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Aleutian Islands beaked whale echolocation signals

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Beaked whales are an elusive group of marine mammals. They are infrequently encountered as they are pelagic, deep diving foragers with short surface intervals between long dives (Tyack *et al.* 2006). In recent years, research has shown that beaked whales produce frequency modulated (FM) upsweep echolocation signals (Zimmer *et al.* 2005, Johnson *et al.* 2006, Gillespie *et al.* 2009, McDonald *et al.* 2009, Baumann-Pickering *et al.* 2010), which appear to be species specific in their spectral and temporal characteristics. Their typical echolocation behavior during foraging consists of FM pulses with very regular interpulse intervals (IPIs) while searching for prey, and discrete click series with short IPIs when closing in on a potential prey target, called a buzz (Johnson *et al.* 2004, Madsen *et al.* 2005).

Around the Aleutian Islands, only three species of beaked whales are currently known to occur. Sightings or strandings of Baird's beaked whales (*Berardius beardii*), Cuvier's beaked whales (*Ziphius cavirostris*), and Stejneger's beaked whales (*Mesoplodon stejnegeri*) have been reported (Jefferson *et al.* 2008). Stejneger's beaked whales are found in cold-temperate and subpolar waters, and they are endemic to the northern North Pacific. Based on stranding records because live sightings are rare, the central Aleutian Islands are considered to be the center of this species' range (Loughlin *et al.* 1982, Walker and Hansen 1999). Stejneger's beaked whale are mostly encountered in small groups of two or three animals and occasionally in larger groups up to 15 animals (Loughlin and Perez 1985). These groups make coordinated dives with a series of five to six short dives, followed by a longer dive of 10–15 min (Loughlin *et al.* 1982). The species is most often found in water depths ranging from 730 to 1,560 m. Their habitat is the steep slope of the continental shelf, which drops off into the

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Aleutian Basin to the north and into the Aleutian Trench to the south, but they are not likely to occur in the shallow northern or eastern Bering Sea (Mead 1989).

Investigative effort to study the behavior of beaked whales has increased due to several mass strandings, which have been linked to military sonar exercises (Cox *et al.* 2006). Numerous mass strandings of Stejneger's beaked whales in the Aleutian Islands have been documented since 1975 (Walker and Hansen 1999), yet to date, no correlation between these strandings and human activities has been established. Passive acoustic monitoring provides a cost-effective technique to investigate the behavioral ecology of these animals over long periods and in remote locations, particularly for species whose echolocation signals are distinguishable (McDonald *et al.* 2009, Baumann-Pickering *et al.* 2010).

We deployed a bottom-moored, autonomous High-frequency Acoustic Recording Package (HARP) (Wiggins and Hildebrand 2007) near Kiska, Alaska (52°19.01′N, 178°31.24′E). It was moored at a water depth of 1,092 m at the mouth of Sitkin Canyon, and continuously recorded from 3 June until 26 August 2010 with a sampling frequency of 200 kHz. The hydrophone was floating at approximately 15 m above the seafloor. The HARP was equipped with an omni-directional transducer (ITC-1042, ITC, Santa Barbara, CA), which had an approximately flat (±2 dB) frequency response from 10 Hz to 100 kHz with a hydrophone sensitivity of −200 dB re V/μPa. We used the MATLAB (Mathworks, Natick, MA) based custom software program *Triton* (Wiggins and Hildebrand 2007) and other MATLAB custom routines for signal processing. Long-term spectral averages (LTSAs) were calculated for visual analysis by a trained analyst (SBP), allowing manual inspection of the long-term recordings. LTSAs are long-term spectrograms with each time segment consisting of an average of 1,000 spectra, which were created using the Welch algorithm (1967). They were averaged with the discrete Fourier transform (DFT) of nonoverlapping 5 ms Hann-windowed frames. The averaged spectra were then arranged sequentially resulting in long-term spectrograms with a resolution of 100 Hz in frequency and 5 s in time. When echolocation sequences were noticeable in the LTSAs, the corresponding original time series and fine-scale spectrograms were inspected more closely. Upsweeps were best observed with 1 ms window lengths, 100-point FFT and 99% overlap. The sequence was categorized to species level or group of unknown origin due to similarities to other sequences. Additionally, to provide statistical values of click parameters, all echolocation clicks, independent of which species produced them, were automatically detected within the entire HARP long-term data set using a two-step approach (Soldevilla *et al.* 2008). The recording sequences with detections were digitally filtered with a 10-pole Butterworth band-pass filter. The low frequency cutoff was set to 8 kHz to minimize the influence of low frequency noise from boats and weather. The high frequency cutoff was set to 95 kHz to minimize aliasing effects. Spectra of each detected signal were calculated using 2.56 ms of data and a 512-point Hann window centered on the click. Clicks with a signal-to-noise ratio (SNR) of less than 10 dB were discarded. Due to frequent detections of sperm whales, all clicks with peak frequencies below 15 kHz were not further considered in the analysis. All clicks, independent of beam direction, were used for the spectral and temporal characterization of FM pulses. Duration

