Acoustic properties of humpback whale songs

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A vertical array of five hydrophones was used to measure the acoustic field in the vertical plane of singing humpback whales. Once a singer was located, two swimmers with snorkel gear were deployed to determine the orientation of the whale and position the boat so that the array could be deployed in front of the whale at a minimum standoff distance of at least 10 m. The spacing of the hydrophones was 7 m with the deepest hydrophone deployed at a depth of 35 m. An eight-channel TASCAM recorder with a bandwidth of 24 kHz was used to record the hydrophone signals. The location (distance and depth) of the singer was determined by computing the time of arrival differences between the hydrophone signals. The maximum source level varied between individual units in a song, with values between 151 and 173 dB *re* 1 μPa. One of the purposes of this study was to estimate potential sound exposure of nearby conspecifics. The acoustic field determined by considering the relative intensity of higher frequency harmonics in the signals indicated that the sounds are projected in the horizontal direction despite the singer being canted head downward anywhere from about 25° to 90°. High-frequency harmonics extended beyond 24 kHz, suggesting that humpback whales may have an upper frequency limit of hearing as high as 24 kHz. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2211547]

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I. INTRODUCTION

There is a growing concern on the effects of anthropogenic sounds on marine mammals, especially on mysticetes or baleen whales (NRC, 2003). As noise in the oceans continues to increase (Richardson *et al.*, 1995) there is a need to have appropriate regulations limiting the production of man-made sounds. However, one of the major problems in establishing standards and enacting regulations and guidelines is our poor understanding of the hearing sensitivity and frequency range of hearing of baleen whales. Our knowledge of the hearing capabilities of baleen whales is extremely limited and, without having any audiograms, we cannot estimate the sound pressure levels at various frequencies at which a whale may be affected behaviorally or when it will incur temporary and even permanent hearing threshold shifts. However, we can gain insight as to the amount of acoustic energy baleen whales, such as humpback whales, typically tolerate by knowing the source levels of their song emissions. This notion was expressed in the National Research Council's report on Ocean Noise and Marine Mammals (NRC, 2003), which stated that it is first critical to obtain information on what vocalizations are produced during normal conspecific interactions that might reveal information about the susceptibility of marine mammals to sounds of human origin. Humpback whales on their low-latitude wintering grounds produce so-called "social sounds" (Pack *et al.*, 2005; Silber, 1986) as well as a complex and structured series of vocalizations termed "song" (Payne *et al.*, 1983; Payne and McVay, 1971; Winn and Winn, 1978). While social sounds appear to be produced by females as well as males (Pack *et al.*, 2005), songs are produced exclusively by male humpbacks (Darling

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and Berube, 2001; Glockner, 1983). Although singers typically are lone males, singing sometimes occurs in the presence of other whales. For example, a male humpback will occasionally sing while escorting a female with her calf (Baker and Herman, 1984; Darling and Berube, 2001; Frankel *et al.*, 1995; Herman and Tavolga, 1980). Typically, the "singing escort" is within 100 m and approaches within one to two whale lengths of the mothercalf pair. Also, Darling and Berube (2001) documented 14 cases in which a male humpback whale approached close to a singer. Thus, by obtaining good source level measurements, we can also estimate the maximum amount of acoustic energy singing humpback whales expose to conspecifics.

The list of studies involving humpback whale songs is long and extends from 1970 (Winn *et al.*, 1970; Payne and McVay 1971) to the present time (Mercado *et al.*, 2005). Helweg *et al.* (1992) have written an excellent review on the current understanding of humpback whale songs. The various aspects of humpback whale songs that have been studied include geographic and seasonal variations in songs (Au *et al.*, 2000; Helweg *et al.*, 1998; Cerchio *et al.*, 2001), evolution of song structure throughout the year and between years (Guinee *et al.*, 1983; Payne *et al.*, 1983), size of singers (Spitz *et al.*, 2002), and the behavioral and spatial pattern of singers (Frankel *et al.*, 1995; Tyack, 1981), to name a few.

In all these studies the source levels produced by singing humpback whales have been almost entirely ignored. Frankel (1994) estimated the source level of singing humpback whales to be about 140 to 170 dB *re* 1 μPa with data collected from an array of hydrophones where most of the whales were 2 to 8 km away. The propagation losses were estimated using a simple cylindrical spreading model which is always subject to uncertainty when dealing with shallow coastal waters of varying depth. Furthermore, no consideration was given to the difference in source levels for different units.

