Source of the North Pacific "boing" sound attributed to minke whales

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During a recent cetacean survey of the U.S. waters surrounding the Hawaiian Islands, the probable source of the mysterious "boing" sound of the North Pacific Ocean was identified as a minke whale, *Balaenoptera acutorostrata*. Examination of boing vocalizations from three research surveys confirms previous work that identified two distinct boing vocalization types in the North Pacific. The eastern boing ($n=22$) has a pulse repetition rate of 92 s^{-1} and a duration of 3.6 s and was found only east of 138° W. The central boing ($n=106$) has a pulse repetition rate of 115 s^{-1} and a duration of approximately 2.6 s and was found only west of 135° W. Central boing vocalizations produced by a single source ($n=84$) indicate that variation in repetition rate and duration of the calls of the individual were not significantly different than the variation among individuals of the same boing type. Despite a slight latitudinal overlap in the vocalizations, pulse repetition rates of the eastern and central boings were distinct. [DOI: 10.1121/1.2046747]

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I. INTRODUCTION

The "boing" sound was first described by Wenz (1964) from U.S. Navy submarine recordings made in the 1950s off San Diego, California, and Kaneohe, Hawaii. Despite much attention, the source of the sound has remained a mystery until now. Wenz (1964) noted variation in the duration of the signals (with a possible concurrent variation in the intervals between signals), as well as variation in frequency modulation. Thompson and Friedl (1982) tracked boing sounds made from multiple recordings from bottom-mounted hydrophones off of Oahu, Hawaii, noting long intersound intervals (6 min) for solitary sound sources, and brief intersound intervals (0.5 min) for multiple sound sources. The sources of the boing sounds typically approached the northern coast of Oahu singly, although paired or small groups were detected occasionally (Thompson and Friedl, 1982). Boings were detected seasonally, from November through March, and had an estimated sound source level of 150 dB re 1 μPa at 1 m (Thompson and Friedl, 1982). Given this information, Thompson and Friedl (1982) suggested that the sound source was likely a whale, but they did not speculate as to which species. The first suggestion that the boing may be produced by the minke whale (*Balaenoptera acutorostrata*) was made by Gedamke *et al.* (2001) based on the structural similarity of the boing and the sound produced by the dwarf minke whale in the Great Barrier Reef, Australia.

Antarctic minke whales (*B. bonaerensis*) and northern minke whales have been recorded making low-frequency downswept vocalizations in the Ross Sea (Schevill and Watkins, 1972; Leatherwood *et al.*, 1981) and the St. Lawrence Estuary (Edds-Walton, 2000), respectively. These sounds were described as sweeping from over 100 Hz down to 90 Hz (St. Lawrence Estuary) or 60 Hz (Ross Sea). Winn and Perkins (1976) recorded pulse trains and grunts in the presence of minke whales in the Caribbean. Ratchets, single pulses, and higher frequency clicks were also recorded, although less frequently. Mellinger *et al.* (2000) noted that thump trains recorded in the Caribbean occurred as "speed-up" pulse trains or less often as "slow-down" pulse trains. Pulse trains also were recorded in the presence of group-feeding minke whales in the Gulf of St. Lawrence (Zbinden and Di Iorio, 2003). High-frequency clicks as well as whistles, grunts, and other calls were recorded in the presence of minke whales in the Ross Sea (Leatherwood *et al.*, 1981), although other species may have been present. In the North Pacific Ocean, there have been no published recordings of vocalizations attributed to minke whales.

The Hawaiian Island Cetacean and Ecosystem Assessment Survey (HICEAS) was conducted in the U.S. exclusive economic zone (EEZ) surrounding the Hawaiian Islands between July and December, 2002. This survey combined visual and acoustic methods to determine the distribution and abundance of cetaceans (Barlow *et al.*, 2004) and provided a unique opportunity to investigate the source of these boing sounds. On 7 November 2002, the acoustics team located the source of a series of boing sounds and directed the ship and visual team to this location, where experienced marine mammal observers identified a minke whale. This paper details the events leading us to attribute the boing sound to the North Pacific minke whale and summarizes the characteristics of the boing vocalizations recorded during this particular encounter and during three research cruises in the North Pacific Ocean.

