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Antarctic beaked whale echolocation signals near South Scotia Ridge

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Although beaked whales comprise the second-largest family of cetaceans, they are one of the most poorly known groups of all large mammals (Barlow *et al.* 2006, Jefferson *et al.* 2008). Visual sightings and species identification of beaked whales can be extremely difficult due to their highly elusive behavior and prolonged, deep foraging dives with short surface intervals (Tyack *et al.* 2006). However, beaked whales are the only cetaceans known to use frequency modulated (FM) upsweep pulses to echolocate, and these signals appear to be species-specific in their spectral and temporal characteristics (*e.g.,* Gillespie *et al.* 2009; McDonald *et al.* 2009; Baumann-Pickering *et al.* 2010; Rankin *et al.* 2011; Baumann-Pickering *et al.* 2013*a*, *b*, *c*). As a result, passive acoustic monitoring is a highly useful technique to investigate the behavioral ecology of these cryptic cetaceans, particularly in remote areas and over long periods of time (Baumann-Pickering *et al.* 2014).

At least five species of beaked whales are known to occur in the Southern Ocean waters south of South America, including Arnoux's beaked whales (*Berardius arnuxii*), Cuvier's beaked whales (*Ziphius cavirostris*), Gray's beaked whales (*Mesoplodon grayi*), southern bottlenose whales (*Hyperoodon planifrons*), and strap-toothed whales (*Mesoplodon layardii*) (MacLeod *et al.* 2006). Of these five species, an acoustic description has only been made for the FM pulses produced by Cuvier's beaked whales (Zimmer *et al.* 2005). Arnoux's beaked whales appear to have similar frequency characteristics (Rogers and Brown 1999) to its sister species in the Northern Hemisphere, Baird's beaked whale (*Berardius bairdii*) (Baumann-Pickering *et al.* 2013*b*), but a full description of its FM pulse cannot be made from the existing band-limited recordings. Due to the

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various drawbacks involved with visual surveys and the challenges of working in Antarctic waters (Richardson *et al.* 2012), information on the abundance and distributions of Southern Ocean beaked whales is lacking, and little is known of their natural history.

We conducted a combined visual and acoustic shipboard survey of cetaceans in Antarctic waters in February 2014. Sampling effort was concentrated near the South Orkney Islands, South Shetland Islands, and Antarctic Peninsula (Fig. 1). Visual observations were conducted during daylight hours, subject to weather and sea state conditions, by a team of two observers searching with 7× hand-held binoculars and the unaided eye. Data on species identity, group size, and GPS position were recorded for all sightings.

A four-element oil-filled hydrophone array was towed 200 m behind the vessel at an average depth of 10–15 m at speeds between 7 and 10 knots. Each element of the array was equipped with an omni-directional sensor (BII-7011 Type 3, Benthowave Instrument Inc., Collingwood, Ontario, Canada) that had a sensitivity of −204 dB re V/μPa and an approximately flat frequency response of ±2 dB from 30 Hz to 200 kHz. The sensors were connected to custom-built preamplifier boards and band-pass filters. All the preamplifiers had a uniform gain of 40 dB; three with 1–90 kHz bandwidth, and one with 1–200 kHz bandwidth (−3 dB points). Each hydrophone signal was transmitted over a balanced pair of wires and received differentially, providing common-mode noise protection and an additional 6 dB of gain. The preamplifiers were calibrated in the laboratory to provide a quantitative analysis of the

