

**Vocalizations attributed to humpback whale (*Megaptera novaeangliae*) calves  
recorded in Hawai'i**

Ann M. Zoidis,  
Cetos Research Organization, 11 Des Isle Ave, Bar Harbor, Maine 04609,  
[ann@cetosresearch.org](mailto:ann@cetosresearch.org),  
Mari A. Smultea,  
Smultea Environmental Sciences LLC, 29333 SE 64<sup>th</sup> St, Issaquah, Washington 98027,  
Cetos Research Organization, 3993 Everett Lane, Ferndale, Washington 98248,  
[msmultea@msn.com](mailto:msmultea@msn.com),  
Adam S. Frankel,  
Hawai'i Marine Mammal Consortium, P.O. Box 6107, Kamuela, Hawai'i, 96738-6107,  
[adam.frankel@marineacoustics.com](mailto:adam.frankel@marineacoustics.com),  
Julia L. Hopkins, Andy Day, Sasha Ertl,  
Cetos Research Organization, 3993 Everett Lane, Ferndale, Washington 98248,  
Cetos Research Organization, 11 Des Isle Ave, Bar Harbor Maine 04609,  
[julie@cetosresearch.org](mailto:julie@cetosresearch.org), [andyday69@hotmail.com](mailto:andyday69@hotmail.com), [sasha@cetosresearch.org](mailto:sasha@cetosresearch.org),  
Amy D. Whitt, and Dagmar Fertl  
Geo-Marine, Inc., 2201 Avenue K, Suite A2, Plano, Texas 75074,  
[awhitt@geo-marine.com](mailto:awhitt@geo-marine.com), [dfertl@geo-marine.com](mailto:dfertl@geo-marine.com)

Running Title – Humpback calf hydrophone array recordings

December 12, 2007

Abstract: Humpback whale (*Megaptera novaeangliae*) calves are reported to vocalize but this has not been measurably verified. During March 2006, an underwater video camera and two-element hydrophone array were used to record non-song vocalizations from a mother-calf-escort off Hawai'i. Acoustic data were analyzed; measured time delays between hydrophones provided bearings to 21 distinct vocalizations produced by the male calf. Signals were pulsed (71%), FM (19%), or AM (10%). They were of simple structure, low frequency (mean = 220 Hz), brief duration (mean = 170 ms), and relatively narrow bandwidth (mean=2 kHz). The calf produced three series of "grunts" while approaching the diver. During winters 2001-2005 in Hawai'i, non-song vocalizations were recorded in 109 (65%) of 169 groups with a calf using an underwater video and single (omnidirectional) hydrophone. Non-song vocalizations were most common (34 of 39) in lone mother-calf pairs. A subsample from this dataset of 60 signals assessed to be vocalizations provided strong evidence that 10 male and 18 female calves vocalized based on statistical similarity to the 21 verified calf signals, proximity to an isolated calf (27 of 28 calves), strong signal-to-noise ratio, and/or bubble emissions coincident to sound.

PACS numbers: 43.80.Ka

## I. INTRODUCTION

Humpback whales (*Megaptera novaeangliae*) produce song, non-song social vocalizations, and non-vocal, surface-generated percussive sounds (e.g., caused by breaches, fluke slaps, pectoral fin slaps, etc.) during migration (e.g., Kibblewhite *et al.*, 1966; Payne and McVay, 1971; Norris *et al.*, 1999; Dunlop *et al.*, 2005, 2006, 2007), on low-latitude winter breeding/calving grounds (e.g., Payne and McVay, 1971; Winn and Winn, 1978; Tyack, 1981, 1982; Darling, 1983; Silber, 1986; Payne, 1983; Helweg *et al.*, 1992, and Au *et al.*, 2000), and on higher-latitude summer feeding grounds (e.g., Thompson *et al.*, 1977; Jurasz and Jurasz, 1979; D’Vincent *et al.*, 1985; Sharpe *et al.*, 1998). Songs are well-documented vocalizations produced by males predominantly on the wintering grounds where they appear to be part of breeding displays (e.g., Payne and McVay, 1971; Winn *et al.*, 1973; Tyack, 1981; Darling, 1983; Helweg *et al.*, 1992; Au *et al.*, 2000; Darling and Bérubé, 2001; Darling *et al.*, 2006). Singers are typically alone but may also accompany other whales including a mother and calf (e.g., Tyack, 1981; Darling, 1983; Glockner and Venus, 1983; Darling and Bérubé, 2001). Songs are characterized by continuous, repetitive, highly structured phrases and themes that contain units with harmonics above 15 kilohertz (kHz) and sounds above 24 kHz (Payne and McVay, 1971; Darling, 1983; Payne, 1983; Helweg *et al.*, 1992; Au *et al.*, 2000, 2001, 2005, 2006; Fristrup *et al.*, 2003; Potter *et al.*, 2003).