The source levels of nonsong emissions of humpback whales in southeast Alaska, a summer feeding ground, have previously been measured by Thompson *et al.* (1986). Levenson (1972) has also reported on nonsong emissions of humpback whales. Thompson *et al.* (1986) measured grunts, moans, pulse trains, and other externally produced water interactive sounds such as slaps. Maximum source levels were 162–171 dB for low-frequency pulse trains from a visible feeding whale, 179–181 dB for blowhole shrieks, and 181–185 dB for trumpet like horn blasts. The values provided by Thompson *et al.* (1986) were considerably higher than those reported by Levenson (1972), who found a range of 144–175 dB *re* 1 μPa at 1 m for 64 *song* components from humpback whales in the Atlantic. However, the source levels of sounds produced by singing and nonsinging whales can be considerably different because of differences in the characteristics of nonsong and song emissions.

The Hawaiian Islands is the principal area of congregation for wintering North Pacific humpback whales (Calambokidis *et al.*, 2001). Humpback whales migrate to Hawaii from Southwest Alaska each winter to mate and give birth, though neither event has ever directly been observed. Most singing by humpbacks takes place on the winter grounds, although singing also occurs, but not as widespread, during the northbound migration (Norris *et al.*, 1999) and in the summer feeding grounds (Clark and Clapham, 2004).

In this study, the acoustic characteristics of singing humpback whales were measured with a vertical line array of five hydrophones deployed in close proximity to the whales. From these measurements, the distance of a whale from the array could be accurately estimated and the source level determined. Other features of the sound emissions such as the extent of the high-frequency harmonics and the directionality of the high-frequency components of the sounds were also investigated.

II. METHODS

Recordings of humpback whales (*Megaptera novaeangliae*) were made in the waters of the Auau channel between the islands of Maui, Lanai, Kahoolawe, and Molokai from 22–25 February 2002. The waters of this region contain one of the densest concentrations of humpback whales in the Hawaiian Island chain during the winter and spring months (Herman and Tavolga, 1980; Mobley *et al.*, 1999). Singers were located using a hand-held two-element horizontal hydrophone array termed "Aquahead" (Pack *et al.*, 2003). Singing humpback whales often suspend themselves in the water column with the longitudinal axis of their body between 0° and 75° from the vertical. Eventually they rise to the surface to expel spent gases and to recharge their respiratory system with fresh air before submerging again to take up a singing posture. When a singer was spotted surfacing to recycle its air supply and then resubmerging again, two swimmers with snorkeling gear entered the water. One swimmer was equipped with a digital video camera in an underwater housing, and also a hand-held 200–400-kHz range finder to determine the body length of the whale as it surfaced using underwater videogrammetry (Spitz *et al.*, 2000). The other swimmer swam to the location at the surface above the whale and indicated the heading of the whale. The whale was usually at a depth of about 15 to 25 m. The boat was then driven in front of the submerged whale, the engine was turned off, and a vertical array of five hydrophones was deployed (Fig. 1) while a swimmer oriented the boat by tugging on the bow line. Both the whale and the boat would drift over a period of minutes.

The hydrophones were spaced 7 m apart with the shallowest hydrophone submerged to a depth of 7 m. The whale's song was recorded on an eight-channel Teac TASCAM (Model DA-78HR) for as long as the whale remained in the vicinity of the boat. The sampling rate of the TASCAM was set at 48 kHz. The hydrophones were constructed of lead zirconate titanate (PZT) piezoelectric ceramic tubes having an o.d. of 1.3 cm, a wall thickness of 1.1 mm, and a length of 1.3 cm. The inner diameter of the tube was filled with corprene (a cork-neoprene material) and the element was encapsulated in degassed epoxy. The sensor was attached to an amplifier-line driver having a gain of 30 dB. The hydrophones were calibrated in a test tank and had similar responses and a sensitivity of approximately -175 ± 3 dB *re* 1 v/μPa between 100 Hz and 15 kHz. The

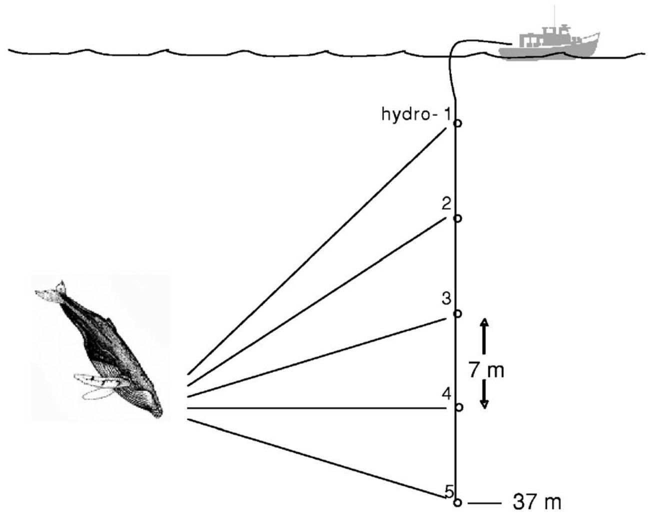

FIG. 1. Experimental geometry showing a singing humpback whale and the vertical array of hydrophones.

program Cool-Edit Pro was used to digitally transfer the multi-channel recordings from the TASCAM to a PC via a Mixtreme PCI card. Cool-Edit Pro controlled the Mixtreme card that performed as the interface to transfer the data.

