The acoustic calls of blue whales off California with gender data

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The acoustic calls of blue whales off California are described with visual observations of behavior and with acoustic tracking. Acoustic call data with corresponding position tracks are analyzed for five calling blue whales during one 100-min time period. Three of the five animals produced type A-B calls while two produced another call type which we refer to as type D. One of the animals producing the A-B call type was identified as male. Pauses in call production corresponded to visually observed breathing intervals. There was no apparent coordination between the calling whales. The average call source level was calculated to be 186 dB *re*: 1 μPa at 1 m over the 10–110-Hz band for the type B calls. On two separate days, female blue whales were observed to be silent during respective monitoring periods of 20 min and 1 h. © *2001 Acoustical Society of America.* [DOI: 10.1121/1.1353593]

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I. INTRODUCTION

The blue whale (*Baleanoptera musculus*) call repertoire includes intense, long-duration continuous calls, having the greatest acoustic power of any animal (Aroyan *et al.*, 2000). Little is understood of the behavioral function/role of blue whale calls. Possible functions include sensing the environment, prey detection, and communication. The behavioral significance of communication is typically determined by observing natural interactions and quantifying changes in behavior following a call (Tyack, 2000). Among the baleen whales, the behavioral function of acoustic calls is best studied for the humpback (*Megaptera noveangliae*), somewhat studied for the right (*Eubalaena glacialis* and *Eubalaena australis*), bowhead (*Balaena mysticetus*), and fin (*Baleanoptera physalus*) whales, and less well studied for the other species (Edds-Walton, 1997). For humpback whales there is an established gender bias in calling, where males produce the songs (Tyack, 1998).

To better understand the acoustic calls of blue whales, this study was undertaken to collect visual behavioral observations, photo-identification history, and gender for whales which were monitored acoustically for call behavior. The acoustic monitoring system allowed simultaneous tracking of multiple calling blue whales, some of which were not observed visually. To test for any communication context associated with a whale call we looked for either consistent behavioral interactions associated with the call, or an acoustic response (Edds-Walton, 1997). An important parameter in understanding blue whale call context would be the determination of any gender bias in the types of calls produced.

The blue whale population, which occupies the west coast of North America, numbers about 2000 animals (Barlow, 1995), of which more than 1100 individuals have been documented by photo-identification (Calambokidis *et al.*, 1999). This may be the largest population of blue whales in the world, and is among the best studied. These animals are believed to range from the Queen Charlotte islands of British Columbia to the Costa Rica Dome based on photo-identification, satellite tagging, and acoustic recordings (Calambokidis *et al.*, 1999; Mate *et al.*, 1999; Stafford *et al.*, 1999b). The most commonly recorded blue whale call type is that which we refer to as broadcast calls, typically 15 to 20 s each part, produced repeatedly with a nearly fixed interval for long periods of time, hours to days (Tyack, 1998; Watkins *et al.*, 2000). We believe the term broadcast call is appropriate because of the apparent lack of acoustic countercalling and the long duration of these call series. We do not intend the term broadcast call to imply a specific function. There is now extensive remote monitoring of the broadcast-type blue whale calls (Clark and Charif, 1998; Curtis *et al.*, 1999; Stafford *et al.*, 1999a; Watkins *et al.*, 2000), but few recordings have been made together with behavioral observations, and none, previous to this study, with genetic material from the calling animals. A better understanding of these acoustic calls will contribute to the acoustic monitoring efforts.

II. DATA COLLECTION

A. Effort

The 53.3-m National Oceanic and Atmospheric Administration (NOAA) ship *McArthur* was used to survey whales off the coast of Oregon and California from 30 September through 16 October 1997. There were 172 h of survey effort for the *McArthur* during 16 days. Procedures and equipment on the flying bridge of the *McArthur* were similar to National Marine Fisheries Service (NMFS) line transect surveys, including computer logging of data with an integrated global positioning system (GPS) and pedestal-mounted 25 power binoculars with range finding reticles (Fiedler *et al.*, 1998).

At least three observers were always on watch on the *McArthur* flying bridge. Two rigid hull inflatable boats (RHIBs) sometimes ran ahead and to the side of the *McArthur*, weather permitting, to increase the chance of encountering whales for biopsy, photo-identification, and acoustic monitoring, but these vessels were not directly involved in line-transect survey efforts.

The primary goal of the survey was to collect photo-identification of blue and humpback whales with a secondary goal of collecting blue whale acoustic recordings. When a blue whale was sufficiently separated from other animals to be certain acoustic recordings could be correlated to a specific animal, there was an additional goal of collecting genetic material for gender determination. The cruise focused on areas where blue whales were likely to be found but remained relatively far offshore where whales would be difficult to study using small vessels alone.