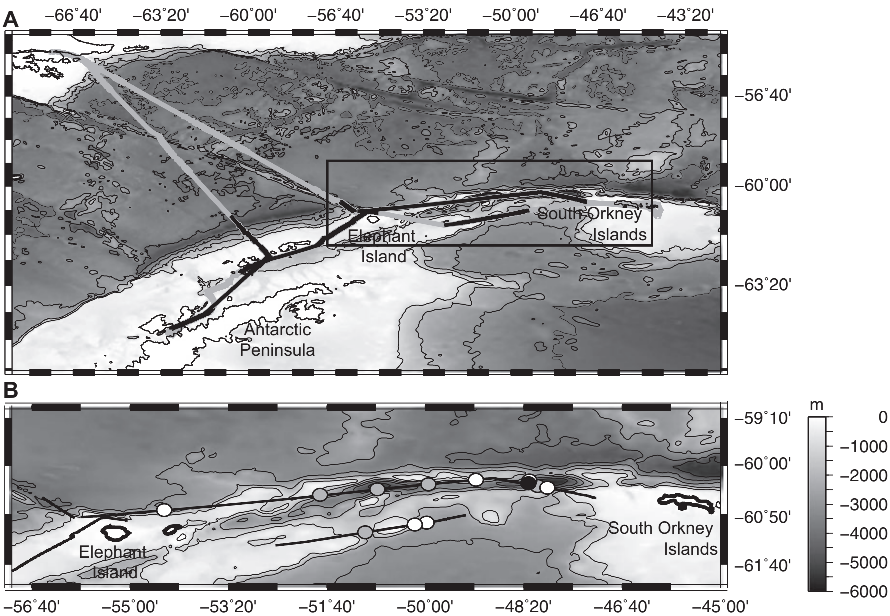

Figure 1. Bathymetric map of the area of putative beaked whale acoustic encounters. (A) Vessel tracklines with acoustic effort indicated in black. (B) White circles: sequences used in Antarctic BW29 analysis; gray circles: sequences containing ≤10 pulses excluded from analysis; black circle: Antarctic BW37 sequence.

received sound field. Each preamplified element was high-pass filtered at 200 Hz to decrease flow noise at low frequencies. The calibrated system response was corrected for during analysis. The mid-frequency 1–90 kHz bandwidth hydrophone channels were recorded at a 192 kHz sample rate using a MOTU 896HD (Mark of the Unicorn, Cambridge, MA). The high-frequency 1–200 kHz bandwidth channel data were recorded at a 500 kHz sample rate using an Avisoft UltrasoundGate 116 (Avisoft Bioacoustics, Berlin, Germany). Both analog-to-digital converters had a 16-bit quantization. Towed array data were recorded directly to a computer hard-disk drive. An acoustic technician monitored the incoming signals from the towed array by visually scanning a real-time scrolling spectrogram in Ishmael 1.0 (available at http://www.bioacoustics.us/ishmael.html) and listening on headphones, and notified the visual observers of any acoustic encounters *via* radio communications. The start and end times were noted for all observed acoustic encounters, and the GPS position and track was also logged. Acoustic surveys were generally conducted while on-effort visual observations were underway, but on three occasions the towed hydrophone array was left unmonitored to continuously record overnight. A total of 102 h of acoustic recordings were obtained.

Postcruise signal processing was performed on data from a mid-frequency towed array channel using custom routines in MATLAB (Mathworks, Natick, MA). Towed array recordings were visually inspected for echolocation signals using the MATLAB-based custom software program *Triton* (Wiggins and Hildebrand 2007). Long-term spectral averages (LTSAs) were calculated in *Triton* for visual analysis of the cruise 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 nonoverlapped 10 ms Hann-windowed frames. The resulting long-term spectrograms have a resolution of 100 Hz in frequency and 5 s in time. When acoustic signals were noticeable in the LTSA, the sequence was inspected more closely. Start and end times of all cetacean acoustic encounters were noted, and those with FM echolocation pulses were used for further analysis.

The towed array data revealed upsweep FM pulses of unknown origin, likely produced by beaked whales. All acoustic encounters with these FM pulses occurred in deep waters along the South Scotia Ridge while the vessel was in transit between the South Shetland Islands and South Orkney Islands (Fig. 1). Associated visual confirmations of the animals in question were not obtained due to poor visibility, adverse sea conditions, and presumably dives by the animals during which echolocation occurred at depth (Johnson *et al.* 2004). However, a sighting of an unidentified species of beaked whale occurred on 20 February 2014 at 0950 GMT, shortly before an acoustic encounter was detected (Table 1).