On the wintering grounds, non-song social vocalizations have been documented among adults (Tyack, 1981; Silber, 1986). In contrast to song, adult non-song vocalizations (i.e. “social sounds”) are produced erratically (variable through time, often interrupted by silent periods), are unpredictable, do not contain the rhythmic, consistent and continuous patterning of song, and are known to range from 50 hertz (Hz) to over 10 kHz, with dominant frequencies below 3 kHz (Tyack, 1981; Silber, 1986). Early publications on non-song vocalizations in surface-active groups of wintering humpbacks coined the term “social sounds” to describe that specific behavioral context (Payne, 1978; Tyack, 1982, 1983; Tyack and Whitehead, 1983; Silber, 1986). These social sounds have been reported to occur predominantly in groups of three or more adults composed of a mature female accompanied by a male “principal escort” and other males aggressively vying for a position near her (Tyack and Whitehead, 1983; Silber, 1986; Clapham *et al.*, 1992). Common behaviors include chasing, charging, inflated head lunges, underwater blows, aggressive contact, and fast surface traveling (e.g., Darling, 1983; Tyack and Whitehead, 1983; Baker and Herman, 1984). Although the full function of social sounds in these surface-active groups remains uncertain, they appear to invoke approach or avoidance responses from other whales, depending on sex and composition (Tyack, 1983). They also seem to signal aggression or agitation among males fighting for dominance or proximity to a female (Silber, 1986).

Despite numerous underwater and/or acoustic studies of humpback whale groups containing a mother-calf in Hawaiian waters (e.g., Glockner and Venus, 1983; Tyack, 1983; Silber, 1986; Glockner-Ferrari and Ferrari, 1990; Zoidis and Green, 2001; Cartwright, 2005; Zoidis *et al.*, 2005), only recently have vocalizations been attributed to

individual calves based on observational evidence and underwater video-acoustic data recorded with a single omnidirectional hydrophone (Zoidis and Green, 2001; Pack *et al.*, 2005; Zoidis *et al.*, 2005). Reported evidence includes vocalizations recorded in closest proximity to a calf with no other whales nearby, strong signal-to-noise ratio, and/or vocalizations produced coincident to underwater bubble production by the calf. Though this is strong evidence that humpback calves vocalize, it cannot be ruled out that the sounds did not come from another source/whale that was nearby or not visible (i.e., the omnidirectional hydrophone used in those studies could not provide measurable evidence such as directional bearings linking acoustic data to a source). Published documentation that individual calves of other baleen whale species vocalize is limited to one calf from each of three different species (the first two of which were captive animals): gray (*Eschrichtius robustus*), Bryde's (*Balaenoptera edeni*), and North Atlantic right whales (*Eubalaena glacialis*) (Wisdom *et al.*, 2001; Edds *et al.*, 1993; Parks and Tyack, 2005; Parks and Clark, 2007, respectively).

Dunlop *et al.* (2005, 2006, 2007) remotely recorded non-song vocalizations among migrating humpback mother-calf pairs and other groups with a calf off eastern Australia using an array of five separately anchored hydrophone buoys; however, it was not possible to differentiate which individual vocalized. Dunlop *et al.* (2007) collectively termed these and other non-song vocalizations recorded from any migrating humpback as “nonsong social vocalizations”, although songs were also recorded. Vocalizations were further defined as being internally produced by a whale, including sounds generated from the blowhole. For the purpose of this paper and terminology consistency, we use the term “non-song vocalizations” for sounds attributed to humpback calves that did not meet the aforementioned definition of song and were not percussively generated by body contact with the water surface.

In this paper, directional acoustic data from a two-element hydrophone array combined with underwater video empirically confirm that a male humpback whale calf produced non-song vocalizations. Additional data indicate that both male and female calves vocalize. Descriptions of these vocalizations are presented and compared to earlier reports and vocalizations from calves of other large whale species. Contexts of some calf vocalizations are also described.

## II. METHODS

Underwater humpback vocalizations and behavior were recorded during winters 2001-2006 off southwest Maui and Kaua'i, Hawai'i. Data were collected by one or two snorkelers off a 6-8 meter (m) inboard or outboard vessel and by personnel above water. Divers used two systems: a Panasonic GS200 and/or GS300 digital underwater video camera equipped with a single omni-directional hydrophone (Biomon BM 8263-3c mounted 1 m below the camera), and a two-element hydrophone array used one day in March 2006. The two-element array consisted of two HTI MIN-96 hydrophones mounted 1.5 m apart on a bar perpendicular to the optical axis of the camera. This configuration was used to determine left-right bearings to the source of sounds produced in mother-calf groups (i.e., the offset of a sound source from the plane between the two

hydrophones was measured by the time delay of the signal arriving at the two hydrophones). The unit was held parallel to the water's surface. A zero offset would indicate that the sound source was equidistant from the two hydrophones and located on a vertical plane parallel to the optical axis of the camera. Verification that sound(s) were produced by a calf for the two-element array was defined as repeated measurements of signals within a 10-degree angle of the plane bisecting the two hydrophones, with the calf centered in the video frame and no other whales present in that plane. Frequency response curves were obtained from the manufacturer specifications for the hydrophones and recording equipment. Hydrophones were calibrated by the manufacturer.

To analyze acoustic data, the recorded videotapes were connected to an Apple Mac Mini and raw video data were transferred to hard disk using the program iMovie HD. Recordings were divided into a series of video clip files. The digital video files were aurally and visually reviewed for potential acoustic signals. Visual inspection of spectrograms was useful, particularly if signals were low frequency or pulsed. All digital video clips with audible pulses were exported as audio interchange file format files (AIFF). Clips downloaded from mini digital video tapes were processed using audio editing software. The sample rate of acoustic recordings was 32 or 48 kHz. Single-element recordings were downsampled by a factor of three to allow more detailed visualization of relatively low-frequency sounds, although the original sampling rate data were used to determine the time delay differences.