B. Methods

1. Sonobuoy calibration and recording systems

Broadband sonobuoys of type 57B, and directional sonobuoys (DIFAR) of types 53B and 53D (Richardson *et al.*, 1995) were used to obtain the recordings described here. Sonobuoy signals were received on five radios specially modified and calibrated by GreeneRidge Sciences, Inc. (Goleta, CA) to an accuracy of 0.1 dB. Recording systems included two Sony TCD-D8 stereo digital recorders sampling at 48 kHz. A second system simultaneously recorded all five sonobuoy channels using a National Instruments A/D board sampling each channel at 1 kHz through custom-built active anti-aliasing filters, each calibrated to less than 0.3 dB. Data recorded on the National Instruments system were used for quantitative analyses of received levels and for time delay sound source tracking methods, while data from the Sony recorders were used for DIFAR processing of bearings to calling whales. The National Instruments recording system and the Sony recording system each time stamp the acoustic data with internal clock time which was synchronized to GPS time to within 1-s accuracy. The time jitter between channels on the National Instruments system was less than 1 ms. The frequency response of the DIFAR sonobuoys differs from that of the omni-directional sonobuoys and appropriate corrections were made in the frequency domain to flatten the total frequency response of all the sonobuoys and the frequency response of the active filters. The greatest potential error in our sound level measurements is the sonobuoy manufacturer specification which is ±2 dB for type 57 buoys and ±3 dB for type 53 buoys. Some reduction in overall error was obtained by averaging ambient noise spectrum levels on each buoy in an array during time periods where ship noise did not appear to cause a bias across the array. Sonobuoys are expected to always have a self-noise below ocean ambient noise levels.

A verification of the sound pressure level calibration was obtained for the 15 October data by comparing observed ambient ocean noise levels at 500 Hz, largely above shipping noise frequencies, with expected ocean ambient levels. The 15 October recordings were made during Beaufort zero conditions. A 500-Hz spectrum level of 42 dB *re*: 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$ was observed, corresponding to a Knudsen curve level of 46.5 dB (Urick, 1983). More recent work suggests the Beaufort zero Knudsen levels to be too high for the Pacific (Chapman and Cornish, 1993), indicating our sound pressure level calculations are in agreement with expected ambient noise levels. Four of the five sonobuoys used on this occasion showed the same levels within our 2–3-dB measurement accuracy. The signal recorded from the fifth sonobuoy (a type 53D) showed a totally unexpected frequency response as judged against the ambient noise spectrum measured by the other sonobuoys and was not used for source level estimates, though it was used for direction finding. The 0–500-Hz noise spectra was examined for each measurement of whale call received level, and when the sonobuoy or some other component of the recording system appeared to be overloaded by ship or whale sound, these data were not used.

2. Photographic identification of individual blue whales

Identification photographs were taken using standard procedures employed in past research off California and Washington (Calambokidis *et al.*, 1990). Both the right and left sides of blue whales in the vicinity of the dorsal fin or hump were photographed as well as the ventral surface of the flukes. Identification photographs were first compared to others from the same time period and then compared to a catalog of 1070 blue whales identified along the California coast from 1975 to 1997 (Calambokidis *et al.*, 1999). Individual whales that did not match past years and that were of suitable quality were assigned unique identification numbers and added to the blue whale catalog.

3. Biopsies of blue whales

Skin samples were collected to determine gender of individual whales (Baker *et al.*, 1991). Biopsy samples were collected from whales using a biopsy dart system (Lambertsen, 1987). The biopsy dart consisted of an aluminum crossbow bolt (arrow) and a stainless steel biopsy punch, which has a flange or ‘‘stop’’ to prevent its penetrating too deeply. The punch is 7 to 9 mm in diameter and 2 to 5 cm in length and is fitted with two or three internal pins to secure the sample. A hole drilled transversely through the punch and just distal of the flange prevents pressure buildup inside the punch as it penetrates the skin. The dart was fired from a commercially available crossbow having a 125- to 150-lb draw. The recoil from the bolt stop striking the whale dislodges it from the whale and the free-floating bolt is retrieved by hand. Dart recoveries were sometimes aided by luminescent dyes added to the bolts. Gender determinations were made by the molecular genetics laboratory at Southwest Fisheries Science Center.

4. Tracking methods

On several occasions when whales were sighted, line transect efforts were terminated, allowing both the *McArthur* and the RHIBs to deploy an array of sonobuoys in the vicinity of the whales. Visual whale positions were maintained using bearings and ranges from the pedestal-mounted binoculars and an integrated GPS recording system when a RHIB was not available to directly record the GPS position of the final flukeprint of a surfacing series. Sonobuoy deployment positions were recorded using GPS. Personnel on the *McArthur* flying bridge watched for previously unseen whales and coordinated the RHIBs.