To determine the source level of the singing whale, an accurate distance between the whale and the array was needed. By using the signals from three of the hydrophones the whale could be localized in depth and distance from the array. The localization of any sound source using the signals received by a line array can be achieved by determining the time of arrival differences between the center hydrophone and the other two hydrophones. The specific equations relating the time of arrival differences to the location of the source are given in the appendix of Lammers and Au (2003). The differences in the time of arrival of the signal at the three hydrophones are determined by calculating the cross-correlation integral for the signals measured by any two of the hydrophones. The time difference occurs at the time corresponding to the peak in the cross-correlation integral.

There are several ways to describe the acoustic source level of a singing humpback. The source level can be described in terms of the peak-to-peak, the root mean square (rms), and the energy flux density of the acoustic pressure. The rms source level can be expressed as

$$\mathrm{SL}_{\mathrm{rms}} = 20 \log \sqrt{\frac{1}{T}\int_0^T p^2(t)dt} + 20 \log R$$

$$= \mathrm{SE} - 10 \log T, \qquad (1)$$

where SE is the source energy flux density, T is the duration of the signal, $p(t)$ is the acoustic pressure waveform, and R is the range of the source from the measuring hydrophone. The source level will be presented in terms of the peak-to-peak, the rms, and the energy flux density of the acoustic pressure. The duration of the signal will be determined by calculating the energy flux density [the integral in Eq. (1)], choosing the time at which the energy is between 1% and 99% of the maximum energy.

III. RESULTS

The vertical hydrophone array was deployed in the near vicinity of nine singing humpback whales. The duration of each recording varied from 1 to 17 min depending on how long the whale remained in the vicinity of the boat. For the shortest recording, the whale moved out of the vicinity of the boat only a minute after the array was deployed. Four themes were aurally classified from the songs recorded for the nine whales, although this process can be very subjective and other researchers may actually identify different numbers of themes.

Payne *et al.* (1983) defined a humpback whale song unit as "the shortest sounds in the song which seem continuous to the human ear." We aurally classified nine distinct units and confirmed our judgment by examination of the spectrograms of the songs. An example of the waveform and spectrogram of each of the nine units is shown in Fig. 2 and the aural description of the units is listed in Table I. The descriptions were agreed upon by two listeners discussing their subjective sense of the best description.

The spectrograms can be separated into two groups, those units that have some tonal quality and higher frequency harmonics (units C, E, E_2, and H) and those that are relatively broadband with rumble, grunts, or gurglelike qualities

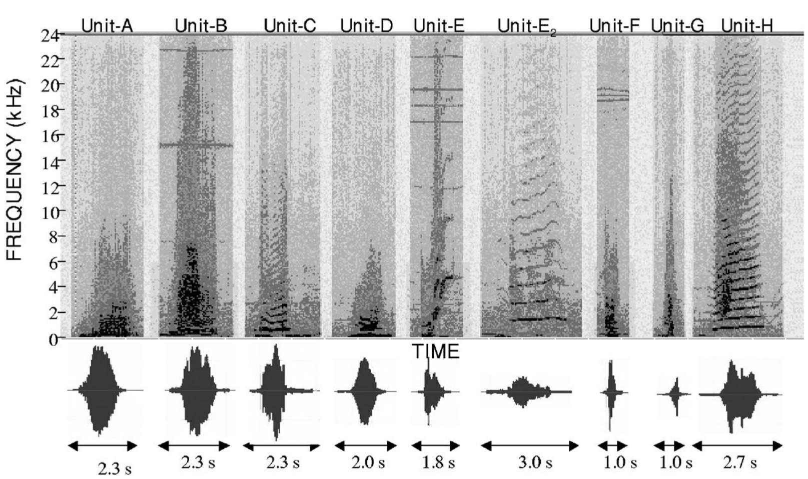

FIG. 2. Spectrogram and waveform representation of the nine units contained in the humpback whale songs during the winter season in Hawaiian waters in 2002. The units were from the recordings of several whales and were chosen because they showed the characteristics of the unit most clearly.

TABLE I. Aural description of the nine units for the humpback whale songs during the 2002 wintering season in Hawaii.

