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An acoustic survey of beaked whales at Cross Seamount near Hawaii (L)

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An acoustic record from Cross Seamount, southwest of Hawaii, revealed sounds characteristic of beaked whale echolocation at the same relative abundance year-around (270 of 356 days), occurring almost entirely at night. The most common sound had a linear frequency upsweep from 35 to 100 kHz (the bandwidth of recording), an interpulse interval of 0.11 s, and duration of at least 932 μs. A less common upsweep sound with shorter interpulse interval and slower sweep rate was also present. Sounds matching Cuvier's beaked whale were not detected, and Blainville's beaked whale sounds were detected on only one occasion.
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I. INTRODUCTION

Two species of beaked whales, Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*), are known to use frequency upswept echolocation sounds, in contrast to the short duration clicks of most echolocating cetaceans. Cuvier's beaked whales echolocation sounds are 200 μs duration linear upsweeps with a center frequency near 42 kHz, interpulse interval (IPI) of 0.38 s, source level up to 214 dBp.p. 1 μPa at 1 m, and bandwidth of 23 kHz (Zimmer *et al.*, 2005). The characteristic sounds of Blainville's beaked whales are only subtly different from Cuvier's beaked whales, with a sharper cutoff below 25 kHz (Johnson *et al.*, 2006). We describe a one-year-long acoustic study of the most common type of whale recorded at Cross Seamount; a preliminary analysis was described by Johnston *et al.* (2008). It is thought that these sounds were produced by a species of beaked whale other than Cuvier's or Blainville's.

II. METHODS

A high-frequency Acoustic Recording Package or HARP (Wiggins and Hildebrand, 2007) was placed on top of Cross Seamount (18° 43.325′ N, 158° 15.230 W) at 395 m depth,

290 km south of Oahu. The HARP frequency response is 2 dB more sensitive at 40 kHz than at 25 kHz and 12 dB more sensitive at 80 kHz than at 40 kHz, rolling off above 80 kHz. The electronic noise floor of the HARP is equivalent to the ambient ocean noise in sea state 5 at frequencies above 3 kHz. The HARP sampled at 200 ksamples/s for five of every 25 min from 26 April to 28 October 2005 and from 11 November 2005 to 11 May 2006.

Automated detection of beaked whale sweeps was performed using spectrogram correlation with frequency bounds of 40–85 kHz and a sweep rate of 0.075 kHz/μs. The detector provided a low false alarm rate ($<10\%$) at the cost of missing a larger percentage ($>75\%$) of sweeps. All detections were reviewed to eliminate false detections. Call sequences occurring less than 0.25 s between sweeps were counted as a single detection; thus a continuous train of sweeps was counted as one detection.

The highest amplitude pulse within each detection was selected for a detailed analysis to minimize range and orientation bias. Pulse modulation was measured by least squares fitting of the instantaneous frequency with linear and second order equations before applying the HARP response function. When signal to noise ratio was poor, the pulse was discarded, leaving about 15 000 pulses to compute start frequency, modulation rate, curvature of modulation rate, and duration.

III. RESULTS

The most common type of pulse (Fig. 1) was often truncated by the 100 kHz bandwidth limit, with some leakage through the antialias filter. The pulse bandwidth [Fig. 1(c)]

