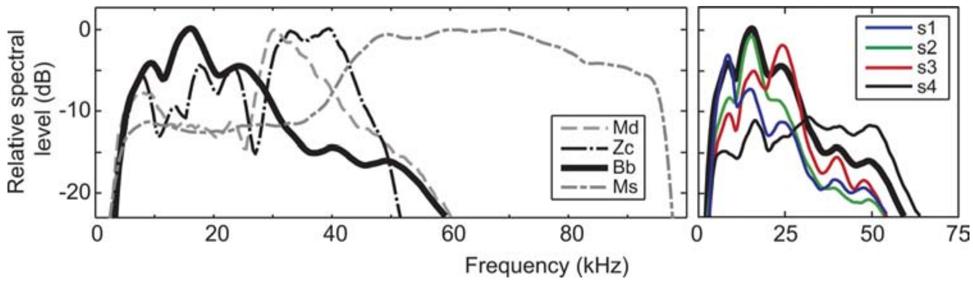

FIG. 10. (Color online) Mean spectra of Baird's beaked whale (bold black, Bb) in comparison to Blainville's (Md), Cuvier's (Zc), and Stejneger's (Ms) beaked whales (left). While these species have overlapping geographic distributions, their echolocation signals are species-specific allowing passive acoustic monitoring to be used for population assessment. Mean spectra of the four Baird's beaked whale subsets (s1–s4, right) indicate variability in the relative use of the consistent spectral peaks. The mean spectrum (bold, right) retains the relevant spectral features of all subsets (s1–s4, right), and emphasizes consistent spectral peaks, despite varying peak signal level, independent of subset or signal type.

subset 4. The median peak frequency reported from the HARP data was 7 kHz higher than that reported from the towed-array data. Additionally, the 90th percentile range value reported from the HARP data was 15 kHz higher than that reported from the towed-array data. One potential reason for these differences would be that the two instrument types are recording different phases of the foraging dive. For example, the towed array recordings likely do not record the bottom phase of the decent in all cases whereas the HARP recorders may be more likely to miss the upper portion of the ascent phase. It is recommended that future research explore these differences in more detail, particularly the inherent differences in dive behavior that different systems will record.

Burst pulses and whistles, likely used for communication purposes, were previously described by Dawson *et al.* (1998). Some of the burst pulses presented herein were considerably longer than those previously described, but the data described does not include quantified results on all burst pulses and likely represent easily detectable extremes. Similar signal repetition rates, as in burst pulses with up to 5 ms IPIs, are also achieved during buzz periods, the terminal phase during a prey capture attempt (e.g., Madsen *et al.*, 2005). Most beaked whale species (Johnson *et al.*, 2006; Baumann-Pickering *et al.*, 2010b; Wahlberg *et al.*, 2011), except for Stejneger's beaked whale (Baumann-Pickering *et al.*, 2013), switch to a dolphin-like click instead of the FM pulse during the buzz phase. All signals within burst pulses of Baird's beaked whales were of the FM pulse type. While no clear foraging buzz sequences were detected in either the towed array or HARP data, it is very possible, given the similarity between bursts and buzzes in other species, that Baird's beaked whale would also use the FM pulse type for their buzzes. Two of the three whistles found in the HARP data had a similar frequency range between 4 and 8 kHz as those published by Dawson *et al.* [1998; Figs. 7(B) and7(C)]. The third whistle [Fig. 7(A)] appears to be a new whistle type, which had a frequency range of 9–12 kHz and was much shorter in duration than previously reported descriptions. Although these could have been made by other nearby species, we believe this is highly unlikely given the echolocation signal analysis, which shows that Baird's beaked whales were nearby, and given that no other clicks or whistles were detected over several hours before and after these new whistle types.

Over 55 000 echolocation signals were measured during this analysis. This provides the most extensive description of Baird's beaked whale echolocation to date. The description of Baird's beaked whale vocal behavior provided here will allow for studies of their distribution and abundance using towed array data without associated visual sightings and data from autonomous seafloor hydrophones. Passive acoustic monitoring will be of great value to future conservation and management efforts for this species.

ACKNOWLEDGMENTS

S.B.P. and T.M.Y. contributed equally to this manuscript. We would like to acknowledge our funding sources, namely, Mike Weise and Dana Belden at the Office of Naval Research, Frank Stone, Ernie Young, and Bob Gisner of U.S. Navy, Chief of Naval Operations, Environmental Readiness Division (OPNAV N45), and Curt Collins and John Joseph at the Naval Postgraduate School. Also, many thanks to the scientists aboard the Southwest Fisheries Science Center 2008 ORCAWALE survey and to the crew of the NOAA vessel McArthur II who assisted in collection of towed-array data. We thank H. Bassett, C. Garsha, B. Hurley, M. McDonald, M. Roch, E. Roth, A. Simonis, M. Stone, and K. Wyckoff for HARP fieldwork and analysis assistance.

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