Unit	Description
A	vibrating upsweep
B	double upsweep
C	frequency sweeping cry
D	flat tonal groan
E	low gulp jumping to very sharp upsweep
E_2	high-frequency tonal wail
F	short low-frequency downsweep
G	short low-frequency upsweep
H	mid-frequency tonal wail

and with weak harmonics (units A, B, D, F, and G). The units with some tonal elements and high-frequency harmonics were described as cries or wails. Four distinct themes were found for the nine whales that we recorded. The sequence of units producing each theme is listed in Table II.

We found that certain units resulted in relatively unambiguous peaks in the cross-correlation function whereas others did not. Unit A was one of the better units to use, however, only three whales had this unit for a sufficient length of time to provide a good track. The tracks of three humpback whales given in terms of the horizontal distance from the boat and the depth of the whales are shown in Fig. 3. Once the whales sounded and moved into their singing position in the water column, they seemed to be relatively stationary whereas the boat housing the array was free to drift with the engine turned off. However, the three tracks show that the depth of the whale varied from about 15 m for whale E4 to slightly over 10 m for whales I2 and L2.

The peak-to-peak and rms source levels and the source energy flux density for the three whales tracked in Fig. 3 are shown in Table III for the nine units. Several results are noteworthy. The relationship between the rms source level and the peak-to-peak source level is slightly different for the different units. SL_{pp} was between 17 and 20 dB greater than SL_{rms}, and variation is probably due to difference in the shape of waveform shown in Fig. 3. If we consider the difference between SL_{pp} and SL_{rms} across the 778 units for the results on Table III, the following relationship is obtained,

TABLE II. The general sequence of units producing the four themes observed in the recordings of nine singers. There is considerable variability in a theme associated with the number of or sequence of the units. The units in parentheses are those that are repeated seemingly randomly from one to seven times, depending on the specific whale.

Theme	Units
1	B C (B-C) D D A
2	D A D E F D (E-F-D) E A
3	A F F F A F F E F D (E-F-D) E2 E
	A F F F A F F F F E E E [without (E-F-D)]
4	G G G G H

The specific number of F units can vary between 2 and 7, and E units between 1 and 3.
Sometimes the H unit is not emitted.

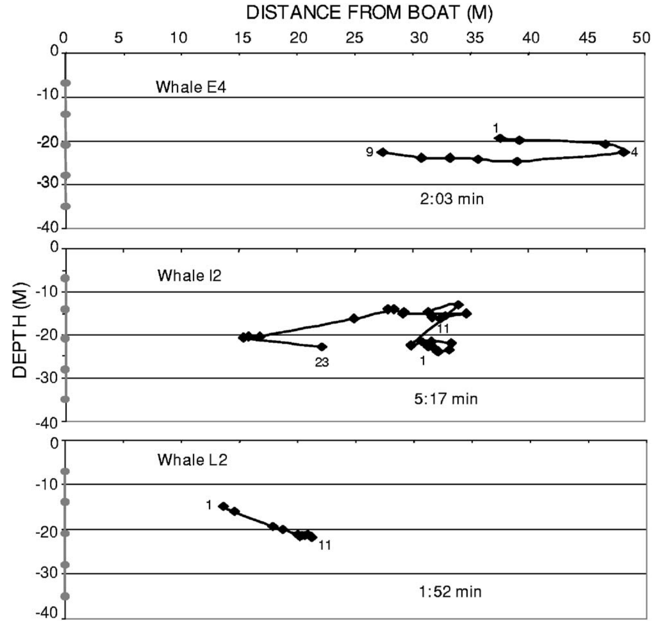

FIG. 3. Tracks of three singing humpback whales from the boat carrying the vertical line array. The numbers next to the points are the order of the localization with 1 being the first localization. The time shown on each plot is the total amount of time the whale was localized. The circles on the left vertical axis represent the hydrophones in the line array.

$$SL_{rms} = SL_{pp} - 17.1 \pm 2.7 \text{ dB}, \quad (2)$$

where 2.7 is the standard deviation. For a continuous sine wave signal, the difference between the peak-to-peak and the rms values is 9 dB. The 17.1 dB difference for the humpback whale originates from the pulse nature of the units and the slow rise and fall times of the waveforms.

The highest average rms source level recorded was 169 dB for whale E4 producing units A and D, and for whale I2 producing unit B. Unfortunately, units B and C were not recorded for whale E4. The lowest average rms source level was 149 dB for whale I2 producing unit G and whale L2 producing unit F, representing a unit-related 20-dB range in the average source levels. Unit H produced by whale I2 was not considered since only a single H unit was attributed to whale I2. The source level for unit E_2 was also among the lowest levels for all three whales.