Audio data were reviewed in Raven 1.2.1 (Charif *et al.*, 2004) in 30 second (s) segments. Individual A/D samples were plotted and reviewed as a function of time. Detected pulses were copied and pasted into two different files to allow separate analyses of the same data. In the first file, data were low-pass filtered and decimated to allow higher resolution of low-frequency components. These data were used to create spectrograms to provide descriptive measurements of sounds. Spectrograms were calculated with a 1024 fast Fourier transform (FFT), 75% overlap, and a Hamming window. In the second file, the same original sounds recorded with the two-element array were band-pass filtered between 100 and 3000 Hz to allow more accurate measurement of time delays of each sound between the two left and right channels. Time delays were determined by hand-measuring the temporal differences between a waveform's arrival time at each sensor in milliseconds (ms). A lookup table in the equipment specifications was used to convert the time delays and angles to bearings relative to the sound source assuming far-field propagation. Resultant bearings indicated the angular position of the sound source relative to a plane parallel to the camera's optical axis and normal to the line between the two hydrophones. These bearings are actually cones (or hyperbolic surfaces) relative to the plane parallel to the optical axis of the camera. Video from both divers was then examined to determine the position of the animal(s) in the frame at the time of sound production. The relationship between the time delay and the angle from the plane parallel to the optical axis of the camera to the sound source consists of the simple linear formula

$$\text{angle} = \arcsin ((\Delta t \times c)/A), \quad (1)$$

where  $\Delta t$  = time difference between elements (s),  $c$  = speed of sound in water (m/s), and  $A$  = aperture (distance) between elements (m). Any single-measured angle could

represent a source in any direction on the hyperbolic surface defined by the array geometry and the time delay differences (not necessarily the object in view of the camera, i.e., the sound source could be directly behind the camera). This was addressed by conducting both underwater and surface constant scans for animal presence and locations in relation to the recording diver. We inferred that the source animal was the one in front of the diver if no animal occurred behind the diver and no animals were visually detected on the same plane as the source animal. In addition, during calf vocalizations, no other whales were visible underwater or at the surface, and no other groups were detected within 300 m.

Representative spectrograms were selected from clips to illustrate typical acoustic parameters attributable to calf vocalizations (Fig. 1). Clips were downsampled by a factor of eight, reducing the sample rate to 6 kHz. Spectrogram illustrations were made with a Hann window, a 512 FFT size, and a 98% overlap. A subsample of vocalizations with loud signal-to-noise ratios (10 dB, indicating close proximity), and data supporting the proximal position of the calf relative to other whales was selected for further analyses. Sounds with low signal-to-noise ratios, repetitive sounds similar to song, and/or sounds with more than one animal in the same plane based on video and field notes were discarded. Selected sounds were divided into pulsed, amplitude-modulated (AM), and frequency-modulated tonal (FM) signals. Pulsed signals had a distinct amplitude onset as opposed to the sinusoidal amplitude envelope of a typical AM signal. Duration and bandwidth, initial and ending AM and FM frequencies, number of pulses in a pulsed signal, and the first and last inter-pulse interval were measured. It was noted if the interval was constant, increasing, or decreasing with time. It was not possible to calculate amplitude of sound from the source animal because we did not have the precise distance measurements necessary to estimate transmission loss with any degree of certainty.

Statistical analyses were conducted to compare vocalizations produced by the one calf recorded with the two-element hydrophone vs. the selected subsample of 60 calf-attributed vocalizations recorded with the single hydrophone. Three measures of three signal types (AM, FM, and pulsed) were considered: lowest frequency, bandwidth, and duration. These measures were chosen since they are independent of each other. A mean value for each whale, measurement type, and signal type was calculated. Means were used to avoid unequal representation of one animal compared to another, since the number of vocalizations produced by each animal varied between focal sessions. Means were compared using a MANOVA, with the three dependent measures compared for the two-element hydrophone array recordings of one calf in 2006 against the single-element hydrophone recordings of 21 different calves in 2001-2005.

Underwater behavior from the recorded video of all whale groups was analyzed using a modified behavioral sampling methodology based on Mann (1999). Behavioral state, individual behaviors, and vocalizations were noted for 30 s periods that the calf was in view for at least 15 s. Distance between mother, calf, and diver and depth of animals below the water surface were estimated in mother-whale body lengths similar to Glockner and Venus (1983), assuming an average body length of approximately 13 m for a Hawaiian mother humpback per Spitz *et al.* (2000). For example, if a calf was

separated from its mother by two mother-body lengths this separation distance was estimated to be approximately 26 m; the margin of error was not measured but was believed to be approximately  $\pm 2$  m based on the standard deviation and range of measured body lengths of 26 mother whales per Spitz *et al.* (2000). The mother was identified based on its closer consistent contact with the calf and genital morphology, the latter which was also used to determine sex of calves (True, 1904; Glockner, 1983).