II. METHODS

Boings were detected during three cetacean research surveys, the 1997 Sperm Whale Abundance and Population Structure Survey (SWAPS), the 2002 HICEAS cruise, and the 2003 *Stenella* Abundance Research Survey (STAR). These research cruises combined visual and acoustic line-transect surveys of cetacean populations. Visual observation of cetaceans were conducted during daylight hours and consisted of six experienced visual observers rotating between two "big eye" binocular (25×150) stations and one station observing with $7\times$ binoculars and unaided eye. The acoustics team consisted of two to four rotating acoustic technicians monitoring a hydrophone array aurally and visually (from a real-time spectrogram display).

The 1997 SWAPS survey,[1] on the R/V *McArthur*, covered the waters of the N. Pacific Ocean from 20°–45°N, from the west coast of the United States to 158°W. Emphasis was placed on detecting, locating, and recording sperm whales. The hydrophone array used during this survey consisted of a 60 m, five-element, solid array (made by Innovative Transducers, Inc) which had a relatively flat frequency response between 32 Hz and 8 kHz (±2 dB). The array was attached to a 120 kg depressor weight which was towed 600 m behind the vessel at a depth of 100 m. Signals from two hydrophone elements were monitored day and night, and recordings of sperm whales, boings, and other sounds of interest were made using DAT recorders (Sony D-7, 48 *k* samples/s). These recordings were recently reviewed and boing vocalizations were analyzed for this report.

The 2002 HICEAS survey, aboard the R/V *David Starr Jordan*, included the EEZ of the Hawaiian Island chain and transit to and from San Diego, CA (Barlow *et al.*, 2004). The STAR 2003 survey,[2] aboard the R/V *McArthur II*, surveyed the eastern tropical Pacific Ocean, from San Diego, California, south to Peru. During both of these cruises, a hydrophone array was towed 200 m behind the ship at an average speed of 10 knots and an average depth of 6 m. The arrays used during the HICEAS and STAR surveys were built in-house and contained two elements, with 3 m spacing between elements. All hydrophones in both arrays had an effective frequency response from 500 Hz to 25 kHz (±10 dB). In addition, a small hydrophone array was installed on the bow of the Jordan during the HICEAS survey; this unit consisted of three closely spaced hydrophones. The bow hydrophones had a small range and were occasionally monitored when animals were near the bow; output from the bow hydrophones were recorded with the output from the towed hydrophone array. Hydrophone output was passed through a Mackie CR1604-VLZ sound mixer for equalization and high-pass filtering of low-frequency noise. All recordings were made using a Tascam DA-38 digital recorder, sampling at 48*k* samples/s.

Recordings from all three cruises containing boing sounds were reviewed visually using ISHMAEL software, which uses time delay between two hydrophones (estimated by cross correlation) to calculate a bearing to the sound source (Mellinger, 2001). Bearing angles were plotted relative to the ships' bow using Whaltrak, a mapping and data-logging program. The location of the sound source was determined by the convergence of beamform angles. Left/right ambiguity was addressed by making a 30° turn; angles converge on the side of the sound source. One sample from each acoustic detection of a boing series was examined for comparison of vocalizations between individuals. Measurements of beginning and end frequency, pulse repetition rate, and signal duration were taken from each sample vocalization using SpectraPlus software.

