Frequency synchronization of blue whale calls near Pioneer Seamount

Michael D. Hoffman
Department of Physics and Astronomy, San Francisco State University, San Francisco, California 94132

Newell Garfield
Department of Geosciences and Romberg Tiburon Center, San Francisco State University, San Francisco, California 94132

Roger W. Bland[a]
Department of Physics and Astronomy and Romberg Tiburon Center, San Francisco State University, San Francisco, California 94132

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Vocalizations of blue whales were recorded with a cabled hydrophone array at Pioneer Seamount, 50 miles off the California coast. Most calls occurred in repeated sequences of two-call pairs (***A***, then ***B***). The ***B*** call is a frequency-modulated tone highly repeatable in form and pitch. A model of this sound is described which permits detecting very small frequency shifts. ***B*** calls are found to be aligned in frequency to about one part in 180. This requires very fine pitch discrimination and control over calling frequency, and suggests that synchronizing to a common frequency pattern carries some adaptive advantage. Some possibilities for acoustic sensing by whales requiring this fine frequency resolution are discussed.
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I. INTRODUCTION

The vocalizing of the blue whale (*Balaenoptera musculus*) off the California coast has been studied by many researchers (Calambokidis *et al.*, 2007; Rivers, 1997; Clark and Fristrup, 1997; Stafford *et al.*, 1998, 2001; McDonald *et al.*, 2001; Oleson *et al.*, 2007; McDonald *et al.*, 2009). The most common pattern of vocalization consists of an alternation of two distinct calls, the "***A***" call and the "***B***" call. This repetitive sequence of calls is sometimes referred to as "song" (Thompson and Friedl, 1982), and has been associated with "fast traveling," as opposed to feeding or other behavior not involving directed travel (Calambokidis *et al.*, 2007; Oleson *et al.*, 2007). The ***A*** call consists of a series of pulses, with power peaking near 15 and 90 Hz. The ***B*** call has been described as a "moan," and consists of a frequency-modulated tone with fundamental near 16 Hz and a rich harmonic structure, descending in frequency throughout the call. Whales calling in a given season are observed to synchronize their calls in frequency (Rivers, 1997; Stafford *et al.*, 2001); however, this collective calling frequency has been decreasing steadily over the last 50 years (McDonald *et al.*, 2009; Oleson *et al.*, 2007).

In September of 2001 a cabled hydrophone array was installed on Pioneer Seamount, 50 miles off the California coast. This provided an opportunity to study a large sample of whale calls, and the tonal quality of the blue-whale ***B*** call made it suitable for a very accurate frequency determination. We hoped that this study would reveal interesting aspects of behavior of the blue whale. We have carried out an analysis of ***B*** calls which determines their central frequency to very high precision. We give the details of this analysis, and discuss possible implications for acoustic sensing by whales.

II. INSTRUMENTAL DETAILS

We have analyzed acoustic recordings from the Pioneer Seamount Underwater Observatory, established in 2001 by NOAA, the Pacific Marine Environmental Laboratory (PMEL) and San Francisco State University (SFSU) (Matsumoto *et al.*, 2003). A vertical array of four hydrophones was anchored at a point near the summit of Pioneer Seamount, at 36°21.2′ N, 123°26.1′ W, 998 m below sea level. The hydrophones were spaced 30 m apart, with the lowest 10 m above the anchor. The hydrophone signals were transmitted to shore via a marine communications cable. On land (on the site of the Pillar Point Air Force Station) the signals were digitized at 1000 Hz, and transmitted to PMEL. There the data were made publicly available in near real time (Matsumoto *et al.*, 2003), until it failed in 2002, possibly due to damage from fishing activity. The data reported here cover the time period of September 1 to November 24, 2001.

III. DATA ANALYSIS

The raw sound files were downloaded to SFSU for analysis. Figure 1 shows a spectrogram (plot of frequency *vs.* time) for one 15-min time series, which includes part of one of the clearer blue-whale calling sequences. The ***B*** call is seen as a slowly descending frequency band, with prominent first and third harmonics in this sequence. The presence of the first harmonic (the fundamental) was the most consistent

[a]Author to whom correspondence should be addressed. Electronic mail: rogerbland@gmail.com