The sonobuoy array allowed us to determine the location of calling whales for correlation with visual positions of whale surfacings. Both time delay localization methods and DIFAR processing of bearing angle from each sonobuoy were applied to the data (D'Spain, 1994; D'Spain *et al.*, 1992). The DIFAR bearing errors were found to have a standard deviation of two degrees (McDonald, unpublished data). DIFAR localization of calls was found to provide more accurate positions than time delay localization and was used exclusively in the acoustic tracks presented here. Sonobuoy drift corrections were made with visual/GPS buoy drift information and with acoustic location surveys using weighted light bulbs as sound sources (Heard *et al.*, 1997) processed with root mean square (rms) residual grid search localization methods (Wilcock and Toomey, 1991).

5. Source level estimation

Received levels were converted to source levels using only spherical spreading losses (Urick, 1983). Source levels were calculated only for the one animal for which a GPS position was available for every surfacing. The location of each call from that animal was interpolated by the time of the call between consecutive surface positions. Only calibrated receivers at greater than 2.5 km were used because range errors become less significant to the source level computation at greater ranges. Sonobuoy calibration is lost for very short range recordings because the received amplitude exceeds the dynamic range of the sonobuoy. Only calls free from interference were used for these measurements, and many of these calls were recorded without interference on four calibrated sonobuoys, each at a different range.

A detailed propagation model was not considered to be viable due to the many poorly known variables including sound speed profiles, bathymetry, seafloor characteristics, and depth of the calling animals. Several hundred propagation loss models were computed with parabolic equation methods using a range of best estimates for each variable. The average of these models suggests propagation losses slightly higher on average than spherical spreading, but a spherical spreading model was chosen for simplicity.

Fine scale variability in propagation loss was examined by comparing computed source levels over the 10–110-Hz band from the same call to different sonobuoys and observed to be ±3 dB. To determine if source levels varied from call to call, computed source levels were examined and observed to be ±3 dB, about the same as observed from the same call to different sonobuoys. Variability in spectrum levels of components from the same call on multiple sonobuoys and from multiple calls on the same sonobuoy was observed to be much greater than 3 dB. Greater variability is to be expected in tonal propagation losses when compared to band level variability given the multi-component calls observed in this study. Fine-scale variability in propagation losses may be responsible for all the observed variability in source levels.

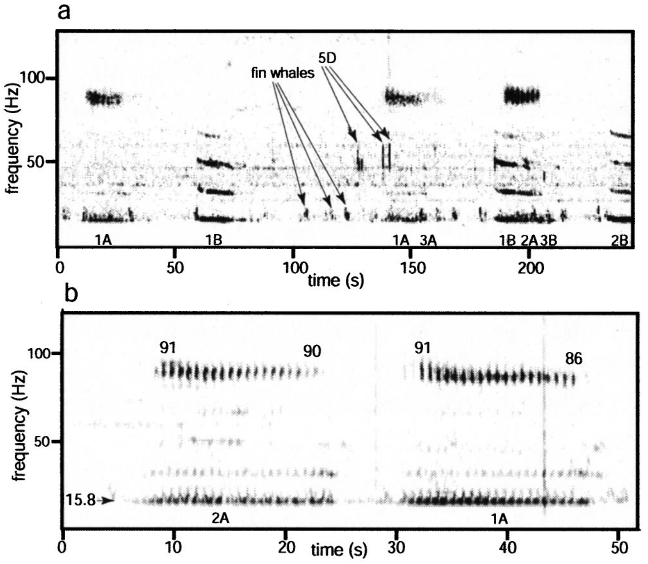

FIG. 1. (a) Acoustic data west of San Nicolas Island from 15 October at 1833 local time on the furthest west sonobuoy shown in Fig. 3, computed with a 1-s FFT, Hann window, and 75% overlap. Each call is labeled with the whale number shown in Fig. 3 and the call type designation. (b) Detail of type A calls from 15 October at 1759 local time, showing variability of 19 to 23 pulses between 92 and 85 Hz for the prominent overtone. Note the 90-Hz components are not harmonics of the 15.8-Hz fundamental. The FFT length is 0.5 s and overlap is 87.5% with a Hann window. The spectrograms shown have a frequency response emphasizing the higher frequencies by 4.5 or 6 dB per octave, depending whether a type 53 or 57 sonobuoy was used for the recording. This emphasis is built into the sonobuoy design and is intended to compensate for lower ambient noise levels at higher frequencies and thereby to maximize dynamic range.