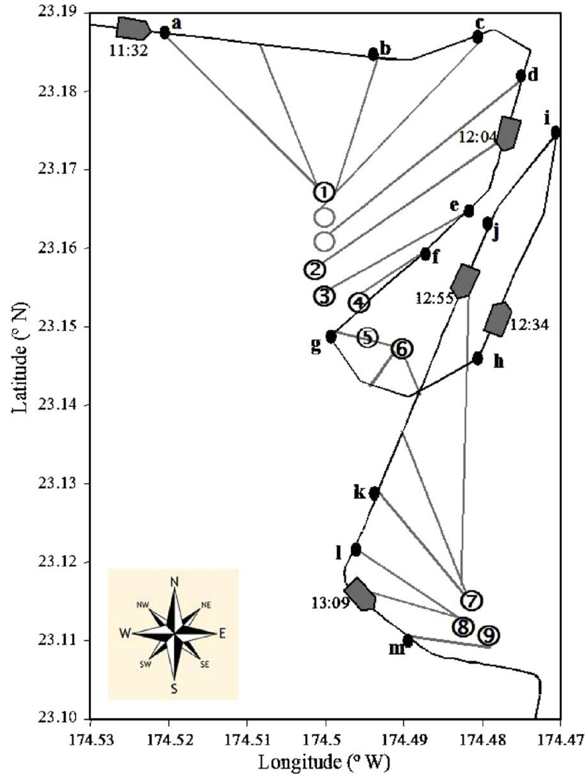

FIG. 1. (Color online) Diagram of ship movement along the trackline, with visual and acoustic detection events. Axes are in decimal degrees of north latitude and west longitude. Ship position and direction, with the associated time, are shown at intervals along the trackline. Select bearing angles and lettered points indicate events described in the text. Numbered circles indicate acoustic position for sound source and/or visual location for minke whale. Gray lines represent acoustic bearing angle to sound sources, gray circles represent probable location of sound source based on continuous acoustic tracking. For clarity of presentation, we do not show all acoustic bearing angles.

The vocalizations recorded in the presence of the single individual minke whale sighted during the HICEAS survey (sighting number 267) were identified and localized using bearing angles estimated with ISHMAEL software. Three angles from different sections of each boing vocalization were measured to determine the precision of beamform angles. The average maximum difference in bearing angles from different sections of the same boing sound was 2.8 degrees$(n=99)$. Vocalizations in which consistent angles to the sound source could not be verified were not used to provide location information. Boing vocalizations recorded from sighting number 267 were measured to estimate the variation in the call characteristics within a single individual, as well as to examine the intercall interval. The mean swimming speed and direction of travel was determined using the updated visual and acoustic methods independently.

III. RESULTS

A. Account of acoustic localization linked to *B. acutorostrata* sighting

At 11:32 local time on 7 November 2002, one author (S.R.) detected a distinct series of boing sounds [Fig. 1(a)].

The convergence of successive angles suggested that the sound source passed 2 km from the ship's beam at 11:53 [Fig. 1(b)]. The visual team did not detect any animals, despite good observing conditions (Beaufort sea state 2). The ship was directed 30° left of the trackline to address the left/right ambiguity of the bearing angles [Fig. 1(c)]; a subsequent 150° angle indicated that the animal had passed the ship on the starboard side at the position 23° 10.0′N and 174° 30.0′W (Fig. 1-1). A turn of 130° to the starboard was made to approach the sound source. Boing vocalizations were continuously detected during the turn; however, the increased noise from cavitation interfered with our ability to determine the angle to the sound source for 2.5 minutes. After the completion of the turn, the boing vocalizations were detected at 36° from the bow, coinciding with the expected location of the sound source [Fig. 1(d)]. Continuous detection of boing vocalizations allowed for tracking of the sound source. The acoustics team provided the visual observers with continuous updates on the estimated position of the calling animal to assist them in visually detecting the source of the boings.

The acoustics team continuously detected boings at progressively greater angles, and at 12:04 the acoustics team obtained an updated position for the sound source at 30° right and 3.7 km ahead of the ship (Fig. 1-2). This position was 1.2 km from the initial acoustic location determined at 11:53. At 12:09, computer records indicate an initial sighting of a whale at 5° left and 1.16 km from the ship. The observers did not inform the acoustics team of this detection, and this position was 1.9 km from the resighted location 2 minutes later. There were no further sightings in the vicinity of this initial sighting, and it appears that this initial sighting information was recorded in error. A turn of 30° to the right was made at 12:09 to approach the sound source. Immediately after the turn the acoustics team detected boings at 13° off of the bow [Fig. 1(e)], and notified the visual team of the updated location (Fig. 1-3). This position was 0.33 km from the latest acoustic boing location made at 12:04. At 12:11 one observer briefly detected an animal 13° to the right of the ship and identified it as a baleen whale. The dorsal fin and part of the back were seen as the animal rolled, and the animal was lost immediately. Three minutes later, the acoustics team detected seven extremely intense boings between 6° and 10° off the bow of the ship using the towed array [Fig. 1(f)]. For the first (and only) time, the sounds were detected on the bow hydrophones. The boing vocalizations ceased at 12:15 for a brief period. Less than 1 minute after the boings stopped, the observers on the flying bridge reported a baleen whale 100 m off the bow, at a position 43 m from the estimated position obtained by the acoustic team based on continuous tracking of the boing source (Fig. 1-4). The animal then breached 100 m off the starboard beam and was positively identified as a minke whale.