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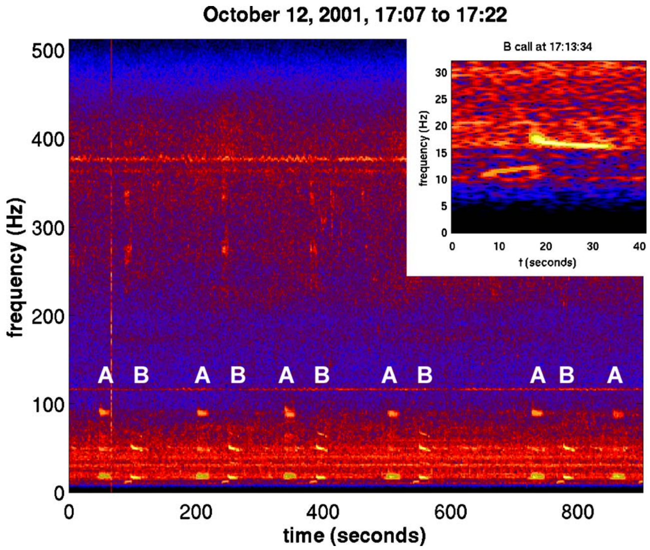

FIG. 1. (Color online) Spectrogram for a 15-min period showing a series of ***A-B*** calling pairs. (FFT made with 1024 points, Hanning window, 50% overlap.) The inset shows the fundamental of one ***B*** call on an expanded scale.

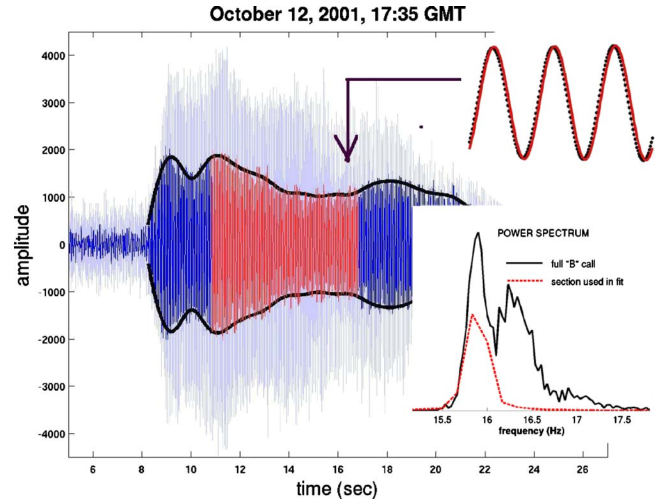

FIG. 2. (Color online) Signal from one ***B*** call. The light trace (largest variation) shows the unfiltered signal; the dark trace (smaller, full length) the signal after band-pass filtering; and the central part (roughly 11–17 s), the signal used in the least-squares fit. The heavy line shows the signal envelope used in the analysis (see text for details). The upper inset shows three cycles of signal (dots) and fitted function (line), taken from near the end of the fitted portion of the time series; the fit to the data is seen to be almost exact. The lower inset shows the power spectrum for the signal.

throughout our data set, and we only analyzed the frequency content of the fundamental. The interval between ***A-B*** calling pairs is about 130 s (Oleson *et al.*, 2007). It is common to see more than one such calling sequence present at one time.

To automate the data collection, a matched-filter computer algorithm (Stafford, 1995; Mellinger *et al.*, 2004) was used to detect blue-whale ***B*** calls. Pioneer Seamount is located near shipping lanes, and sounds in the frequency range of the blue-whale ***B*** call are often obscured by noise from passing ships. In addition, the intensity of observed ***B*** calls varies over a large range according to the distance of the calling whale from the hydrophones. For this reason we used a rather low detection threshold, resulting in a data sample including many false detections, mainly due to shipping noise, and a substantial number of ***B*** calls with rather noisy signals. This yielded a sample of 4378 detections. The separation of the clean whale calls in this sample from triggers due to noise is based on the fitting process described in the next section.

Visual scanning of ***B*** calls for stronger signals, like those seen in Fig. 1, show the call frequency to generally decrease with time, with a central section where the frequency is most nearly constant in time. We have carried out an analysis aimed at determining this central frequency as accurately as possible. This consists of (a) locating the center of the call in a reproducible way, and (b) matching the waveform of the call with a sinusoidal form, slowly decreasing in frequency with time, using nonlinear regression.

For each event, a 30-s time series centered on the trigger time was selected. Part of one such time series is plotted in Fig. 2, and the call is seen to be well centered, with the power concentrated in the central 15 s. The time series is band-pass filtered via FFT, keeping frequencies in the range 10–20 Hz, a frequency band including the fundamental of the ***B*** call with room to spare. (See power spectrum in Fig. 2.) This filtered signal is used in the remainder of the analysis. First an envelope is calculated which follows the peaks of the oscillating sound wave. Figure 2 also shows the filtered signal, and the envelope. It can be seen that the envelope bounds the signal rather accurately. The center-point of the signal is found using an energy-weighted average, with the square of the envelope function used to represent the energy in the wave.