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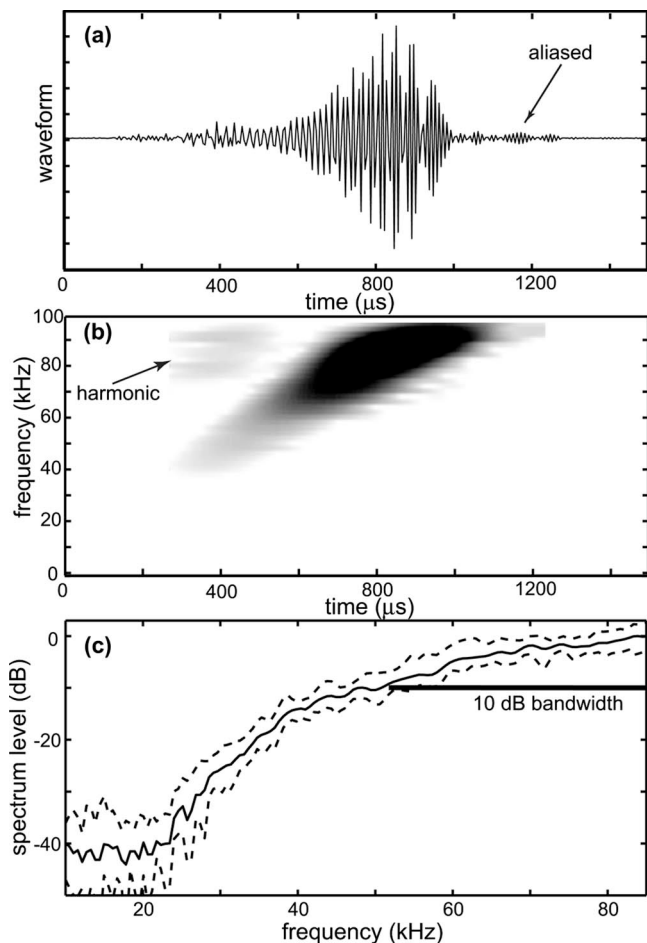[e] Electronic mail: jeffrey.polovina@noaa.gov

FIG. 1. (a) Waveform and (b) spectrogram (Hann window, 60 sample fast Fourier transform, 59 sample overlap) of the echolocation sweep. (c) Mean received spectrum level for 20 of the highest amplitude echolocation sweeps, with 10% and 90% shown as dashed lines and 10 dB bandwidth after applying the instrument frequency response function. The waveform shown in (a) and the spectrogram (b) are not corrected for instrument response and thus correspond more or less to the signal to noise ratio of the signal, given the instrument response approximately corresponds to the change in ocean ambient noise with frequency. The spectra (c) has been corrected for instrument frequency response.

may shift to higher frequency with higher bandwidth recordings. The 20 highest amplitude signals had an average duration of 987 μs [standard deviation (SD)=82], with a shortening bias because of bandwidth limitations. Received level for these sweeps was 145 dBp.p. re 1 μPa over 50–85 kHz. Other sounds from 50 kHz echo-sounders, sperm whales, and probable pilot whales commonly had higher received levels. Linear and quadratic fitting was applied to 15 211 of the highest amplitude sweeps. The quadratic fits randomly distributed about the linear sweep rate. For the linear fits, the mean start frequency was 35.1 kHz (SD=3.6), the sweep rate was 0.069 kHz/μs (SD=0.019), and the duration (downward biased from bandwidth limitation) was 932 μs (SD=186).

The detector found 25 612 beaked whale echolocation sounds in the first deployment (185 days), and 16 451 in the next (181 days). Manual inspection revealed that about 80% of the sweeps were missed by the detector. The high percentage of missed sweeps was due to seafloor reflections, result-

ing in smeared arrivals when the animals were near the seafloor. This caused a bias for better detection when arrival angles were more than a few degrees above the horizontal. A bias in seasonal call detection would result if the whales have a seasonal change in feeding depth relative to the seafloor.

Three signal categories were evident: (1) a single echolocation sweep, (2) long duration sweep trains, and (3) short intersweep interval bursts. Approximately 60% of the detections had only a single sweep present, while 40% consisted of sweep trains. The short IPI burst category was less than 0.5% of the total detections. When more than one sweep occurred in sequence (a sweep train), the durations of these sequences had a mean of 0.62 s and a median of 0.35 s. These data were best fit with a lognormal distribution (σ =0.95, μ=−0.95, K−Sp<0.001). A subset of sweeps with the highest signal levels had a mean IPI of 110 ms (SD =35).