The numerical values of SL_{rms} and SE are very similar, keeping in mind that the units of measurements are different. The duration of the units typically varied between 0.4 and 1.4 s except for units E_2 and H, of which we had very few samples. From Eq. (1), the difference in the value of SL_{rms} and SE is in the 10 log T term. With durations close to unity, the log term is negligible. For a duration of 0.4 s, the 10 log term is only 4 dB.

The variation in the mean and standard deviation of SL_{rms} for the nine units of the three tracked whales are shown in Fig. 4. An analysis of variance test was applied to the units produced by the three whales to test if the source levels were significantly different. If they were significantly different, the Tukey HSD *posthoc* test was applied to determine which pairs were significantly different at $p < 0.05$. If only two whales were involved, as in units B and C, a two-tailed t test was applied to determine if the levels were sig-

TABLE III. Results of source level estimation for the three whales whose tracks are shown in Fig. 3. The unit for SL_{pp} and SL_{rms} is dB *re* 1 μPa and the unit for SE is dB *re* 1μPa^2 s.

Unit	SL_{pp} (dB)	SL_{rms} (dB)	SE (dB)	*T* (s)	*N*
			Whale E4		
A	184±4	169±3	169±4	0.9±0.2	19
B					
C					
D	184±4	169±3	169±4	0.9±0.2	19
E	178±2	162±2	160±2	0.7±0.1	17
E_2	172±2	153±3	156±2	2.3±0.9	9
F	173±3	156±3	152±3	0.4±0.2	64
G	181±3	162±4	158±3	0.5±0.3	27
H	179±1	162±0	162±1	1.0±0.2	2
			Whale I2		
A	182±2	165±3	165±2	1.1±0.6	26
B	184±1	169±2	169±1	1.1±0.1	15
C	180±5	162±8	163±7	1.3±0.5	12
D	176±4	161±5	159±4	0.6±0.2	73
E	179±3	163±3	160±3	0.6±0.3	50
E_2	171±6	151±7	155±5	2.9±2.1	9
F	171±6	154±7	151±6	0.5±0.2	39
G	170±3	149±2	147±2	0.8±0.6	16
H	165	144	152	5.7	1
			Whale L2		
A	181±3	164±2	165±3	1.4±0.6	42
B	181±3	164±2	165±2	1.2±0.4	23
C	183±2	167±3	166±2	0.9±0.2	21
D	173±6	160±4	157±5	0.6±0.2	56
E	177±4	160±4	158±4	0.6±0.2	52
E_2	172±4	153±5	157±3	3.3±2.0	26
F	167±3	149±4	148±4	0.8±0.3	143
G	177±3	157±3	155±2	0.6±0.2	18
H	169±7	153±10	156±8	1.8±0.0	2

nificantly different at $p < 0.05$. Whale E4 produced louder sounds than the other two whales for units A and G. For the other units, the level of whale E4 was not significantly different from either whale I2 or L2. Whale L2 had the lowest source level when producing units B, D, E, and F. However, for units C and G, whale L2 sounds were louder than those of whale I2. Unit H was hardly recorded for the three whales, occurring twice for whale E4 and L2 and once for whale I2.

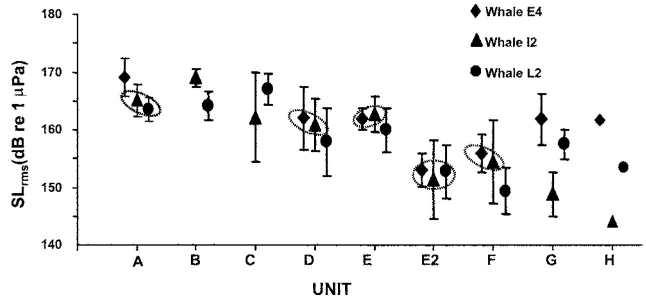

FIG. 4. The mean and standard deviation of the rms source level of the different units for the three whales tracked in Fig. 3. The means that are enclosed within a dashed oval are not significantly different. All other units are significantly different at $p < 0.05$.

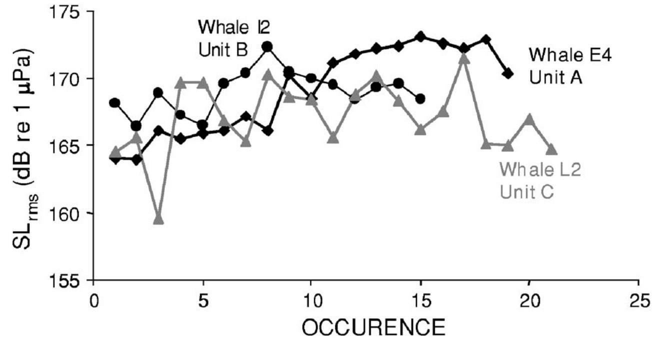

FIG. 5. The rms source level for the unit having the highest intensity for each of the three whales tracked in Fig. 3.