### **III. RESULTS**

Underwater video recordings of 170 groups containing a mother-calf humpback were filmed off Maui and Kaua'i from January-March for one to three months each year of 2001, 2002, 2004, 2005 and 2006. A total of 1007 min of videotape was recorded (mean=5.0 min per group, SD=4.9, range=<1-30 min). Non-song vocalizations were recorded in 110 (65%) of the 170 groups with a calf. Of the total 170 calf pods, non-song vocalizations were detected in 87% or 34 of 39 lone mother-calf pairs and 68% or 76 of 111 mother-calf-escorts; no calf non-song vocalizations were detected among the 20 mother-calves with two or more escorts. Many vocalizations were of relatively low amplitude and were not detected until later aural and spectral analyses of video and acoustic data.

The two-element array system was used off Maui for one day on 9 March 2006 for a total of 51 min on three separate mother-calf groups. Quality acoustic data were obtained for only one group, a male calf accompanied by a mother and escort; they were observed and recorded for 38 continuous min of which 18 min was recorded with the two-element array set up simultaneous with a second underwater video camera and single hydrophone. The remaining 109 (95%) calf groups with non-song vocalizations were recorded using the single hydrophone-video camera set up. Nearly all (97%) of these 109 groups and videotape (96%) were recorded near Maui; the remaining four were near Kauai. Acoustic data and videotape were analyzed for the one calf recorded with the two-element array and for a selected subsample of 28 calves from 109 groups as described below. All 29 calves consisted of different individuals based on examination of physical attributes of both the calf and mother [e.g., fluke, pectoral fin, and body pigment patterns, body creases, sex, and/or scarring (e.g., Katona *et al.*, 1979; Glockner and Venus, 1983)]. The one vocalizing calf recorded by the two-element array was male while the 28 calves recorded with the single hydrophone consisted of 10 males and 18 females. All 29 whales assessed to be mothers based on close association with the aforementioned calves were sexed via underwater video data as females.

#### **A. Two-element array recording of one calf**

Directional bearings were determined for 21 distinct biological sound signals from the one male calf based on measured time delays of recordings between the two hydrophones of the two-element array (Table I). We analyzed nine different representative video clips (separate time segments from the 18 min data series) of this encounter providing real-time visual corroboration that the calf was the only animal present in the area of the recorded sounds. The calf is clearly visible in the center of all

these frames. For example, a signal identified as a grunt occurred 160.8 s into Clip 15 (Fig. 2). The measured time delay between the left and right hydrophones was 0.104 ms, corresponding to an angle of -6.14 degrees, just slightly offset from the plane between the two hydrophones. No other animals were behind the calf being videoed or behind the first diver, verifying that the calf in front of the hydrophone made the sounds. A different animal behind the first diver is the only other scenario in which this time delay difference and resulting acoustic signals could possibly have been recorded. This was ruled out based on analysis of underwater video taken by the second diver, by constant vessel observer scans confirming that no other animals were nearby, and data indicating that the mother and escort were resting at deeper water depth and were not within the angle offset range.

The types and structures of the 21 vocalizations measurably attributed to the same calf via the two-element array were predominantly pulsed signals (71%), followed by 19% FM and 10% AM signals (Tables I, II and III). All 21 signals were relatively short in duration (<1 s; mean=208 ms, SD=147, range=89–664 ms) and of predominantly low frequency (Table II). Mean lowest frequency of the 21 signals was 220 Hz (SD=391.5, range=10–1464 Hz). Mean highest frequency was 2221 Hz (SD=1861.4, range 312–7719 Hz). Vocalizations had a relatively narrow bandwidth (2004 Hz, SD=1891, range=238–7118 Hz) with a mean maximum frequency of 2.22 kHz (range=239–7719 Hz). Table II shows summary statistics for the AM, FM, and pulsed signals recorded from this calf. “Grunt” vocalizations were the most commonly heard signal (90% of 21) from this calf based on aural analyses (Fig. 2).

The calf made a total of four close (1 to 5 m) approaches to the diver, once during each of four surfacing bouts. During three approaches, the calf emitted 4 - 8 repetitive “grunts” and looked directly at the diver at its closest point of approach. The group (consisting of the mother, calf, and adult escort) remained in the same approximate location, resting near the shallow (<30 m) bottom throughout the encounter except when surfacing to breathe. The calf surfaced by itself during all four approaches.

Supplemental information providing a detailed description of this encounter, including behaviors associated with calf vocalizations and types of vocalizations, is available at the Cetos Research Organization website (Cetos 2007).

### **B. Single hydrophone recordings of calves**

A subsample of 28 of the 109 calf groups with non-song vocalizations recorded only with the single hydrophone was selected for detailed analyses based on quality of videotape and acoustic signals. These 28 groups yielded a subsample of 60 sound signals considered of reasonable quality and circumstance to be attributable to a calf using methods similar to previous reports (Zoidis and Green, 2001; Pack *et al.*, 2005; Zoidis *et al.*, 2005) and data from the two-element array as follows: (1) The same 21 vocalizations made by the calf verified with the two-element array were recorded simultaneously by the single hydrophone, i.e., the omnidirectional hydrophone had coincident sounds that were verified separately as coming from the calf by the two-element-array data. (2) No

significant differences were found between the characteristics of three acoustic parameters of selected single-hydrophone vocalizations and those recorded and linked to the calf by the two-element array (Table II). (3) 27 of the 28 calves that produced vocalizations were alone (defined as isolated with no other whales in view within at least 15 m for at least 15 min and no humpback song sounds recorded). (4) Non-song vocalizations were detected significantly more frequently when the calf was at or near its closest point of approach to the single hydrophone (<5 m) facing the diver/recorder while the mother and/or escort were resting in deeper water >10 m from the diver and calf ( $n = 49$ ,  $X^2 = 49.0$ ,  $p = 0.002$ ,  $df = 2$ ). (5) The vocalizations had a relatively strong signal-to-noise ratio (10 dB). (6) Two different calves emitted bubbles concurrent with the time of the vocalizations.