Table 1. Echolocation pulse parameters of FM pulses compared to literature values.

	Unit	Aleutian bw	Blainville's bw[a]	Cuvier's bw[b]	Gervais' bw[c]	Palmyra bw[d]	Cross bw[e]
Peak frequency	kHz	48.4 (45.7, 63.7)	–	–	–	45	–
Center frequency	kHz	54.7 (49.2, 61.8)	38	42	~45	46	>70
−10 dB bandwidth	kHz	20.3 (9.8, 38.7)	25	23	~25	26	>50
Teager energy duation	μs	425 (270, 660)	–	–	–	360	–
98% energy duration	μs	115 (65, 200)	270	200	200	130	985
IPI	ms	77 (16, 190)	370	380	270	230	110
Sweep rate	kHz/ms	92 (4, 160)	110	–	–	253	70

[a] Johnson *et al.* (2006).
[b] Zimmer *et al.* (2005).
[c] Gillespie *et al.* (2009).
[d] Baumann-Pickering *et al.* (2010).
[e] McDonald *et al.* (2009).
Note: Number of pulses = 18,336; values are given as medians with 10th and 90th percentile in brackets; bw = beaked whale.

was calculated as Teager energy duration (Soldevilla *et al.* 2008) as well as 98% energy duration (Au 1993). Center frequency, bandwidth and IPI were calculated (Au 1993). All sequences were manually inspected to assess group size by counting the approximate number of overlaying sequences in the time series, by noting amplitude similarities with corresponding IPIs. The automated IPI calculation was not adjusted for periods with multiple animals signaling; however, only signals with high amplitude FM pulses were used based on the 10 dB SNR constraint, which reduced coherent detections of multiple animals. On the other hand, an increased number of shorter IPIs than the median were expected to reflect multiple animals calling simultaneously.

The manual inspection of the long-term HARP data revealed unknown signals with upsweep frequency modulation reminiscent of echolocation pulses produced by beaked whales. Fifteen sequences with 18,336 signals with SNRs larger than 10 dB were found that had similar FM pulse characteristics. There were between two and five sequences per week in July but there was only one sequence in both June and August. The detections showed no particular diel preference but were distributed evenly throughout the day. The echolocation sequences had a mean duration of 9 ± 5 min. Nine out of the 15 sequences contained FM pulses of more than one and up to four animals.

The FM pulses had frequency content between 40 and 100 kHz with a median peak frequency of 48 kHz (Table 1, Fig. 1B–D). The median IPI was 77 ms (Fig. 1E). The IPI distribution had a very distinct peak, representing the single animal preferred IPI. The fairly large number of shorter inter-pulse intervals than the median was largely due to multiple animals calling simultaneously. Eleven buzzes were found with IPIs between 8 and 2 ms. Median duration of theses buzzes was 600 ms with a minimum of 200 ms and a maximum of 1,600 ms. There were 4–7 transitional