The second stage of the analysis consisted of a least-squares fit to the filtered fundamental time series, to determine the frequency at the center-point. The fitting function is approximately sinusoidal, with the peaks following the predetermined envelope function, and the frequency varying slowly with time. The function used is given by

$$f(t) = e(t)\sin\varphi(t), \qquad (1)$$

where

$$\varphi(t) = \varphi_0 + 2\pi\left(f_0(t-t_0) - \tfrac{1}{2}\alpha(t-t_0)^2\right), \quad -\tfrac{T}{2} < t < \tfrac{T}{2}, \qquad (2)$$

with the parameters φ_0, f_0, and α determined by the fit. The meaning of the parameters is as follows:

f_0: frequency at the center-point of the call $(t=t_0)$
α: rate of linear decrease of frequency with time
φ: phase of the oscillation at $t=t_0$

Since the envelope $e(t)$ was determined separately for each call from the observed waveform, the information used in the fit is effectively just the phase of the oscillation and not the amplitude.

A series of fits was used, starting by fitting a rather short segment of the time series. An initial guess for the central frequency had to be supplied for the first fit. In order not to bias the fit toward any particular value, the peak of the power spectrum from the selected segment was used. This power spectrum for one call is shown in Fig. 2, "Power Spectrum" inset, dotted curve. The initial guess for the phase was esti-

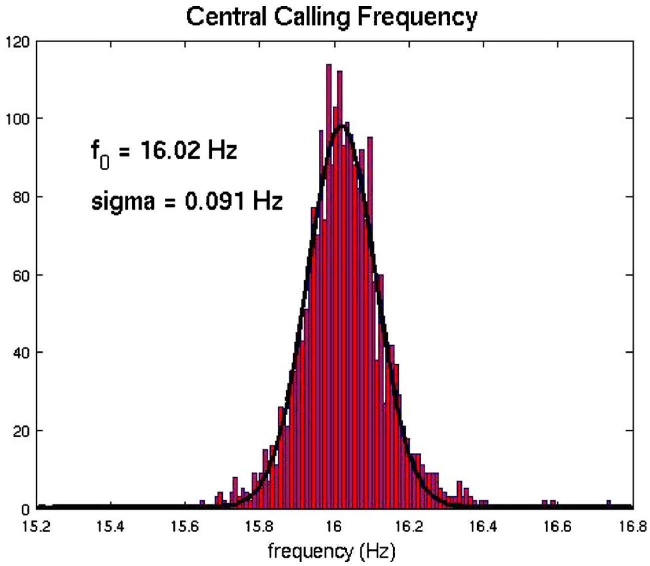

FIG. 3. (Color online) Distribution of center frequency f_0 for all well-fit ***B*** calls. The curve represents a Gaussian with center frequency 16.02 Hz and standard deviation 0.091 Hz (N=2375).

mated from the zero crossing of the signal nearest to the center-point ($t=t_0$). And the initial guess for the frequency-decrease parameter α was based on matching the slope of the ***B*** calls in the spectrograms. The series of fits to progressively longer time-series segments helped the fitting program to avoid converging to a false minimum. Each fit after the first used the result of the preceding fit as its initial guess.

The frequency-modulated sine wave from the fit was found in general to follow the time series rather accurately over the full 6-s interval used in the fit. This is illustrated on an expanded scale in the upper inset of Fig. 2, showing data and fitted parameterized curve. In this case the fitted function and the data are almost indistinguishable, and this was generally the case for signals which appeared well separated from noise (usually ship noise) on the spectrograms. Noisier signals generally resulted in a less accurate agreement of data with fitted curve, and we found that the residuals from the fit could be used to reject noise. From the residuals we calculated the correlation coefficient r (Taylor, 1997) and selected events which gave $r>0.6$, resulting in a data set of 2465 calls. Most of these calls gave frequencies forming a narrow peak near a common value, while about 170 fits of noisy signals gave a very broad distribution between 10 and 20 Hz. Events in this broad tail were regarded as outliers in the analysis described below.

IV. RESULTS

Figure 3 shows the distribution of fitted values of the central frequency f_0 for the selected well-fit calls. The curve through the data is a Gaussian, with center and standard deviation

$$f_0 = 16.02 \text{ Hz}$$

$$\sigma = 0.091 \text{ Hz}$$

As an independent check of these results, we carried out a separate analysis of the signals from a long, strong sequence of 62 calls from October 12, 2001. The calls were located by a visual scan of the spectrograms, recording by hand the time of the center of each call. All calculations were carried out with new computer routines, coded independently, making no reference to a particular frequency beyond selecting a broad frequency band of 10–30 Hz to isolate the call fundamental. The results were

$$f_0 = 16.05 \text{ Hz}$$

$$\sigma = 0.05 \text{ Hz}$$

This small-statistics result is not as significant as the result given above for the full data sample, but it confirms the blue whale's ability to tune its calling frequency with very high precision. The smaller value of the standard deviation obtained from this sample may indicate that synchronization in a particular calling sequence can be even more accurate than the spread of frequencies in the full sample would indicate.