All of the putative beaked whale echolocation signals were FM pulses, and no other click types were observed within these acoustic detections. To obtain statistical values of the FM pulse parameters, individual echolocation signals within the towed array recordings were automatically detected using a two-step approach (Roch *et al.* 2011). In the first step, signals were detected in the spectral domain within an approximate start and end point defined as 12.5% of the frequency bins larger than an 8 dB threshold across a defined bandwidth of 10–90 kHz. The second step determined the exact start and end points using a Teager energy operator, thus resulting in signal durations (Kaiser 1990, Kandia and Stylianou 2006). The waveforms and spectrograms of all detections were reviewed in WaveSurfer (available at http://www.speech.kth.se/wavesurfer/) to eliminate any false signals within the automatic

Table 1. Summary of putative beaked whale acoustic encounters from towed array data. Signal count refers to the number of automatically detected FM pulses above detection threshold used for characterization of the Antarctic BW29 signal type described herein (the sequences containing 10 or fewer FM pulses were not included in analysis).

Encounter ID	Date/time (GMT)	Latitude	Longitude	Signal count
1	19 February 2014 2309–2315	60°45.7′S	54°25.1′W	85
2	20 February 2014 0718–0719	60°30.1′S	51°46.9′W	0
3	20 February 2014 0725–0728	60°30.1′S	51°46.9′W	0
4	20 February 2014 0747–0748	60°30.1′S	51°46.9′W	0
5	20 February 2014 1007–1007	60°24.6′S	50°48.7′W	0
6	20 February 2014 1244–1245	60°19.4′S	49°56.8′W	7
7	20 February 2014 1516–1523	60°14.7′S	49°8.3′W	232
8	20 February 2014 1724–1730	60°15.4′S	48°14.2′W	340
9	20 February 2014 1812–1817	60°18.3′S	48°15.1′W	10
10[a]	20 February 2014 1820–1821	60°18.3′S	48°15.1′W	6
11	20 February 2014 1850–1851	60°21.0′S	48°5.7′W	2
12	20 February 2014 1926–1928	60°22.9′S	47°55.8′W	73
13	23 February 2014 1703–1705	60°58.5′S	49°58.6′W	69
14	23 February 2014 1744–1751	61°0.3′S	50°10.4′W	455
15	23 February 2014 2029–2030	61°8.2′S	51°1.0′W	1

[a]Antarctic BW37 signal.

detections. Echolocation click trains were identified based on their temporal, spectral, and amplitude features. Signals that appeared to be echoes of these click trains or other random and impulsive noise, primarily originating from the ship, were removed. The sequences were then digitally filtered with a 10-pole Butterworth bandpass filter with a pass-band between 3 kHz and 95 kHz. The low frequency cut-off was set to minimize the influence of low frequency noise from the vessel. Peak and center frequencies, as well as −3 and −10 dB bandwidths were calculated using methods from Au (1993). Peak frequency values were computed between 8 and 95 kHz, disregarding low frequency noise peaks that may have occurred below 8 kHz. Inter-pulse intervals (IPIs) were taken from the start of an FM pulse to the start of the previous one. Echolocation pulses with IPIs less than 100 ms or greater than 700 ms were not included in the analysis of IPI, in order to adjust for periods of multiple animals signaling simultaneously and to delineate separate pulse trains within the same encounter. These cutoff values were chosen based on an IPI histogram of the Antarctic BW29 signal. Spectra of each detected signal and noise before each signal with a 0.25 ms break in between were calculated using 2.56 ms of data and a 512-point Hann window centered on the signal. Mean spectra and mean noise were computed by averaging individual spectra for all FM pulses combined. To calculate sweep rate, spectrograms of each FM upsweep pulse were computed (Hann window, 60-point DFT, 98% overlap). For each time bin, the frequency bin with the highest amplitude was selected. The beginning and ending of a sweep was defined by the −8 dB level from the highest power point, and a linear regression was calculated through the highest amplitude frequency bins over time. Negative values, which primarily result from FM pulses with low signal-to-noise ratios, were discarded from the sweep rate analysis.