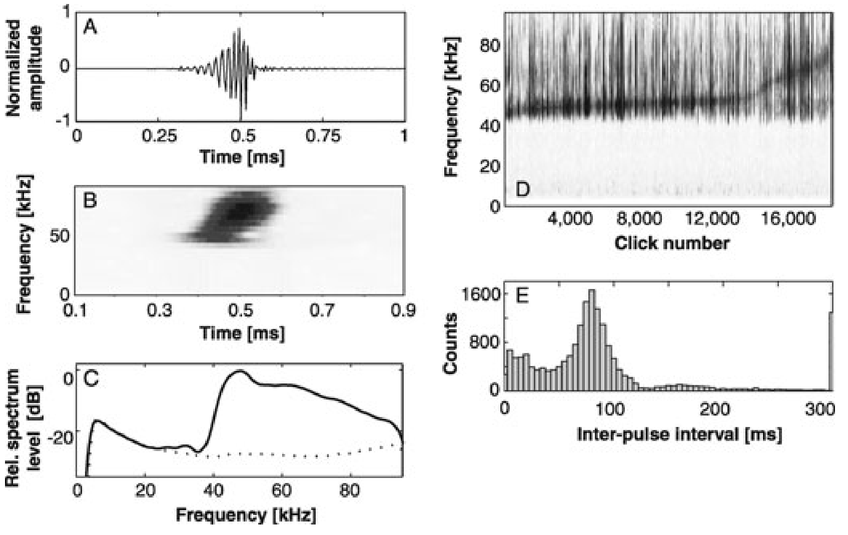

Figure 1. FM pulses recorded near the Aleutian Islands. (A) Time series and (B) spectrogram of FM pulse (100 point FFT, 99% overlap). (C) Mean spectra (solid line) and mean noise (dashed line) of all clicks. (D) Concatenated spectrogram of all clicks sorted by peak frequency showing most of the peaks to appear within 45–55 kHz and a lesser number of higher peak energy. (E) Histogram of IPIs of all clicks in 5 ms bins.

clicks with reduced IPIs between regular FM pulses and the following buzz IPIs (Fig. 2). Buzz signals were the same FM signal type as the preceding FM pulses, but approximately 20 dB lower in sound pressure level, which reduced the SNR, resulting in apparently shorter signal durations.

Only three species of beaked whales are currently known to use the waters around the Aleutian Islands. Cuvier's beaked whale signals are well described (Zimmer *et al.* 2005). Their FM pulses range between 20 and 60 kHz with a regular IPI of approximately 400 ms and are therefore distinctly different spectrally and temporally from

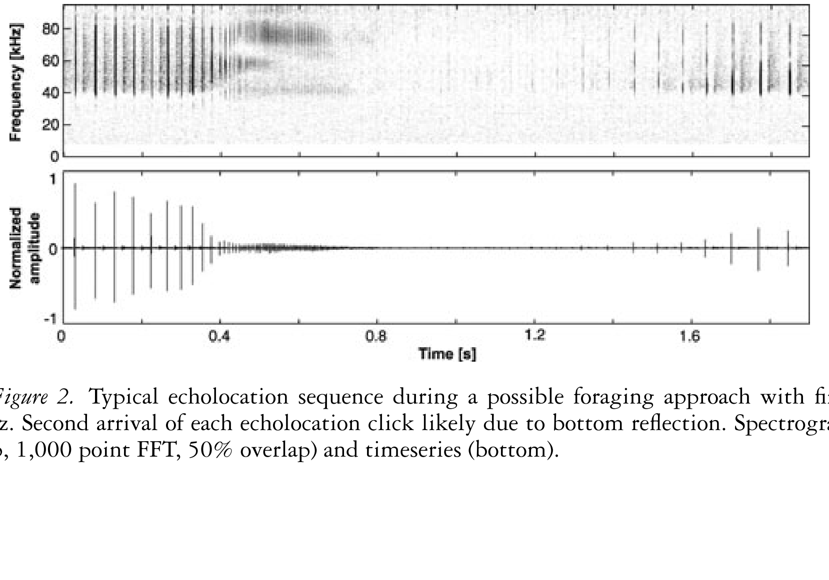

Figure 2. Typical echolocation sequence during a possible foraging approach with final buzz. Second arrival of each echolocation click likely due to bottom reflection. Spectrogram (top, 1,000 point FFT, 50% overlap) and timeseries (bottom).