Short IPI bursts make up a third temporal pattern, their 0.5% occurrence probably being an underestimate. These bursts had a longer IPI between the first two and last two sweeps and are clustered in time. The frequency modulation of the sweeps in the short IPI bursts is nonlinear with decreasing sweep rate toward higher frequencies. The highest amplitude sweeps, selected from each of 227 short IPI bursts, were fitted with quadratic equations. The mean start frequency was 37.2 kHz (SD=7.7), the slope was 0.070 kHz/μs, the curvature was 0.000 018 (SD=0.000 010), and the end frequency was 89.1 kHz (SD=5.7). Unusual examples were found, some of which truncate abruptly near 60 kHz, inconsistent with frequency dependent attenuation, and few of these sweeps exceeded the 100 kHz recording limit. The mean IPI was 14.7 ms with SD of 3.8 ms (n =25) and mean duration of 1145 μs with SD of 282 μs (n =25). The first and last sweep of each sequence had a longer interval and was ignored for the IPI calculation. Multiple animals were producing sweeps 10% of the time when 200 randomly selected sequences were examined. This suggests a highly correlated occurrence, as total detection durations represent only about 0.4% of the total nighttime hours when the recorder was on.

Only 12 feeding buzzes were discovered when examining the 25 612 echolocation detections from the first deployment. These lacked the decreasing IPI of buzzes from Blainville's beaked whales and had no apparent relationship with the echolocation sweeps (Johnson *et al.*, 2008). Buzzes not associated with beaked whale echolocation sweeps were common throughout the recordings; thus the buzzes recorded adjacent to beaked whale echolocation sweeps may be coincidental recordings from another species, such as false killer whales (*Psuedorca crassidens*). During the second deployment more buzzes were coincident with the beaked whale signals, but the overall presence of buzzes was greater, suggesting a seasonal increase in the other species believed to be producing the buzzes.

Detections occurred in about 50% of the nighttime hours monitored, over the duration of the two deployments (Fig. 2). Detections had a strong diel pattern (Fig. 3), with a peak near sunset and nearly all sounds occurring during darkness.
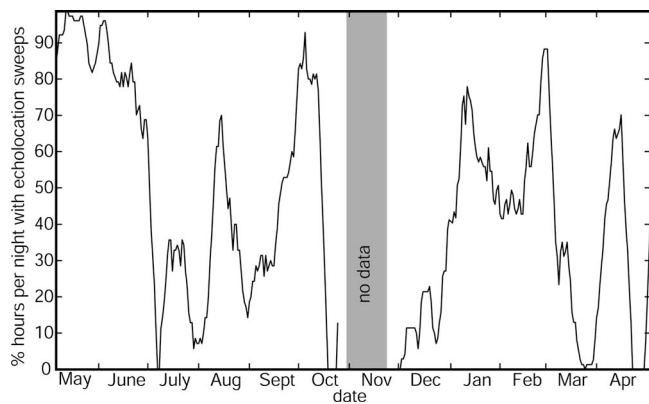
FIG. 2. Daily presence of frequency swept sounds (42 063 verified detections) plotted as the percentage of 1 h intervals in the night which contains one or more detections using a 7 day smoothing filter. Percentage is calculated starting at sunset, ignoring fractional hours near sunrise. Each 1 h time window containing a beaked whale sound was counted, the integer total of these being divided by the integer number of hours in the night.

Sounds nearly stop about 1 h before sunrise. Sounds occur during the day but were too rare to be visible in Fig. 3. Sounds matching Cuvier's beaked whale were not detected and sounds matching Blainville's beaked whales were detected only once [February 11, 2006 at 15:18 Greenwich Mean Time (GMT)].

IV. DISCUSSION

The sweeps reported here have longer durations, higher peak frequencies, shorter IPIs, and greater variability than either Cuvier's or Blainville's beaked whale sounds (Zimmer *et al.*, 2005; Johnson *et al.*, 2006). The Cross Seamount sounds may be from either a geographic variant of Cuvier's or Blainville's beaked whales, Longman's beaked whale (*Indopacetus pacificus*) or another beaked whale species not yet known to occur in this region. The difference in inter-pulse interval, the relatively shallow water depths, and the strong diel pattern observed here argue against these signals being a geographic variant of Cuvier's or Blainville's echolo-
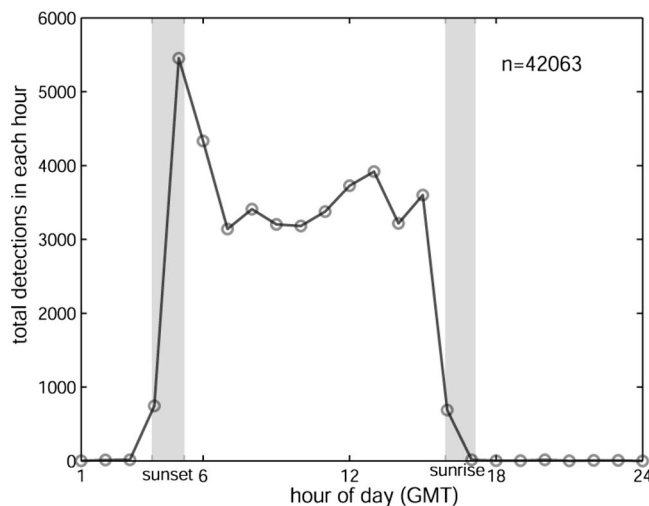