Fourteen sequences were found that had similar FM pulse characteristics (Table 1), although eight of these were excluded from further analysis. These discarded sequences tended to originate from short, faint acoustic encounters containing weak signals that generally did not have high enough signal-to-noise ratios to be detected in the automatic two-step approach; as a result, only 10 or fewer pulses were automatically detected in each of these pulse trains and were of a quality to not be useful for a signal description. However, manual inspection of all eight of these eliminated sequences confirmed a match with the predominant signal type described below. The six remaining sequences, containing a total of 1,254 FM pulses meeting the criteria described above, were used for the description and characterization of the FM pulse type herein referred to as Antarctic BW29 (named after the peak frequency of this signal).

The median peak frequency of this echolocation signal was 28.7 kHz with a −10 dB bandwidth of 14.3 kHz (Table 2). Median pulse duration was about 600 µs and IPI was about 400 ms. In addition to the predominant Antarctic BW29 signal (Fig. 2), a single sequence was found to contain six FM pulses of higher frequency content (median peak frequency at 36.9 kHz) and shorter IPI (120 ms) than all other encounters. Although only one brief pulse train of this pulse type was present, this signal is tentatively categorized as Antarctic BW37 (Fig. 3).

The spectral and temporal characteristics of the Antarctic BW29 pulse type are distinctly different from the well-described signal of Cuvier's beaked whales (Zimmer *et al.* 2005, Baumann-Pickering *et al.* 2013*c*) (Fig. 4). Similarly, this signal is unlikely to belong to Arnoux's beaked whales, the largest of the Antarctic beaked whales, which is expected, based on its size, to have a lower peak frequency and to possibly have similar frequency characteristics to Baird's beaked whales (Rogers and Brown 1999, Baumann-Pickering *et al.* 2013*b*). Based on the beaked whale species known to occur in the Southern Ocean, the source of the FM pulses described herein is therefore most likely to be Gray's beaked whales, southern bottlenose whales, or strap-toothed whales. Strap-toothed whales are not the most probable candidate as they generally are not sighted south of 60°S (Kasamatsu *et al.* 1990, MacLeod *et al.* 2006); however, their southern range limit is not well-defined and thus they cannot be ruled out as a potential source of these FM pulses. In contrast, the southern bottlenose whale is one of the most abundant Antarctic cetaceans (Kasamatsu and Joyce 1995), and is commonly encountered near the South Shetland Islands (Santora and Brown 2010). However, sightings of Gray's beaked whales have occurred as far south as the Antarctic Peninsula and other Antarctic coastlines, particularly during the austral summer (Dalebout *et al*. 2004, van Waerebeek *et al.* 2010). Consequently, the identity of the beaked whale species producing the Antarctic BW29 signal cannot be

Table 2. Signal parameters for the Antarctic BW29 and BW37 echolocation FM pulses given as median values with 10th–90th percentiles of distribution in parentheses.

	BW29 (n = 1,254)	BW37 (n = 6)
Peak frequency (kHz)	28.7 (26.6–32.6)	36.9 (36.0–37.1)
Center frequency (kHz)	28.7 (24.9–32.0)	36.6 (35.0–37.7)
−3 dB bandwidth (kHz)	6.0 (4.1–9.4)	6.4 (5.1–6.9)
−10 dB bandwidth (kHz)	14.3 (9.0–19.5)	13.1 (10.7–14.4)
Teager-energy duration (µs)	586 (391–782)	662 (612–704)
IPI (ms)	403 (226–514)	119 (117–127)
Sweep rate (kHz/ms)	45.0 (24.5–68.2)	36.9 (26.9–41.7)