Most (90%) of the above 60 signals were short in duration (<1.1 s, mean=559 ms, range=75 ms–2.5 s) and of predominantly low frequency (overall mean low-frequency of all 60 was signals=306 Hz, range=10–1710 Hz). FM signals were most common (50%) followed by pulsed (30%) and AM (20%) signals (Table I). Of the 30 FM signals, eight were simple upsweeps, six were simple downsweeps, eight had near-flat frequency contours, and the remaining eight had inflections in their contours (e.g., U-shaped). Nine of the twelve AM sounds had no strong changes in AM frequency, two increased, and one had a complex pattern of modulation. The large single hydrophone AM value of the ‘highest frequency’ (Table II) is the result of measuring all of the side bands for the 12 AM sounds. The measured bandwidth of these AM signals is larger than that of the FM signals, partially because only the fundamental was measured and the harmonics were excluded from the measurement.

We recorded unusual behavioral events when calf-attributed vocalizations were recorded that to our knowledge have not been previously reported. A selective representation of these include the following: Repeated grunt series by three separate calves that increased in amplitude followed by the mother joining the calf from depth and “herding” the calf away from the diver, who was less than 5 m from the calf at the time of sound production; this type of directed movement behavior by the mother was not seen when no sounds were recorded. Two of these calves repeatedly produced grunt sounds while simultaneously creating underwater bubble streams. One of these calves was recorded for a 3:04-min continuous sequence of grunts, the longest duration of any year and the farthest (>30 m) a calf was away from its mother who was in deeper water and not visible to the diver. The grunts increased in tempo and coincided with repeated bubble streams and an underwater “jaw clap”.

## **IV. DISCUSSION**

Non-song vocalizations occur in all adult humpback group compositions on the wintering grounds, including those with a calf, as documented previously and herein (Tyack, 1983; Silber, 1986; Zoidis and Green, 2001; Pack *et al.*, 2005; Zoidis *et al.*, 2005). For the first time, measured time delays between array bearings provide measurable evidence corroborating that a male humpback calf produced 21 non-song vocalizations as recorded with a non-static two-element array mounted on an underwater



video camera. Previously, vocalizations have been attributed to individual humpback calves on the wintering grounds based only on observational evidence and recordings with a single-hydrophone video camera (including the 60 vocalizations from 28 other calves reported herein) (Zoidis and Green, 2001; Pack *et al.*, 2005; Zoidis *et al.*, 2005). While convincing, the methodology used in these studies cannot unequivocally rule out that the sounds did not come from another source/whale that was nearby or not visible because one omnidirectional hydrophone cannot provide directional bearings spatially linking acoustic data to a source. However, the two-element-array calf recordings combined with similarities in sound characteristics between this calf and other calf-attributed vocalizations provide further substantiation that both male and female humpback calves vocalize.

Non-song vocalizations appear more common among wintering humpback calf pods than previously reported. Herein, non-song vocalizations were recorded in 65% of 170 calf pods. Silber (1986) recorded non-song “social sounds” in only 7% of 14 mother-calf-escort groups and in none of seven lone mother-calf pairs. Pack *et al.* (2005) attributed 49 vocalizations to eight humpback calves off Maui (the number of calf pods that did not vocalize was not reported). In addition, we found non-song vocalizations more common in lone mother-calf pairs than among mother-calf-escort groups. Similarly, Zoidis and Green (2001) reported a significantly higher vocalization rate (10.9 vocalizations per whale per hour) among 12 mother-calf pairs compared to 50 mother-calf-escort groups (4.4), 25 surface-active groups of three or more adults with no calves (4.2), and seven adult dyads (1.7). In contrast, both Silber (1986) and Pack *et al.* (2005) reported non-song or calf vocalizations primarily among mother-calf-escorts. Per Pack *et al.* (2005), five of eight calves that vocalized were escorted by a mother and one escort including one singing escort; the remaining three groups with such sounds were a mother-calf pair, one mother-calf with two escorts, and one lone calf (the definition, i.e., duration of how long a calf was “alone” was not indicated). Five of these calves were males and three were females (Pack *et al.*, 2005). In comparison, we attributed vocalizations to 11 male and 18 female calves.

Calf vocalizations recorded with the two-element array were simple in structure and limited in repertoire with short duration and inter-pulse interval, and predominantly low frequency and relatively narrow bandwidth. These characteristics were not significantly different from other vocalizations attributed to humpback calves in this study and are similar to acoustic characteristics reported in earlier reports of calf vocalizations (Zoidis and Green, 2001; Pack *et al.*, 2005; Zoidis *et al.*, 2005) (Table III). Calves appear to produce sequences of the same sound in some instances. Repeated “grunt” bouts were made by the two-element-array-recorded calf and were also recorded near calves by the single hydrophone. Similarly, Pack *et al.* (2005) reported that four calves produced sound sequences at a mean interval of 4.4 s, the spectral characteristics of which were similar to the grunt sounds we recorded (Fig. 2). In addition, vocalizations were documented simultaneous to bubble emissions from the blowhole for both the two-element-array-recorded calf as well as calves recorded with the single hydrophone herein and in Pack *et al.* (2005) (Figs. 1 and 2).