Many other determinations of the frequency for the blue-whale ***B*** call exist in the literature. A recent paper by McDonald, Hildebrand and Mesnick (McDonald *et al.*, 2009) analyzed these data and other measurements and found their values for the central calling frequency to follow a linearly decreasing trend over the last 45 years. Their trend line interpolates to about 16.2 Hz at the time of our observations. They also report recent measurements of the frequency with errors at the 95% confidence level as low as 0.2% of the frequency value, corresponding to an rms variation of individual calls of 1%. This is to be compared with our rms variation of 0.56%, based on a phase-sensitive method optimized for accurate frequency determination. Our result seems consistent with present knowledge about frequency synchronization of the blue-whale ***B*** call.

V. DISCUSSION AND INTERPRETATION OF RESULTS

We observe the pitch of the ***B*** calls in our sample to be extremely reproducible. At the same time, it is generally agreed that the frequency of the ***B*** call has drifted down by as much as two Hertz over the last 45 years (McDonald *et al.*, 2009; Oleson *et al.*, 2007). This suggests the following questions.

- How does the whale control the frequency of its call?
- To what source do the whales synchronize their calls?
- What advantage does this provide the whales, if any?

Little is known about the mechanism of hearing in mysticete whales, and less about the way in which the ***B*** call is produced (Au, 2000; Ketten, 2000). The source to which the whales tune is not known either. However, since sound at 16 Hz travels very long distances in the ocean with only spreading losses (Urick, 1983), it seems plausible that the combined sound from all blue whales over a large range of the ocean constitutes the frequency reference.

It remains to determine what adaptive advantage blue whales might obtain from calling at a single collectively determined frequency. Continuous patterned calling, or "song," is done only by males in the case of humpback whales (Tyack and Clark, 2000) and fin whales (Croll *et al.*, 2002). A limited number of observations indicate that this is also the case for blue whales (Oleson *et al.*, 2007; McDonald *et al.*, 2001). Furthermore, song consisting of repeated ***A***-***B*** pairs seems to be associated with "fast travel," rather than "milling" or feeding (Oleson *et al.*, 2007). Blue whales are fast swimmers. Oleson *et al.* (2007) report fast travel at up to 4.5 m/s; Lagerquist *et al.* (2000) observed an average speed of 3.9 m/s over four hours; and Mate *et al.* (1999) observed travel averaging 2.26 m/s over 4.4 days. Thus it seems reasonable to explore the possibilities provided by calling at a precisely defined frequency while moving at 5 m/s, due to the Doppler shift.

The Doppler shift Δf of sound waves of frequency f, traveling at speed c with respect to the water, due to the motion with velocity v of either the source or the observer, is given by

$$\frac{\Delta f}{f} = \frac{v}{c}, \tag{3}$$

for v small with respect to c (Serway and Jewett, 2004). At a speed of 5 m/s, with $c \cong 1500$ m/s, this shift is about 0.3%. This means that an observer would see a difference in frequency of twice this value, or 0.6%, between approaching and receding from the source, a shift comparable to the frequency width for ***B*** calls which we observe (0.56%). Thus, a female swimming at 5 m/s might be able to locate the direction of a calling male by finding the direction of travel giving the highest observed frequency.

Echoranging has been proposed as a possible function of the blue-whale calls (Clark and Ellison, 2004). A whale emitting a signal at frequency f while moving toward a stationary reflecting object would detect the echo with a Doppler shift given by

$$\frac{\Delta f}{f} = \frac{2v}{c}, \tag{4}$$

or one part in 150 for $v = 5$ m/s. This shift might serve to separate the reflected signal from the background of calls from other whales. Detecting a Doppler-shifted signal has the additional advantage of directionality; an object in the direction of travel would give a positive frequency shift, and one in the opposite direction, a negative shift.

VI. SUMMARY

We have analyzed the acoustic signals from blue whales near Pioneer Seamount. We find the ***B*** calls to have a mean fundamental frequency of 16.02 Hz, with a standard deviation of about 0.56% of the mean. This surprising lack of variation among the observed calls implies that calling whales are capable of fine control over their call frequency. Taken with the fact that the call frequency has decreased regularly over the last 50 years, our result suggests a strong social dimension to the calling behavior of the blue whale. The observed frequency discrimination may be sufficiently accurate to enable detection of the Doppler shift due to a whale's motion, with possible attendant adaptive advantages to the species.

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