III. RESULTS

A. Call characteristics

A total of 117 blue whales were seen in 78 sightings with 43 photographed and 33 identified. Acoustic recordings were obtained from an estimated 43 individual calling blue whales. These calls can be classified into two basic types, either patterned pairs, each of about 17-s duration, or irregular spaced calls of typically 2-s duration. Many of the estimated 43 individual blue whales acoustically recorded were never seen and recording was not always undertaken when blue whales were sighted.

A spectrogram of typical blue whale calls is shown in Fig. 1(a), as recorded on 15 October at 1833 local time. This spectrogram shows three blue whales producing two part broadcast calls, labeled as ''A'' and ''B'' in the spectrogram with each whale designated by a number. Each of these calling whales was individually tracked acoustically as described later. Another whale, designated five during this encounter, was producing downswept calls of about 1-s duration ranging from 60 to 45 Hz, these being labeled as type D calls. Fin whale calls are also present near 20 Hz in Fig. 1(a). In California coastal waters we find the type D call about as common as the type A-B call (A. Teranishi, unpublished data), though type D calls appear less common in mid-ocean recordings. The character of the type D call can be quite variable, sometimes having characteristics intermediate with that of the type B call, and is not produced in such a regular pattern as the type A-B calls.

Figure 1(b) illustrates type A call variance between two animals. Most A calls have a weak tone near 16 Hz which precedes the pulsive part of the call by several seconds, and is followed by 19 to 23 pulses which are particularly apparent near 90 Hz. As previously noted (Thompson *et al.*, 1996), the component near 90 Hz is not a harmonic of the energy near 16 Hz. We encountered one animal producing A-B call pairs in which the type A calls had only five or six pulses. Beginning and ending peak frequencies are noted on the spectrogram of Fig. 1(b), the 90-Hz component typically shifting downward in frequency throughout the call. The average frequency and frequency shift for the 90-Hz component provides a measure of individual identification for each whale producing A-B calls in this encounter, though we do not suggest these differences will remain constant over longer time periods or that all individuals can be distinguished by such measures.

Both high- and low-frequency weak precursory components are commonly seen preceding the type B call when the signal-to-noise ratio is high [Figs. 2(a) and (b)]. In Fig. 2(a), a 10- to 12-Hz upsweep precedes the 16-Hz portion of the call. This precursor is relatively consistent in character (rate of change in frequency and amplitude), frequency, and duration when present, and has been reported previously (D'Spain *et al.*, 1995; Stafford *et al.*, 1999b). The precursory component near 400 Hz [Fig. 2(b)] ranges in different encounters, from about 300 to 500 Hz, from less than one to several seconds in duration, and shows significant variation in character. This component may be analogous to a 390-Hz component which preceded the last call segment in recordings of Chilean blue whales (Cummings and Thompson, 1971).

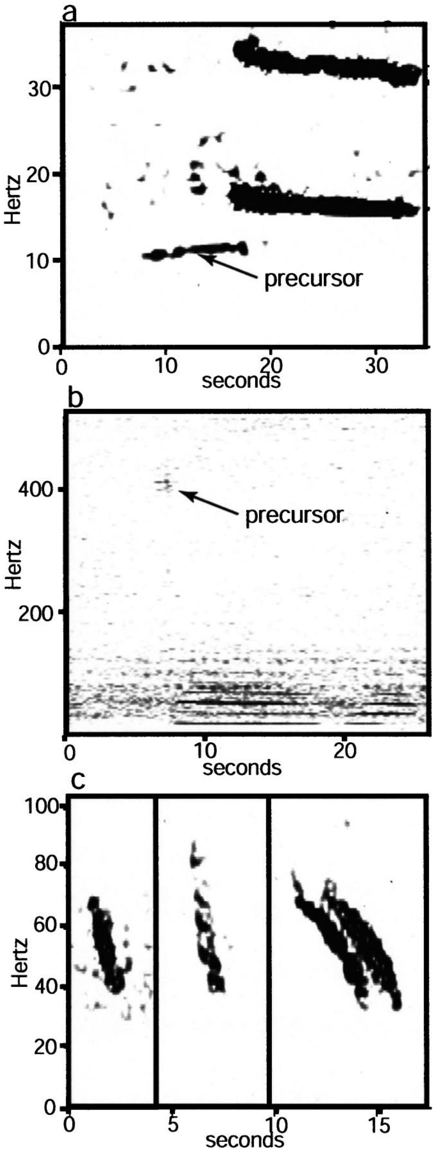

FIG. 2. Blue whale call spectrograms recorded with sonobuoys off California. (a) Onset of a type B call showing the common 10–12 Hz precursor. The FFT length is 2 s and overlap is 98% with a Hann window. (b) An example of the high-frequency precursor to the B call. The duration varies from less than one s to several seconds, the frequency varies by more than 100 Hz and the character is variable. This component is not always observed. The FFT length is 0.75 s and overlap is 75% with a Hann window. (c) A composite spectrogram of three separate recordings of type D calls illustrating the variability. The double call in the third example is considered to be two animals counter-calling rather than a propagation artifact. The FFT length is 0.74 s and overlap is 93.75% with a Hann window.