Pack *et al.* (2005) found that calf-attributed vocalizations were statistically similar to “non-calf social sounds” (terminology from Pack *et al.* 2005) but were significantly different from adult song units, the former which were noted to have a narrower frequency range and shorter duration (Table III). Our results for calf vocalizations based on both the two-element array and single hydrophone recordings generally corroborate these findings, as do earlier reports that song is more complex than non-song adult and calf vocalizations (Silber, 1986; Zoidis and Green, 2001; Zoidis *et al.*, 2005). In addition, pulsed signals were frequent among calves compared to the known repertoire of pulsed sounds produced by adult humpbacks in Hawaii (e.g., Payne and McVay, 1971; Darling, 1983; Payne, 1983; Silber, 1986; Helweg *et al.*, 1992; Au *et al.*, 2000). However, the most common type of signal recorded by the single hydrophone was FM signals, as found by Silber (1986) for groups of three or more adults off Maui (Table III). Most AM signals we recorded near calves had no strong evidence of changes in AM frequency. In contrast, social sounds of surface-active adult humpback groups typically exhibit considerable modulation in the AM frequency, producing the sensation of a frequency sweep (Silber, 1986).

Underwater video documenting behaviors and surroundings concurrent with two-element array recordings were important in providing empirical real-time evidence that a calf produced vocalizations. This approach allows an animal to be monitored visually and acoustically (i.e., it remains in view) for extended periods, so that underwater behaviors can be continuously recorded concurrently with vocalizations. Previous studies (e.g., Tyack, 1981, 1983; Darling, 1983; Silber, 1986) recorded non-song sounds among adult humpback whales by deploying a single hydrophone from a small vessel. More recently, Dunlop *et al.* (2005, 2006, 2007) recorded non-song vocalizations in Australia remotely from shore using a stationary array. No directional data linking vocalizations to individuals were presented in these previous studies.

The function and biological significance of calf vocalizations are unknown. Several potential hypotheses are proposed. Some types of calf vocalizations may elicit the mother’s approach. In most cases, a calf closely (<5 to 10 m) approached the diver either silently or with non-song vocalizations during a surfacing bout, with no reaction from the mother. However, when on three occasions a calf emitted repeated grunt vocalizations, with increasing incidence and amplitude, twice with bubbles and once with an accompanying jaw clap, the mother surfaced quickly, approached, and seemingly intentionally “herded” the calf directly away. Certain sounds (e.g., FM signals, repetitive grunts, particularly those that increase in amplitude) and/or bubble streams may function as either isolation or “alarm” calls by the calf to alert and/or call the mother. Alarm or isolation calls occur among mother-young groups of other mammalian species including dolphins (reviewed in Tyack, 2000), bats (Balcombe, 1990), and primates (Robinson, 1982). The calf may also produce vocalizations when encountering a novel stimulus (i.e., a close encounter with a diver or boat), or as unidirectional contact communication from the calf to the mother [i.e., where only one individual recognizes the call of the other and not visa versa (Torianni *et al.*, 2006)]. Documentation is lacking as to whether humpback mothers or other adults use sound to communicate with calves. To date, the published evidence has not shown this.

A few studies have been able to individually link vocalizations to young of other baleen whale species including gray (Wisdom *et al.*, 2001), northern right (Parks and Tyack, 2005; Parks and Clark, 2007), and Bryde's whales (Edds *et al.*, 1993); however, some of these studies have involved captive animals and may not be representative of free-ranging animals (Table III). Although the vocalizations themselves are quite different between species and are limited to a few individuals, their overall characteristics are generally similar to humpback calf-attributed vocalizations in terms of simplicity, limited repertoire, short duration, and predominantly low and narrower-band frequency when compared to adults of the same species (Edds *et al.*, 1993; Wisdom *et al.*, 2001; Parks and Tyack, 2005; Parks and Clark, 2007) (Table III). A captive juvenile Bryde's whale produced primarily pulsed moans with amplitude and frequency modulation, and on two occasions, free-ranging isolated Bryde's calves were linked with series of 4-11 discrete pulse calls (Edds *et al.*, 1993). Series of pulsed vocalizations (i.e., pulse trains) were also commonly produced by a captive gray whale calf (Wisdom *et al.*, 2001) as well as an entrapped juvenile humpback (Beamish, 1979) and humpback calves reported herein and by Pack *et al.* (2005) (Table III). Published individual sound confirmation of Northern right whale calves is limited to one free-ranging female based on bearing data collected with an acoustic array on the feeding grounds (Parks and Tyack, 2005; Parks and Clark, 2007). This calf produced stuttered "screamlike" calls interrupted by many pauses while alone at the surface as the other adults in the group dove. The calls were generally of higher pitch and often longer in duration than adult female "screams" used to initiate surface-active adult groups (Parks and Tyack, 2005).