Several turns were made to keep the animal within view [Fig. 1(g)]. Boing vocalizations resumed at 12:20, and at 12:23 the animal was resighted at 90° and 0.7 km to the left of the ship (Fig. 1-5). At 12:25 an estimated position of the sound source using the hydrophone array was found to be 0.5 km from this resighted location (Fig. 1-6). A decision was made to launch the rigid-hulled inflatable boat (RHIB) to obtain a biopsy. During the launch procedure the main research vessel could not make course adjustments, so the observers soon lost visual contact with the whale [Fig. 1(h)]. Cavitation caused by the slow vessel speed necessary for RHIB launch made it impossible for the acoustic team to detect boings during the launch. After the launch was complete, the vessel turned towards the last known location of the whale and regained speed for acoustic survey operation [Fig. 1(i)].

At 12:46, boing vocalizations were again detected 16° off of the bow [Fig. 1(j)]. Calls were detected continuously, and the visual observers were provided with updated estimations of the bearing angles. At 13:05 the boing location was determined to be at 64° and 2.1 km from the ship [Fig. 1(k)]; at this time the left/right ambiguity prevented us from determining the exact position to the sound source (for clarity in the diagram, only the port angles and position are shown, Fig. 1-7). At 13:07 the visual team detected an animal at 70° to the left of the ship (Fig. 1-l). After the completion of the turn, the visual observers detected the animal at the same angle and within 0.3 km of the location of the boing source as determined by the acoustic team (Fig. 1-8). The turn also allowed the acoustics team to address the left/right position ambiguity; we had turned towards the direction of the sound source. During the final approach at 13:12, the source of the boing vocalizations was found to be 31° [Fig. 1(m)], which coincided with the final updated visual location at 34° to the left of the ship (Fig. 1-9). Increased ship noise due to decreased ship speed and maneuvering precluded additional acoustic detection for the remainder of the encounter. The animal remained at the surface and at this point did not appear to react to the approach of the vessels. The RHIB approached the minke whale and obtained photographs and a biopsy sample.

The mean swimming speed was determined by calculating the time interval between location updates. The mean swimming speed of the sound source was found to be 5.6 km/h based on four acoustic locations. The swimming speed of the minke whale was 5.7 km/h based on the five visual resights. The average interval between calls was 28 seconds; based on a 5.6 km/h swimming speed, the animal would have moved approximately 45 m between calls.

B. Call characterization and geographic variation

Boing vocalizations consist of a brief pulse followed by a long call that is both frequency modulated (FM) and amplitude modulated (AM) (Figs. 2 and 3). Based on our measurements of 128 boings, the calls can be grouped into two distinct call types with nonoverlapping pulse repetition rates (Fig. 4, Table I). Those with pulse repetition rates of 91–93 s^{-1} were all detected east of 138°W and match Wenz's (1964) description of the San Diego boing (Fig. 5). Those with pulse repetition rates of 114–118 s^{-1} were all detected west of 135°W and match Wenz's description of the Hawaii boing (Fig. 5). The distribution of these boing types clearly extend far from San Diego and Hawaii (Fig. 5), so we will refer to these as eastern and central boings, respectively.