The rms source levels for the most intense unit emitted by the three whales are shown in Fig. 5. Unit A had the highest average source level for whale E4 with a maximum of 173 dB. The source level remained above 170 dB on nine occasions during the period the whale was tracked. Unit B was the most intense unit emitted by whale I2, reaching a level of 172 dB. Six emissions of unit B sounds were equal to or above 170 dB source level. Unit C was the most intense unit emitted by whale L2, with the highest level being 172 dB. However, only 4 of the 27 units were above 170 dB. Although the average source level of unit A emitted by whale E4 was the same as unit B emitted by whale I2, Fig. 5 clearly show that whale E4 emitted higher level signals than whale I2 but had a greater range between the lowest and highest levels which brought down its average source level for unit A.

There were three units (E, E_2, and H) that had very-high-frequency harmonics that extended beyond 24 kHz, which was the upper limit of the TASCAM recorder. The spectrogram and frequency spectrum of unit H sounds produced by three different whales are shown in Fig. 6. These spectrograms show the highest harmonic levels ever reported. The frequency spectra plots alongside the spectrograms indicate that the higher frequency harmonics do not drop off very rapidly. The frequency spectra were computed in Matlab using a 1024-point fast Fourier transform algorithm and a rectangular window. At a frequency of 10 kHz, the amplitude of the spectra is about −20 dB below peak amplitude for whales E4 and F4 and about −22 dB for whale L2. At a frequency of 22 kHz, the amplitude of the spectra is between −38 and −42 dB below the peak amplitude. Although unit H was recorded only 11 times total from nine whales, representing the least recorded unit, it was selected to be reported in Fig. 5 because of its unusually high-frequency harmonic structure.

The source levels measured by four of the five hydrophones in the array for unit H sounds from whale E4 and a unit E_2 sound from whale L2 are shown in Fig. 7. During the field measurements, one hydrophone in the array consistently malfunctioned, which limited the angular resolution of our measurements. Units H and E_2 were specifically chosen because both units were rich in high-frequency harmonics so that the sound field at the fundamental and harmonic frequencies could be easily determined. The closed circles for the fundamental frequency are the estimated source level

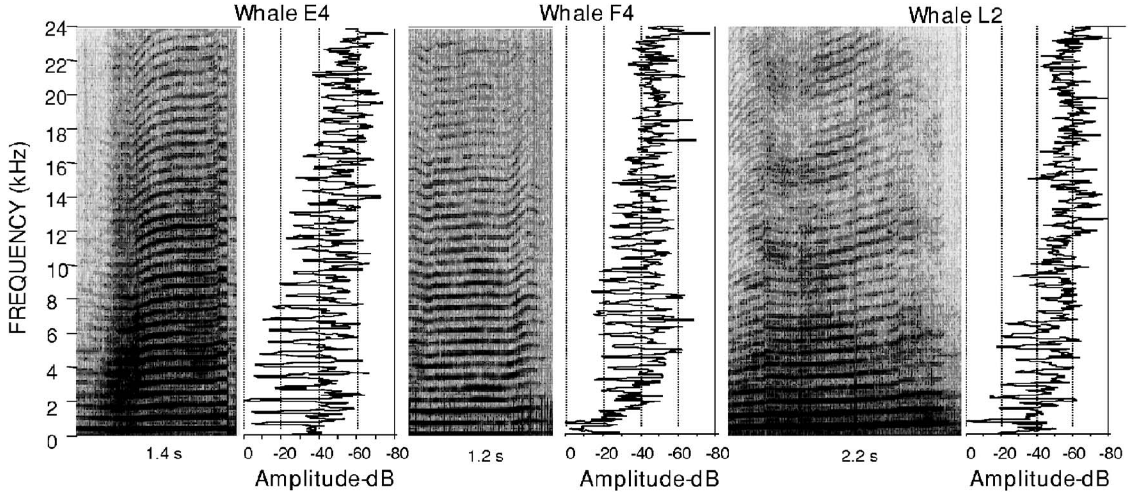

FIG. 6. Spectrogram showing the frequency versus time variation of unit H sounds and corresponding frequency spectra plotting relative amplitude as a function of frequency. The plots depict the high-frequency nature of unit H sounds showing harmonics extending beyond 24 kHz for three different whales.

from each of the four working hydrophones. Specific points were not shown for the higher harmonics to keep the plots relatively simple and uncluttered. The line connecting the points for the fundamental frequency consist of a third-order polynomial fitted to the four source levels.