B. Acoustic activity

On three occasions during the October 1997 cruise sonobuoy arrays were deployed around animals which were biopsy sampled during the acoustic monitoring, and which were sufficiently separated from other whales to be visually tracked. On two of these occasions (12 and 16 October) the tracked animals did not produce any calls during the encounter. During the encounter of 15 October, one of the biopsied animals did produce calls.

On 15 October at 1652 local time, two blue whales (nos. 1 and 3 in Fig. 3) were sighted together in 800-m-deep water 31 km west of San Nicolas island. One of the RHIBs stayed with whale one for the next several hours collecting visual observations along with photo-identification and a genetic sample while the other RHIB obtained photo-identification on whale 3. Both of the visually observed animals were producing broadcast-type calls as was a third unseen animal (whale 2). Two more blue whales (nos. 4 and 5) could be heard in the area producing D calls. Five sonobuoys allowed acoustic tracking of the three animals producing the ''broadcast'' calls and general localization of the two animals producing D calls.

The tracking precision shown in Fig. 3 is highly variable, being as precise as 100 m for each call in the central portion of the track for animal 2 and as poor as providing bearing only on animal 1 when it was far from the array. Sonobuoy drift was less than 100 m during tracking, the largest position errors (~50 m) being GPS errors in the positions taken at buoy deployment time. The positions for each call from animal 1 are interpolated from GPS fixes in the final footprint of each surfacing. We are confident no surfacings were missed for this animal. Bearings from the DIFAR buoys matched the bearing to this animal, but the small array aperture in this direction prevents accurate range

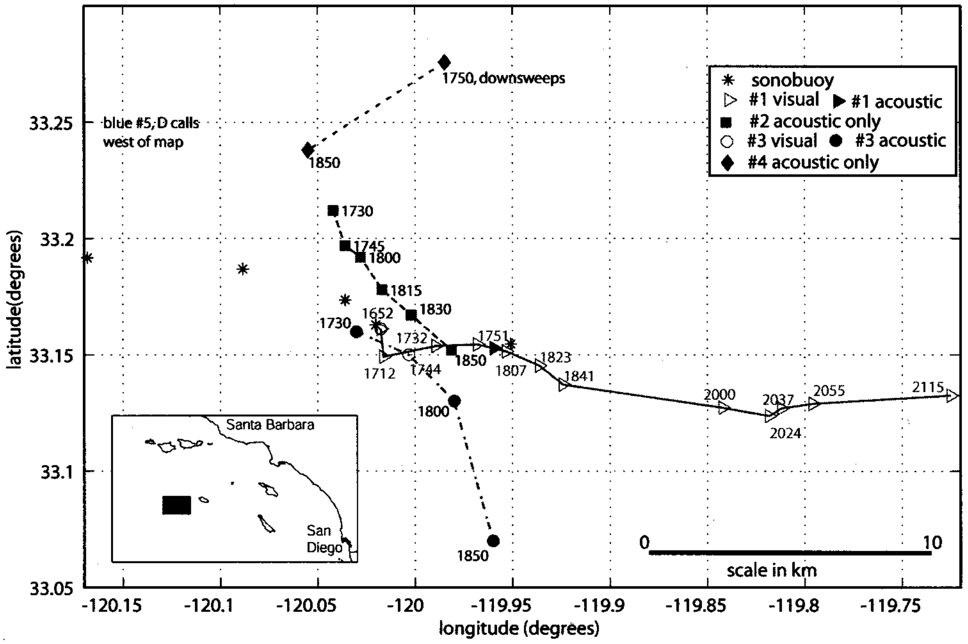

FIG. 3. Location map west of San Nicolas Island showing the positions and interpolated tracks for five blue whales from 1652 to 2115 local time 15 October 1997. Acoustic position errors are relatively small for whale 2 where the sonobuoy array aperture is excellent in the direction of that whale. When whale 1 is east of the sonobuoy array, the acoustic bearings are practically the same from all sonobuoys and acoustics alone cannot determine position.

estimation to this animal from acoustics alone. Sound pressure levels from animal one saturated the nearest buoy during one call near 1800 hours. The DIFAR bearings to each whale call, combined with the saturated signal during this one call, leaves no doubt as to the match between visual and acoustic data for this whale. Average swimming speeds were 5 km/h for animal 1, 7 km/hr for animal 2, and 9 km/hr for animal 3. Subtle but consistent differences in call character [illustrated in Fig. 1(b)] further identified the calls of each individual animal.