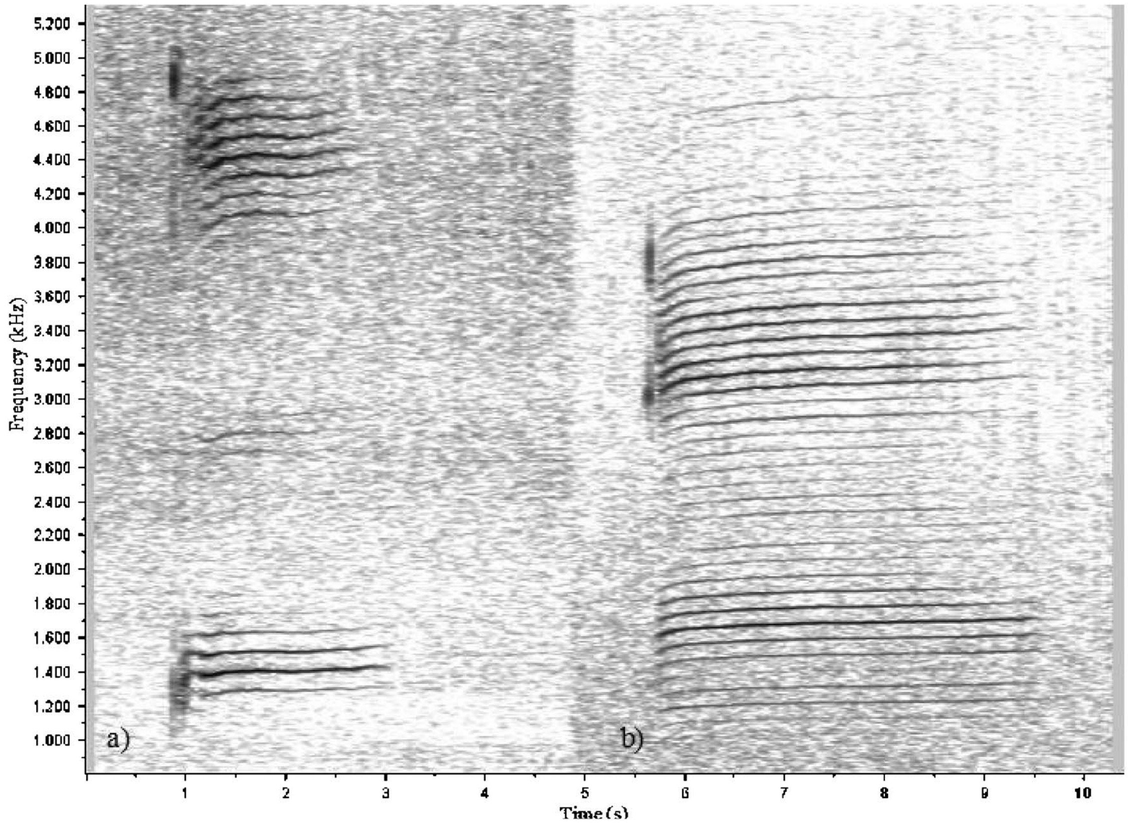

FIG. 2. Spectrogram of the (a) central boing and (b) eastern boing (sampling rate 48 kHz, FFT 8192, 75% overlap, Hanning window).

The eastern boing has a significantly longer duration (mean $=3.6$ s, $n=22$) than the central boing (mean$=2.6$ s, $n=106$) (t-test, $p<0.001$). Within each call type, no significant between-year differences were found for call duration ($p=0.61$ and $p=0.93$ for eastern and central calls, respectively) or for pulse repetition rate ($p=0.06$ and $p=0.11$ for eastern and central calls, respectively).

There were approximately 100 vocalizations made in the location of the single minke whale seen on 7 November 2002 (sighting number 267). Measurements of 84 high-quality boings from this individual indicated a variation in the pulse repetition rate that is within the range noted for the central boing (mean=114, SD=0.8, Table I). The mean duration