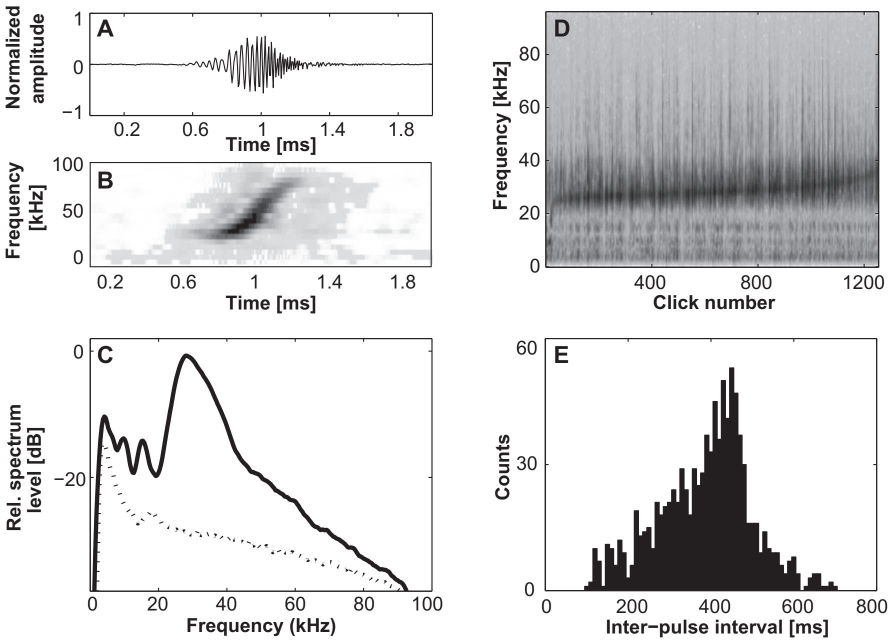

Figure 2. Antarctic BW29 FM pulse type. (A) Time series and (B) spectrogram of FM pulse (Hann window, 40 point FFT, 98% overlap). (C) Mean spectra of all pulses (solid line) and mean noise before each pulse (dashed line) (Hann window, 512-point FFT). (D) Concatenated spectrogram of all pulses sorted by peak frequency, showing most of the energy to occur within 25–40 kHz. (E) Histogram of IPIs of all pulses.

deduced strictly based on where the acoustic recordings were collected, and also given that sighting records as well as numbers on abundance are highly unreliable.

The Antarctic BW29 signal has similar spectral properties to that of the mesoplodont Blainville's beaked whale (*Mesoplodon densirostris*) (Fig. 4), also showing one smaller spectral peak below its main energy, but with overall lower peak and center frequencies and longer IPIs (Johnson *et al.* 2006, Baumann-Pickering *et al.* 2013*c*). It appears very distinct from northern bottlenose whales (*Hyperoodon ampullatus*) (Wahlberg *et al.* 2011), which could possibly have a similar signal type as its sister species, the southern bottlenose whale. Because its spectral shape is reminiscent of mesoplodont signals, the Antarctic BW29 FM pulse is possibly produced by Gray's beaked whales or strap-toothed whales.

Conversely, there may be a negative correlation between body length and center frequency in beaked whales (Baumann-Pickering *et al.* 2013*c*), and thus an expected body size of the animal producing the unknown signal can be extrapolated. Maximum known sizes for Gray's beaked whales and strap-toothed whales are approximately 5.6 m and 6.2 m, respectively, whereas southern bottlenose whales reach body lengths of up to 7.5 m (Jefferson *et al.* 2008). Although the frequency content of BW29 roughly suggests an animal the size of the southern bottlenose whale (Baumann-Pickering *et al.* 2013*c*, fig. 7), there can be high levels of intraspecific variation in body length and the size-frequency relationship argument is greatly weakened by the elimination of Baird's beaked whale from the original analysis used for this rela-

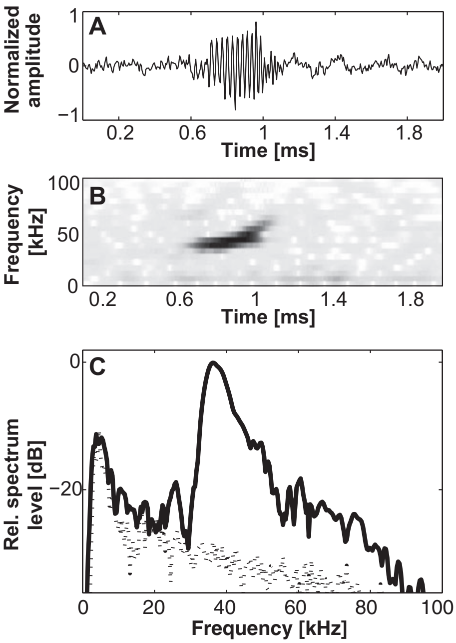

Figure 3. Antarctic BW37 FM pulse type. (A) Time series and (B) spectrogram of FM pulse (Hann window, 40-point FFT, 98% overlap). (C) Mean spectra (solid line) and mean noise (dashed line) of all pulses (Hann window, 512-point FFT).