C. Call patterns

The calls from the five whales acoustically monitored on 15 October show no apparent coordination or interaction (Fig. 4). The visual observations of surface time coincide with gaps in the calling sequence for animal 1, with the possible exception of the last observed surfacing where there may be a small overlap with the onset of the type A call. A timing error of only 15 s in reading the wristwatch and recording our visual observation could account for this discrepancy. Such a match between calling gaps and visual surfacing intervals has been reported previously (Cummings and Thompson, 1971) although a possible exception has also been reported (Edds, 1982). A hypothetical model for sound production in the blue whale suggests the type B calls cannot be produced while at the surface (Aroyan *et al.*, 2000).

The most common call pattern for California blue whale broadcast calls is one type A call followed by one type B call, as produced by animals 1 and 3. The call pattern produced by animal 2, however, is one A call followed by a series of B calls. We have not seen type B calls which were not preceded by an A call, nor consecutive A calls. Each closely spaced call sequence starts with a type A call. From examination of the call timeline alone, we can see no direct evidence of communication between these whales as indicated by use of counter-calls or synchronized surfacing, though there can be little doubt these animals can hear each other. The calls from animals 4 and 5 are plotted as one timeline (Fig. 4) because it was not possible to distinguish which animal produced some of the calls though many of the calls could be attributed to one or the other of the two locations.

D. Acoustic source levels

The received sound pressure levels and implied source levels for the A-B paired broadcast calls from animal 1 are plotted as Figs. 5(a) and (b). The average source level is 178 dB *re*: 1 μPa at 1 m over the 10–110-Hz band for 82 ''A'' calls [Fig. 4(a)] and 186 dB *re*: 1 μPa at 1 m over the 10–110-Hz-band for 61 ''B'' call measurements [Fig. 4(b)], all from whale 1.

Because variability is apparent in the intensity ratios between the 16.5-Hz tone and the third harmonic or 50-Hz tone of the ''B'' calls, these ratios were examined to evaluate if the whale may be controlling the relative intensities of the harmonics. The spectrum level of the third harmonic is on average 10.3 dB lower than the fundamental over 55 calls, with a range of 16 to 0 dB lower. This ratio of fundamental and third harmonic for the same call observed on different sonobuoys shows nearly a 16-dB variability, indicating the variability is primarily due to propagation effects rather than changes in the sound production mechanism at the whale. The source and receiver depths are expected to have a profound effect on such frequency-dependent propagation effects (Urick, 1983). Surface reflection interference affects each frequency component differently and could potentially be used to estimate the depth of the calling whale.

As with the type B calls, the A calls also have most of the sound intensity in the lowest frequency portion of the call, though the 90-Hz portion often has a higher signal-to-noise ratio because of observed lower ocean ambient noise levels at 90 Hz. The spectrum level of the component near 17 Hz averages 2.5 dB lower than the 10–110-Hz band level while the spectrum level of the component near 90 Hz is 14

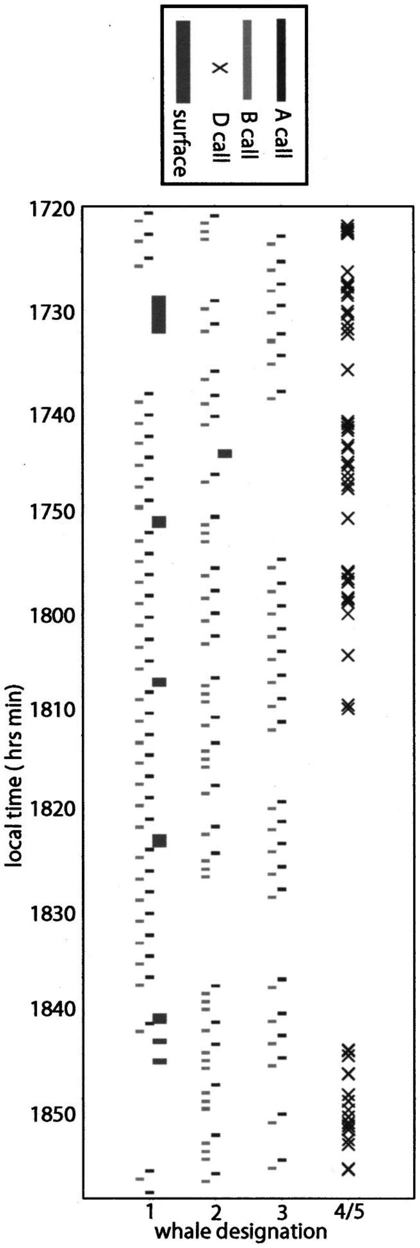

FIG. 4. The acoustic call patterns for five blue whales producing type A, B, and D calls, as well as visual observations of whales surface times. Whales 4 and 5, which produced only type D calls, could not always be separated and thus are plotted together. Note how whale 2 often follows a type A call with three type B calls. The visual observations of surface times correspond to gaps in calling.

dB lower than the band level. Examination of the clearest recordings of the pulsive type ''A'' calls show acoustic energy at five higher frequencies up to 110 Hz, none of which appear to be harmonics.