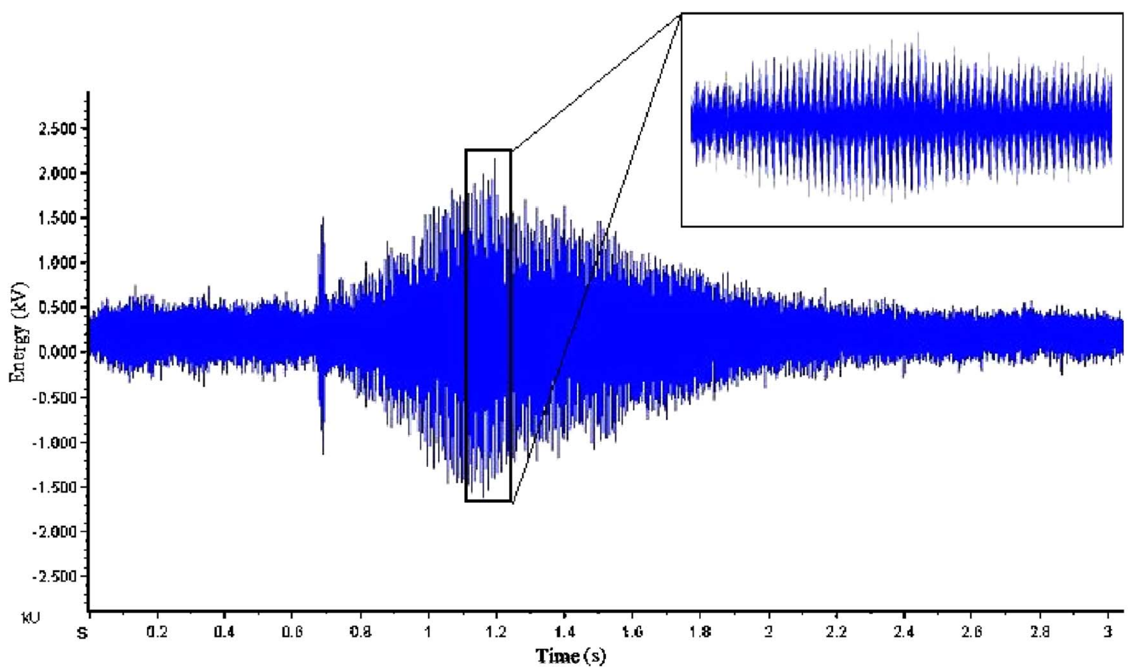

FIG. 3. (Color online) Waveform of the central minke whale boing vocalization. The pulse repetition rate can be seen clearly in the expanded waveform (inset).

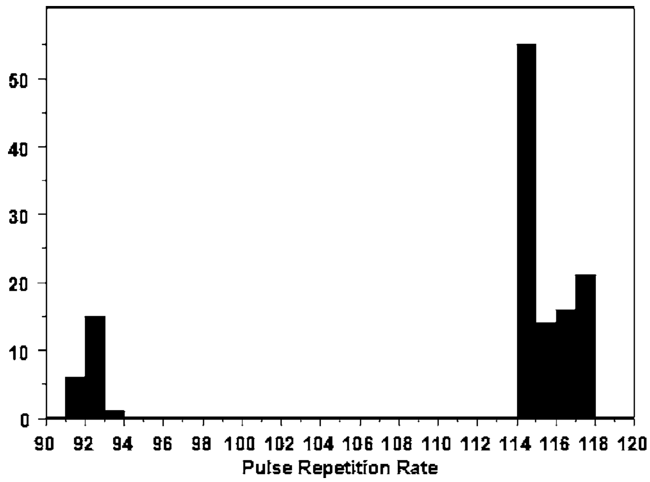

FIG. 4. Frequency distribution for pulse repetition rates of 128 boing vocalizations measured for this study. Boing sounds with pulse repetition rates of 91–93 s^{-1} are referred to as eastern boings, and those with pulse repetition rates of 114–118 s^{-1} are referred to as central boings.

(2.0 s, SD=0.5) was also typical of the central boing. The mean time interval between calls of this individual was 28.7 s (SD=14.1, n=100).

IV. DISCUSSION

Boing sounds are seasonally common in the North Pacific Ocean, yet sightings of minke whales are rare. We believe that the dearth of sightings can be explained by the difficulty in visually detecting this species in rough sea conditions. In over 326 000 km of survey search effort during Southwest Fisheries Science Center (SWFSC) cruises since 1986, 42% of 21 minke whale sightings were in Beaufort sea state 0 or 1, while only 4% of the effort was in these sea states (SWFSC unpublished data). Minke whales are the smallest of baleen whales and are typically encountered individually or in small groups of two or three. They have inconspicuous blows, and do not surface for extended periods of time. Additionally, the waters covered by these surveys are dominated by high sea states associated with the trade winds. Combined, these features reduce the probability of sighting minke whales, and may explain the discrepancy between the low visual detection of minke whales and the high acoustic detection of boings.

One author (S.R.) participated in a survey off Kauai during the peak boing season (February) on the R/V *Dariabar*. On 21 February 2005, in Beaufort sea state 1 conditions, an intense series of boing sounds were detected using a towed hydrophone array as a minke whale surfaced next to the ship. Bearing angles to the sound source agreed with those obtained independently by the visual observers. The presence of other species in the immediate area precluded confirmation that the minke produced the boing vocalizations; however, this detection supports our findings. Additional effort during the peak calling season should be made to confirm these results.