The polar plots suggest that a beam has started to form in the vertical plane at the fundamental frequency of 750 Hz for whale E4. The same is true for whale L2 having a fundamental frequency of 1406 Hz. As the frequency increases the beam becomes narrower, however, there is an anomaly between the fifth and seventh harmonic for whale E4, where the beam of the seventh harmonic is slightly larger than for the fifth harmonic. The reason for this anomaly is not known, but may be related to the orientation of the whale. The angle of the whale to the vertical was not ascertained and the array was initially positioned directly in front of the whale; however, the whale could easily pivot about its longitudinal axis to modify the geometry between the array and the whale.

IV. DISCUSSION AND CONCLUSIONS

The use of a vertical line array has been instrumental in determining some of the basic acoustic properties of singing humpback whales. Although humpback whale songs have been recorded and studied for over three decades, only rough estimates of source level have been reported. The results of

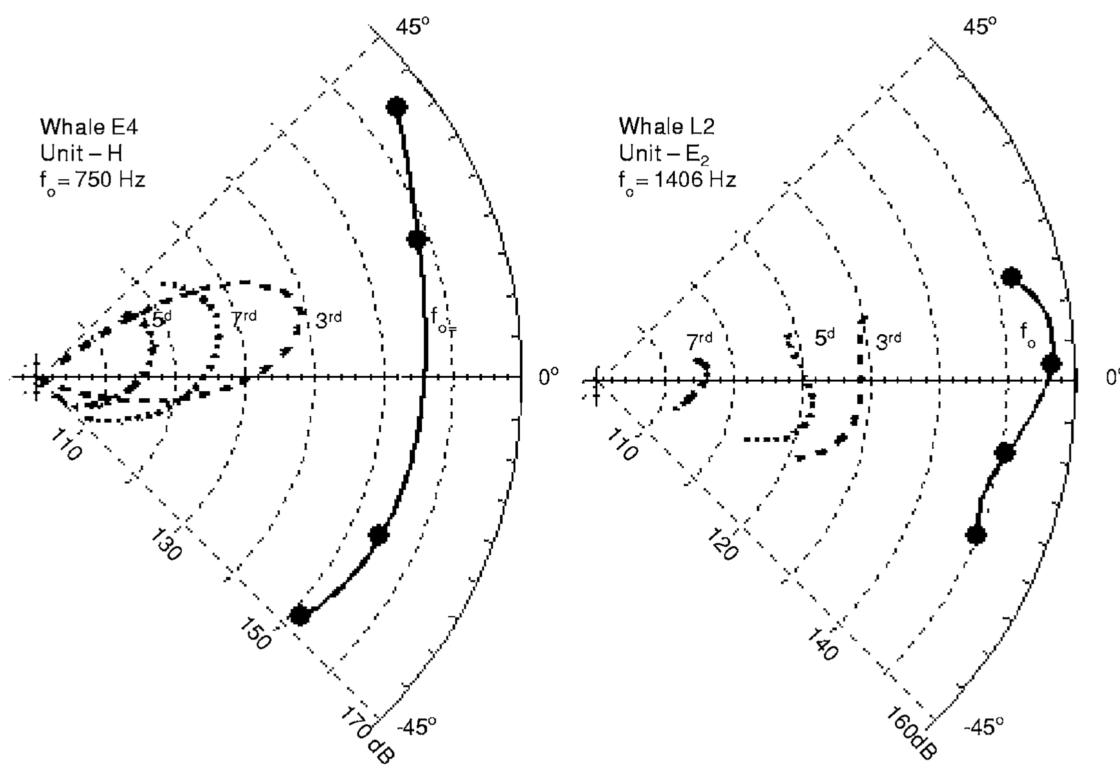

FIG. 7. Polar plot of the rms source level for whale E4 projecting a unit H sound and for whale L2 projecting a unit E_2 sound.

this study indicate that the source level for the different units are not the same but can vary as much as 20 dB between the least intense and the most intense units. The higher level units were the longer broadband units with durations of about 2 s that are described as rumbles, grunts, or gurgles, whereas the lower level units were units with some tonal quality or short broadband sounds such as units F and G. In an anthropomorphic sense, we can usually shout much louder than we can sing. It seems that the same tendency may be true for humpback whales.