The biological significance of vocalizations produced by humpback calves and how it may change depending on social structure, environmental cues, ontogeny, and behavior, as well as whether mothers vocalize, remains to be further investigated. Circumstances of calf-attributed vocalizations recorded with a single hydrophone provide strong indication that the calf is most likely the sound source rather than the mother, including in lone mother-calf pairs. Compelling observational data include vocalizations recorded coincident with bubble emissions by humpback calves during both two-element and single hydrophone recordings, similar to humpback whale calves and a juvenile reported elsewhere (Beamish, 1979; Zoidis and Green, 2001; Pack *et al.*, 2005; Zoidis *et al.*, 2005). A captive juvenile Bryde's whale emitted bubbles only while vocalizing, throughout the vocalizations, and only from the right blowhole (Edds *et al.*, 1993). Dolphins sometimes emit bubbles simultaneous to sound production (Dahlheim and Awbrey, 1982; McCowan, 1995; McCowan and Reiss, 1995; Dudzinski, 1996; Herzing, 1996; Killebrew *et al.*, 1996), although this relationship is not consistent (Caldwell *et al.*, 1990; Fripp, 2005). However, it cannot be ruled out that some sounds recorded by the single hydrophone were produced by the mother without corroboration from directional acoustic data. Northern right whale mothers vocalize to their calves when they become separated, presumably to reunite the two (Parks and Clark, 2007). Similar contact calls may occur between humpback mothers and calves but have not yet been recorded or identified, possibly due to low-amplitude source levels that are difficult to detect except at close range. The relatively low-amplitude of calf vocalizations we recorded may be why calves have only recently been reported to vocalize (Zoidis and Green, 2001).

## Humpback calf hydrophone array recordings

Further analyses of the acoustic characteristics and behavioral context of calf vocalizations are underway, including their role as a potential indicator of stress, with implications for management concerns in areas with elevated anthropogenic activity and underwater noise such as Hawai'i.

### **ACKNOWLEDGMENTS**

We thank Randy Bates, Charles Bishop, Dan DenDanto, Pete Gehring Dr. Marsha Green, Carol Hart, Thea Jenson, Terry McCabe, Don Moses, Dan Shapiro, Ethan Silva, Jessica Sharman, Peter Stevick, Jeff Pantukhoff, and Norbert Wu for their assistance, particularly their support with field portions of this project over the years. We thank Thomas F. Norris, Shannon Rankin, Carol Spencer, and Jenelle Black for reviewing this manuscript and/or for their editorial or technical input. We thank all our donors and patrons that have funded this work so that this publication was possible. We also thank E. M. Blair, J. Dennis, S. Katona, D. Kearney, P. Tadd, A. Waldron, and A. Wright for their support and encouragement over the years.

## V. REFERENCES

- Au, W. W. L., Popper, A. N., and, and Fay, R. R. (2000). Hearing by Whales and Dolphins. Springer Handbook of Auditory Research Volume 12. Springer-Verlag, New York, NY, pp. 1-485.
- Au, W. W. L., Darling, J., and Andrews, K. (2001). "High-frequency harmonics and source level of humpback whale songs," J. Acoust. Soc. Am. **110**, 2770.
- Au, W. W. L., Lammers, M. O., Stimpert, A., and Schotten, M. (2005). "The temporal characteristics of humpback whale songs," J. Acoust. Soc. Am. **118**, 1940.
- Au, W. W. L., Pack, A. A., Lammers, M. O., Herman, L. M., Deakos, M. H., and Andrews, K. (2006). "Acoustic properties of humpback whale songs," J. Acoust. Soc. Am. **120**, 1103-1110.
- Baker, C. S., and Herman, L. M. (1984). "Aggressive behavior between humpback whales (*Megaptera novaeangliae*) wintering in Hawaiian waters," Can. J. Zool. **62**, 1922-1937.
- Balcombe, J. P. (1990). "Vocal recognition of pups by Mexican free-tailed bats, *Tadarida brasiliensis mexicana*," Anim. Behav. **39**, 960-966.
- Beamish, P. (1979). "Behavior and significance of entrapped baleen whales," in *Behavior of Marine Animals*, edited by H. E. Winn and B. Olla (Plenum Press, New York), pp. 291-309.
- Caldwell, M. C., Caldwell, D. K., and Tyack, P. L. (1990). "A review of the signature whistle hypothesis for the Atlantic bottlenose dolphin," in *The Bottlenose Dolphin*, edited by S. Leatherwood and R. R. Reeves (Academic Press, San Diego), pp. 199-234.
- Cartwright, R. (2005). "A comparative study of the behaviour and dynamics of humpback whale (*Megaptera novaeangliae*) mother and calf pairs during their residence in nursery waters," Ph.D. diss., Manchester Metropolitan University, pp. 1-259.
- Cetos (2007). "Calf activity (behavioral and acoustic) during social sound production, as recorded with two-element hydrophone array". Cetos Research Organization Internet website [http://www.cetosresearch.org/research/humpback\\_findings.htm](http://www.cetosresearch.org/research/humpback_findings.htm). Last viewed 7/17/07.
- Charif, R. A., Clark, C. W., and Fristrup, K. M. (2004). *Raven 1.2 User's Manual* (Cornell Laboratory of Ornithology, Ithaca), pp. 1-205.