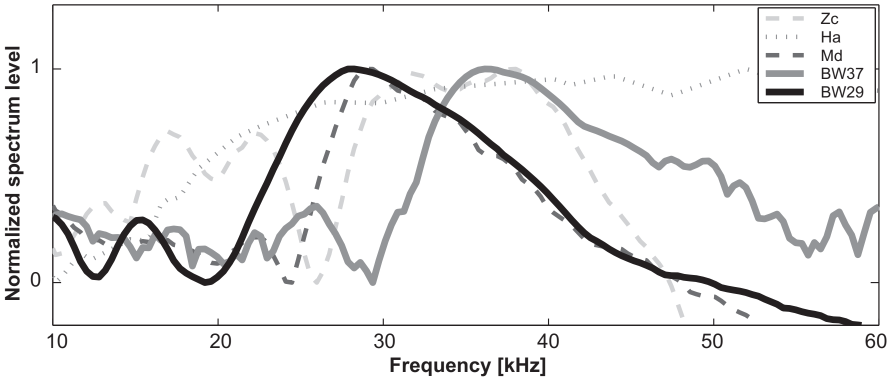

Figure 4. Mean spectra of Antarctic BW29 (bold black line, *n* = 1,254) and Antarctic BW37 (bold gray line, *n* = 6) FM pulses. Mean spectra of Cuvier's beaked whale (Zc, Baumann-Pickering *et al.* 2013*c*), northern bottlenose whale (Ha, Wahlberg *et al.* 2011), and Blainville's beaked whale (Md, Baumann-Pickering *et al.* 2013*c*) are denoted as thin dashed lines.

tionship. Accordingly, it is an insufficient method to draw robust species correlation conclusions.

Although the majority of the beaked whale signals detected were of the new type Antarctic BW29, a single sequence of higher frequency FM pulses with a shorter IPI was also present in the towed array data. Because only six FM pulses occurred during the Antarctic BW37 encounter, the observed pulses may not be highly representative of this signal type. Future recordings will hopefully become available in order to more thoroughly characterize this signal. It thus remains unknown whether this pulse train belongs to a different beaked whale species than the one producing the Antarctic BW29 FM pulse, or if it is the result of intraspecific variability in echolocation signals. If the aforementioned size-frequency relationship were to prove valid, it is possible that the southern bottlenose whale produces the Antarctic BW29 pulse type, whereas the higher frequency Antarctic BW37 pulse type could belong to the smaller Gray's beaked whale. Alternatively, it is possible that a single species could produce multiple FM signal types; however, to date this has not been shown for any species of beaked whale. Lastly, given that new species of beaked whale are still being discovered (Dalebout *et al.* 2002, 2014), the source of these Antarctic signals might be a species that has yet to be identified.

Because beaked whale FM pulses can be discriminated to species level, passive acoustic monitoring holds much potential for beaked whale research in Antarctic waters. Future work in this area could resolve the question of which animals are associated with the unknown echolocation signals described herein, and long-term passive acoustic recordings would increase our knowledge of the spatial distribution and relative abundance of these species (Baumann-Pickering *et al.* 2014). Ongoing data collection would further allow us to explore diel and seasonal patterns of these poorly known marine mammals (McDonald *et al.* 2009). Recordings from an animal-attached acoustic tag or collected from a towed hydrophone array in parallel with a confirmed visual sighting would allow us to make acoustic descriptions for beaked whale species whose signals have not yet been characterized, and to also provide definitive species classifications of the two unknown signals presented in this study. Furthermore, it is also sometimes possible to assign species identity based on geographic occurrence and exclusion of other species (Baumann-Pickering *et al.* 2013*a*), and thus the use of a number of autonomous long-term acoustic instruments would likely prove useful in investigating Antarctic cetaceans.

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