The level of anthropogenic sounds that baleen whales should be exposed to is a topic under much discussion (NRC, 2003). The source level results can be used to estimate the level of sounds that other whales are exposed to when in the vicinity of a singer. Singing escorts have been estimated to be as close as two whale lengths away (about 28 m) from a cow-calf pair and other males have been observed to swim within approximately two whale lengths of a singer (Darling and Berube, 2001). If we assume a whale length as approximately 12–14 m, then sounds from a singer would be only about 28 dB lower at the location of the conspecific so that the conspecific would be exposed to sounds with average value of approximately 141 dB for the duration of the song. However, if the higher levels of unit A signals emitted by whale E4 are considered, then a conspecific may be exposed to sounds having a rms level of 147 dB. This also assumes that the singing whale will not lower the level of its output in the near presence of other whales.

The maximum source level of 173 dB measured in this study for whale E4 is slightly lower than the maximum of 175 dB for a moan and much lower than the 190 dB for a grunt measured by Thompson *et al.* (1986) of humpback whales vocalizing on the Alaskan summer feeding grounds. However, this is not unreasonable because a humpback whale will often sing continuously for many minutes whereas the nonsong sounds measured by Thompson *et al.* (1986) were probably not produced regularly over a long period of time. Therefore, the amount of acoustic energy emitted by a singing humpback whale during a dive that may last up to tens of minutes may indeed be greater than the amount of acoustic energy emitted by the nonsinging whales in their feeding grounds. Unfortunately, Thompson *et al.* (1986) did not provide any clues as to the temporal properties of the sounds they measured.

A simpler method of measuring the source level of singing humpback whales is to adapt the videogrammetry technique of Spitz *et al.* (2000) but include a recording system in an underwater housing that the swimmer would also carry. In this technique the distance to the whale is obtained with the use of a high-frequency (200–400 kHz) hand-held acoustic depth sounder (Spitz *et al.* 2002). A benefit to this technique is that the size of the singer can be estimated and the relationship between size and source levels can be established.

There are very little data available that could provide any indication of the upper frequency limit of hearing in baleen whales. A knowledge of the high-frequency harmonics in a signal may provide clues to the upper frequency of hearing in an organism. If the popular notion that animals generally hear the totality of the sounds they produce is applied in this study, then we could conclude that humpback whales probably hear to frequencies beyond 24 kHz. The harmonic structure shown in Fig. 6 is very prominent and certainly suggests that the high-frequency harmonics extend beyond 24 kHz. Although at that frequency, the level of the signal is reduced by 40 to 50 dB from its maximum value; the large dynamic range of the mammalian ear should be able to accommodate this range of acoustic intensity (Yost, 1994). There are several reasons why such high-frequency harmonics have not been previously reported. The most prevalent reason is that cassette tape recorders have been typically used in the past and these recorders have limited bandwidth. However, in the present age, there are many different types of portable digital recorders commercially available and these generally have analog bandwidths up to about 24 kHz or higher.

Initially, it was surprising to see the beginning of directivity in the sound field at the fundamental frequency of units H and E_2. However, a fundamental frequency of 750 Hz for unit H is associated with a wavelength close to 2 m. The average length of a male humpback whale is approximately 12–14 m (Winn and Reichley, 1985) so that considering the ratio of the linear measurement of the head close to the blowhole from photographs, one can estimate a diameter of roughly 1.5–1.7 m. Here we are assuming that the sound source is in the vicinity of the blowhole (Aroyan *et al.* 2000). Therefore, for the head diameter to wavelength ratio, we have $d/\lambda \sim 0.75–0.85$. For unit E_2 and whale L2, the wavelength corresponding to the fundamental frequency of 1406 Hz is close to 1 m so that $d/\lambda \sim 1.5–1.7$. A linear circular transducer will exhibit a directional characteristic when d/λ is close to unity (Urick, 1983). The fundamental frequencies of other units such as units A and B are relatively low at about 210 Hz. For these units $d/\lambda \sim 0.21–0.24$ so that the sound has no directivity at the fundamental frequency.

Singing humpback whales often suspend themselves with the longitudinal axis of their bodies between 0° and 75° from the vertical. The direction of the higher frequency harmonics suggests that the beam of the sound is directed slightly above the horizon. This implies that the sound generator is directing sounds at a steep angle above the animals' head. For low-frequency fundamentals of 200–400 Hz, the beam will be nearly omni-directional so that the orientation of the whales with respect to the vertical is not relevant. However, for the high-frequency harmonics, the orientation of the whale will affect how these harmonics propagate in the horizontal distance. Unfortunately, the precise position of the whales with respect to the vertical was not measured so the angle above the head of the whales cannot be accurately estimated. Humpback whales may be unique in the directions at which sounds are emitted from the head. It seems that most mammals emit sound in the forward direction with respect to their head.

There has been very little work done on understanding the acoustics of humpback whale sounds. In this project, we have only touched the surface of this intriguing subject. However, more needs to be done in order to gain a deeper appreciation of the physics and physiology of sound production in not only humpback whales but in baleen whales in general.

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