the newly described FM pulses presented here. While the majority of the beaked whale signals detected was of the new type, there was a single sequence of Cuvier's beaked whale pulses in the HARP data set. Baird's beaked whales produce echolocation clicks with peak frequencies below 30 kHz (Dawson *et al.* 1998, authors' unpublished data). No Baird's beaked whale signals were detected in these data. Assuming that FM pulses are sufficient to classify for beaked whales, then Stejneger's beaked whales are most likely the species producing these new FM pulses. In comparison to FM pulses of other currently described signals of beaked whale species (Table 1), the presumed Stejneger's beaked whale FM pulses have one of the highest frequency content and the shortest IPI. The very short IPIs are more like those of dolphins (*e.g.*, Au 1993) than other beaked whales of which we currently know (Table 1). Buzz signals for two *Mesoplodon* species have been reported to be of a different signal type (Johnson *et al.* 2006, Baumann-Pickering *et al.* 2010), as they were not FM, transient clicks. This does not seem to be the case for all *Mesoplodon* species, as shown here for Stejneger's beaked whales, where buzz signals kept the FM structure.

Stejneger's beaked whales seem to utilize the Sitkin Canyon area selectively with more detected sequences during several consecutive weeks, followed by several weeks of no detections. If this behavior persists in a longer time series, then correlations with physical and biological oceanographic features may provide further insight to prey abundance. Unlike the beaked whales at Cross Seamount, Hawaii (McDonald *et al.* 2009), which demonstrated a distinct diel preference, this species of beaked whale seemed to dive, echolocate, and likely forage at any time of day.

Since the first record of a mass stranding of three Stejneger's beaked whales on Adak Island in 1975, a mass stranding of this species with two or more animals has occurred on an average of every 3 yr in the Aleutian Islands (Table 2). This is an alarmingly high number of mass strandings (11 with two or more animals) from unknown causes with potential population risks, especially considering the strong likelihood that some mass strandings on these remote islands are missed. Based on stranding records, Stejneger's beaked whale is the best known species of the genus *Mesoplodon* in both the western and eastern North Pacific, but mass strandings in Japan are much less frequent than in the Aleutians and have consisted of fewer individuals. There are about 40 recorded individuals which have stranded from the Aleutian Islands of which 30 are from the mass stranding events reported here. As of 2005, there were about 118 recorded individuals that stranded in northern Japan (Yamada in Brownell *et al*. 2006), of which only four were from mass stranding events, with only two individuals each (D'Amico *et al*. 2009).

Due to the remote location and inaccessible sea during much of the year, long-term autonomous acoustic monitoring may lead to further understanding of the behavior and ecology of this understudied species of beaked whale, and might provide guidance for mitigating impacts leading to mass strandings.

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Table 2. Mass stranding events of Stejneger's beaked whales in the Aleutian Islands; n = number of animals.

Location	Date	n	Comments	References
Kuluk Bay, Adak Island	17 July 1975	3	Fresh dead	Walker and Hansen (1999)
Cable Bay, Tanaga Island	29 June 1979	2	Dead, same condition[a]	Loughlin *et al.* (1982)
Kuluk Bay, Adak Island	28 July 1980	4	Alive	Walker and Hansen (1999)
Kuluk Bay, Adak Island	18 July 1981	2	Alive, fresh dead	Walker and Hansen (1999)
Kuluk Bay, Adak Island	11 November 1986	3	2 Alive, 1 dead	Walker and Hansen (1999)
Kuluk Bay, Adak Island	11 December 1988	2	Fresh dead, found 12 December	Walker and Hansen (1999)
Kuluk Bay, Adak Island	29 August 1994	4	Fresh dead, found 27 August	Walker and Hansen (1999)
Kuluk Bay, Adak Island	20 August 1999	2	Fresh dead	MME 16317 and 16318[b]
Kalekta Bay, Unalaska	31 August 2002	2	Alive	STR 14019
Shemya Island	1 September 2005	2	Dead	UAM 85500[c]
Atka Island	14 August 2007	4	Alive	Anonymous 2007

[a] Personal communication from Tom Loughlin (retired), National Marine Mammal Laboratory, NOAA Fisheries, Seattle, WA, March 2011.
[b] MME Marine Mammal Event Program records and STR sequential numbers for stranding records in files of Division of Mammals, U.S. National Museum of Natural History.
[c] UAM, University of Alaska Museum, Fairbanks.

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