FIG. 3. The diel pattern is shown for all beaked whale sounds. The gray shaded regions show the seasonal range of sunrise and sunset times. The hour of day is in GMT.

cation. An additional distinction of the echolocation described here is the association with the short IPI burst sounds.

The near absence of other beaked whale echolocation sounds at Cross Seamount provides evidence of niche differentiation. Given the relatively short detection ranges for the Cross Seamount beaked whale sounds (<3 km), and their frequent occurrence, it appears that a visual sighting effort may identify the species during calm weather.

The whale species associated with these sounds is present year-around since gaps in detection are brief. Meso-scale oceanographic patterns that might contribute to the observed seasonal variations were considered, but none were found. Previous beaked whale studies have not found evidence of diel foraging patterns (Baird *et al.*, 2008). It is possible that the whales recorded in this study continue to produce sounds during the day but migrate horizontally off the edge of the seamount beyond the detection range of the recorder. This is unlikely because of the abrupt transitions near sunrise and sunset and the near absence of echolocation during the day.

Either or both horizontal and vertical diel migrations of prey species may cause the observed diel foraging activity if the whales feed within the scattering layer. An asymmetry has been observed in scattering layer movements off Hawaii where the layer moves down well prior to sunrise, mirroring the pattern seen in Fig. 3 (Benoit-Bird and Au, 2006) where foraging stops well before sunrise, providing support for this hypothesis. Preliminary results from active acoustic surveys at Cross Seamount show deep scattering layer migration asymmetry (Domokos PIFSC pers. comm. 2008).

Feeding buzzes are of lower amplitude than normal echolocation signals, so it is possible that the beaked whales at Cross Seamount are producing buzzes that were not detected, although this is unlikely. Otherwise we are left with the mystery of how these animals navigate during the terminal phase of prey capture. The short IPI bursts do not show either the decreasing interval or the very short intervals typical of prey capture attempts by Cuvier's beaked whales (Johnson *et al.*, 2008). These short IPI bursts are more reminiscent of codas in sperm whales, which are believed to serve a social function (Rendell and Whitehead, 2004).

Daylight would reach the top of Cross Seamount at sufficient levels for vision. Foraging effectiveness may be compromised during the day if feeding on bioluminescent species may be more difficult to detect or if prey can see their potential predator. The bioluminescent prey argument gains strength from the lack of feeding buzzes in these data. Wood and Evans (1980) found that a blindfolded dolphin could track live fish without echolocating, arguably using passive listening for fish swimming sounds. Perhaps these beaked whales use echolocation to get within passive listening range of prey and then switch to passive acoustics for a capture attempt. Work by Gannon *et al.* (2005) shows dolphins using passive listening to detect the presence of soniferous fish and then switching to echolocation to capture the potential prey. Different species of beaked whales may use both passive and active acoustics to forage, depending on their ecological niche.

Some signals had nearly vertical incidence angles on the recorder, as evidenced by the seafloor echo time delay. Since these whales were located directly above the hydrophone, and the hydrophone was 385 m below the sea surface, the range to the whale was less than 385 m. Assuming a source level the same as Cuvier's beaked whales, the range to the highest amplitude sweeps would be about 385 m. Since the Cross Seamount beaked whales were undoubtedly closer than 385 m, their source levels cannot be higher than those of Cuvier's beaked whale and are probably considerably lower. Harmonics are present with some signals [Fig. 1(b)] but are not always associated with high amplitude signals, suggesting that variability at the source controls the presence of harmonics.

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