E. Gender, behavior, and history of acoustically monitored whales

A single female whale was acoustically monitored from 1308 to 1410 local time on 12 October (catalog ID #1323) at 33° 33′ N 119° 46′ W. She was traveling slowly and consistently in a NW direction. During the 47-min visual observation period prior to when the animal was struck with the biopsy dart the animal traveled a straight-line distance of 3.2 km. There was no detectable reaction to the biopsy hit. This animal had not been previously photo-identified. We are confident no calls were produced by this animal during the time in which it was acoustically monitored.

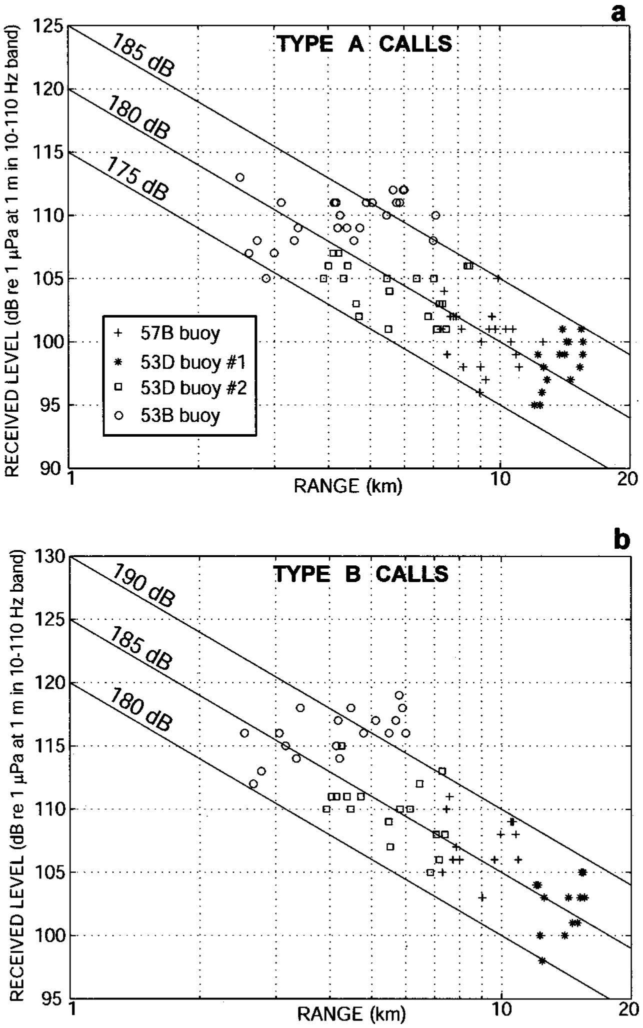

FIG. 5. The received sound pressure levels and inferred source levels for blue whale 1 on 15 October as measured over the 10–110-Hz band *re*: 1 μPa at 1 m. The levels were determined using a 10-s average, starting 1 to 2 s after the onset of each call, using a Hann window, 80% overlap and a 1 s frame length. Source level calculations use spherical spreading losses. The scatter in the data may be attributed to propagation variability, rather than actual differences in source level. The four symbols represent the four sonobuoys used.

Whale 1 of the 15 October encounter was determined to be male. This large whale was initially spotted traveling in the lead of a second slightly smaller whale, although these two quickly separated. The whale traveled consistently in an easterly direction on a fairly direct course. Dive intervals and spacing were longer than typical for blue whales in this area. Most intervals ranged from 14 to 17 min and were interspersed with surface intervals where the animal would surface to breath repeatedly four to five times in close succession. The whale traveled a straight line distance of 34.2 km from first sighting at 1605 and last position at 2215. This animal (Cascadia Research catalog ID #673) had been seen seven times prior to the encounter described. These included six encounters between 27 June and 16 September 1992 with June and July sightings in the Santa Barbara Channel and a

September sighting in the Gulf of the Farallones. There was one sighting on 29 September 1993 in Monterey Bay. This whale was acoustically monitored for 5 h and 25 min and we are confident the broadcast type calls were produced by this animal.