The basic call characteristics of the boing vocalizations measured in this study are similar to those described in earlier research (Wenz, 1964; Thompson and Friedl, 1982). Previous studies referred to these call types as the “Hawaiian” and the “San Diego” boings (Wenz, 1964). These names reflect recording stations rather than the distribution of call types; to avoid confusion we have referred to them as the “eastern boing” (previously the San Diego boing), and the “central boing” (previously the Hawaii boing). An unpublished paper by Turl (1980) identifies anecdotal recordings off of Japan that suggest there may be an additional “western boing” type.

Measurements from a total of 84 calls near the single vocalizing minke whale (HICEAS sighting number 267) indicate that the variation in duration and pulse repetition rate within individual sources is similar to that seen among individuals for the same call type. This suggests that differences in call characteristics found between detections is not necessarily due to individual variation. Limitations of the frequency response of the towed hydrophone array and ship noise interference did not allow for measurement of peak frequencies. Nonetheless, measurements based on the harmonics were similar to previous reports that indicated a variation in peak frequency between the eastern and central boings (Wenz, 1964). Peak frequency may have an individual-specific component that should be examined in future studies.

The swimming speed and direction of the minke whale during this encounter (sighting number 267) was found to be nearly identical based on the visual and acoustic detections (5.7 km/h and 5.6 km/h, respectively). This speed is reasonable, but higher than that found by other researchers (Stern, 1992; Folkow and Blix, 1993; Heide-Jørgensen *et al.*, 2001).

Geographic variation in vocalizations has been found for many cetacean species, including blue whales (Stafford *et al.*, 2001) and Bryde’s whales (Oleson *et al.*, 2003). The

TABLE I. Measurement of repetition rate and call duration for eastern and central boing vocalizations. One sample from each clear detection was measured and divided into Eastern and Central boing types. Measurements of 84 boing vocalizations associated with sighting number 267, *B. acutorostrata* are presented for comparison.

		Repetition Rate (pulses/s)				Duration (s)			
	Count	Mean	St. Dev.	Minimum	Maximum	Mean	St. Dev.	Minimum	Maximum
Eastern boing	22	91.8	0.5	91	93	3.6	0.5	2.4	4.3
Central boing									
Overall	106	115.0	1.3	114	118	2.6	0.4	1.7	4.0
Sighting number 267	84	114.3	0.8	112	116	2.0	0.5	0.8	3.0

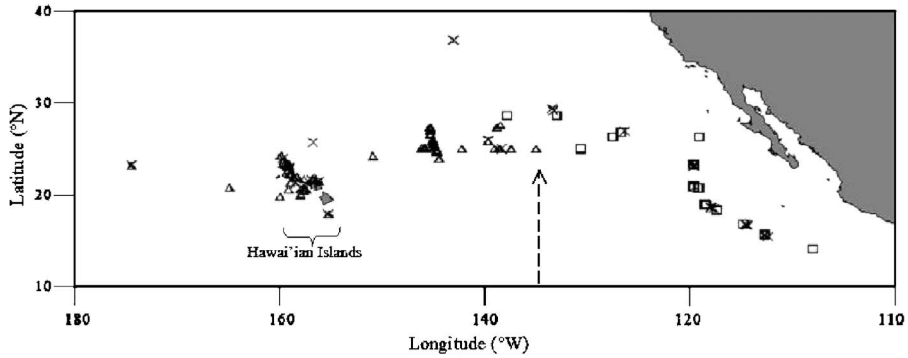

FIG. 5. Map of the location of boing sources from the SWAPS, HICEAS, and STAR surveys. The central boings are represented by open triangles, the eastern boings are represented by open squares, and the ×'s indicate the location of calls too faint for measurement of the call characteristics. The dashed arrow indicates the approximate geographic division between the eastern and central boings.

distinct differences in pulse repetition rate and duration of the central and eastern boing may indicate such geographic variation in North Pacific minke whale populations. Future research should include both acoustic and genetic sampling of minke whales throughout the North Pacific to identify different minke whale populations.

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