A female whale was acoustically monitored for 20 min from 1205 to 1225 local time on 16 October (catalog ID #170) at 34° 52′ N 120° 54′ W. This was a large whale traveling very slowly consistently in a southerly direction. Dive intervals were fairly short (under 4 min) and the animal appeared to be remaining fairly shallow between dives. A biopsy sample was taken midway through the 39-min visual observation period and the animal made a quick dive apparently in response to the biopsy. This whale had been seen seven times prior to the encounter described. The earliest sighting was 1 September 1987 in the Gulf of the Farallones indicating this animal is >10 years old. Three sightings were made in June 1992 in the Santa Barbara Channel. This animal was also seen three times between 12 and 23 July 1997 in the Santa Barbara Channel. We are confident no calls were produced by this animal during the time it was acoustically monitored.

IV. DISCUSSION

A. Call activity and gender

The broadcast calls are often produced in a continuous pattern for many hours at a time, with pauses appropriate for surface breathing intervals as suggested for blue whales elsewhere (Cummings and Thompson, 1971; Edds, 1982) and by the combined visual and acoustic data presented here. The amplitude, duration, and repetitive nature of the broadcast call makes it well suited for long distance signaling. During observation periods of a few hours, an individual whale usually produces only one type of call, either the type D call (A. Teranishi, unpublished data) or the broadcast call (Stafford *et al.*, 1998). Only on a few occasions have blue whales been observed to mix these two call types (M. McDonald, unpublished data) (Thode *et al.*, 2000). Whales producing the broadcast call are often traveling at modest speeds (McDonald *et al.*, 1995; Stafford *et al.*, 1998; Tyack, 1998).

When multiple blue whales are producing the broadcast call in the same area, this study finds no evidence of coordination between the callers, as might be suggested by synchronized respiration intervals or patterns in call behavior among animals. The type D call, however, appears to be used as a counter-call among multiple whales. Type D calls sometimes occur in overlapping pairs, each produced by a different animal, and separated by relatively long intervals [Fig. 2(c)].

Call behavior of fin and humpback whales has been better studied than blue whales and provide a reference with regard to how call types may vary with gender. There may be analogies between the blue whale broadcast call and the fin whale doublet call, and between the blue whale D call and the fin whale irregular call. Acoustic evidence suggests widely separated calling fin whales synchronize respiration intervals and counter-call when using irregular call types, but do not show such coordination when producing the more regular doublet call type (McDonald *et al.*, 1995; Watkins *et al.*, 1987). It has been argued that only the male fin whale produces the doublet call as a breeding display (Watkins *et al.*, 2000), consistent with our finding of a male blue whale producing the broadcast call. The humpback song, which is produced only by males, may be analogous to the fin whale doublet call and the blue whale broadcast call.

B. Source levels

The average blue whale call source levels of 186 dB reported here for the type B call are measured in units comparable to the 188 dB levels previously reported for blue whales off Chile (Cummings and Thompson, 1971). The source level in our blue whale recordings is determined primarily by the fundamental tone, as it is sufficiently stronger than the harmonics and overtones to dominate the signal. The pressure spectrum level of the fundamental tone is therefore nearly equivalent to the band level and the band over which the level is measured is of relatively little consequence. One other calibrated recording of blue whales off California (Thode *et al.*, 2000) reports source levels in units of pressure spectral density over a 0.4-Hz bandwidth. The conversion of these units to either band or pressure spectrum levels for comparison results in an average level slightly greater than 180 dB for the type B call, notably lower than our results or those of Cummings and Thompson (1971). Knowledge of source levels is important in studies of the effects of man-made noise and in determining zones of masking which limit the communication potential of whales (Richardson *et al.*, 1995).

V. SUMMARY

We describe three blue whale encounters in which biopsies were obtained to determine gender and acoustic monitoring was in place to determine if the whales were calling. The observed travel and calling patterns are described for a group of blue whales including one known male producing broadcast calls. Two noncalling females were observed in separate comparatively brief encounters. We describe a previously unpublished characteristic of some blue whale broadcast calls, a 400-Hz precursor to the type B call. The source level of blue whale calls from one animal is found to average 186 dB for the type B, and 178 dB for the type A calls *re*: 1 μPa at 1 m over the 10–110-Hz band. Observed variability in intensity ratios of the third harmonic to the fundamental within the blue whale call is considered to be a propagation artifact. With further work we hope to determine if a gender bias is present in the production of the blue whale broadcast call and to quantify the blue whale acoustic detection function for purposes of abundance estimation. Such work could best be done by visually following acoustically monitored and biopsied animals. Tagging animals with recorders may also be useful, though visual contact may be necessary to determine if a second animal is nearby which could potentially produce calls indistinguishable from those of the tagged animal.

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