## Humpback calf hydrophone array recordings

- Clapham, P.J., Palsbøll, P. J., Mattila, D. K., and Vasquez, O. (1992). "Composition and dynamics of humpback whale competitive groups in the West Indies," *Behaviour* **122**, 182-194.
- D'Vincent, C. G., Nilson, R. M., and Hanna, R. E. (1985). "Vocalization and coordinated feeding behaviour of the humpback whale in southeastern Alaska," *Sci. Rep. Whales Res. Inst.* **36**, 41-47.
- Dahlheim, M. E., and Awbrey, F. (1982). "A classification and comparison of sounds of captive killer whales (*Orcinus orca*)," *J. Acoust. Soc. Am.* **72**, 661-670.
- Darling, J. D. (1983). "Migrations, abundance and behavior of Hawaiian humpback whales (*Megaptera novaeangliae*) (Borowski)," Ph.D. diss., University of California at Santa Cruz, pp. 1-147.
- Darling, J. D., and Bérubé, M. (2001). "Interactions of singing humpback whales with other males," *Mar. Mamm. Sci.* **17**, 570-584.
- Darling, J. D., Jones, M. E., and Nicklin, C. P. (2006). "Humpback whale songs: Do they organize males during the breeding season?" *Behaviour* **143**, 1051-1101.
- Dudzinski, K. M. (1996). "Communication and behavior in the Atlantic spotted dolphins (*Stenella frontalis*): Relationships between vocal and behavioral activities," Ph.D. diss., Texas A&M University, pp. 1-214.
- Dunlop, R. A., Noad, M. J., and Cato, D. H. (2005). "Widespread and contextual use of social communication in migrating humpback whales," *Abstracts, 16<sup>th</sup> Biennial Conference on the Biology of Marine Mammals*, San Diego, CA, p. 79.
- Dunlop, R., Smith, J., Noad, M., and Cato, D. H. (2006). "Bioacoustic communication in humpback whales: The use of social sounds and song," paper presented at the National Whale and Dolphin Research Conference, Adelaide, Australia, available at <http://asa.aip.org/web2/asa/abstracts/search.nov06/asa59.html>. Last viewed 7/17/07.
- Dunlop, R. A., and Noad, M. J. (2007). "The social vocalization repertoire of east Australian migrating humpback whales (*Megaptera novaeangliae*)," *J. Acoust. Soc. Am.* **122**, 2893-2905.
- Edds, P. L., Odell, D. K., and Tershy, B. R. (1993). "Vocalizations of a captive juvenile and free-ranging adult-calf pairs of Bryde's whales, *Balaenoptera edeni*," *Mar. Mamm. Sci.* **9**, 269-284.
- Fripp, D. (2005). "Bubblestream whistles are not representative of a bottlenose dolphin's vocal repertoire," *Mar. Mamm. Sci.* **21**, 29-44.

## Humpback calf hydrophone array recordings

- Fristrup, K. M., Hatch, L. T., and Clark, C. W. (2003). "Variation in humpback whale (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts," *J. Acoust. Soc. Am.* **113**, 3411–3424.
- Glockner, D. A. (1983). "Determining the sex of humpback whales (*Megaptera novaeangliae*) in their natural environment", in *Communication and Behavior of Whales*, edited by R. Payne (Westview Press, Boulder), pp. 447–464.
- Glockner, D. A., and Venus, S. C. (1983). "Identification, growth rate, and behaviour of humpback whale (*Megaptera novaeangliae*) cows and calves in the waters off Maui, Hawai'i, 1977-79," in *Communication and Behavior of Whales*, edited by R. Payne (Westview Press, Boulder), pp. 223–258.
- Glockner-Ferrari, D. A., and Ferrari, M. J. (1990). "Reproduction in the humpback whale (*Megaptera novaeangliae*) in Hawaiian waters, 1975-1988: the life history, reproductive rates and behavior of known individuals identified through surface and underwater photography", *Rep. Int. Whaling Com. Special Issue* **12**, 161-169.
- Helweg, D. A., Frankel, A. S., Mobley, J. R., and Herman, L. M. (1992). "Humpback whale song: Our current understanding," in *Marine Mammal Sensory Systems*, edited by J. A. Thomas, R. A. Kastelein, and A. Ya. Supin (Plenum, New York), pp. 459–483.
- Herzing, D. L. (1996). "Sounds and associated underwater behavior of free-ranging Atlantic spotted dolphins, *Stenella frontalis*, and bottlenose dolphins, *Tursiops truncatus*," *Aquat. Mamm.* **22**, 61–79.
- Jurasz, C. M., and Jurasz, C. M. (1979). "Feeding modes of the humpback whales, *Megaptera novaeangliae*, in southeast Alaska," *Sci. Rep. Whales Res. Inst.* **31**, 69–83.
- Katona, S., Baxter, B., Brazier, O., Kraus, S., Perkins, J., and Whitehead, H. (1979). "Identification of humpback whales by fluke photographs", in *Behavior of Marine Animals – Current Perspectives in Research, Vol. 3: Cetaceans*, edited by H. E. Winn and B. L. Olla (Plenum Press, New York), pp. 33-44.
- Kibblewhite, A. C., Denham, R. N. and Barnes, D. J. (1966). "Unusual low frequency signals observed in New Zealand waters," *J. Acoust. Soc. Am.* **41**, 644-655.
- Killebrew, D. A., Mercado III, E., Pack, A. A., and Herman, L. M. (1996). "Burst-pulse sounds of a neonate bottlenosed dolphin," *J. Acoust. Soc. Am.* **100**, 2610.
- Mann, J. (1999). "Behavioural sampling methods for cetaceans: A review and critique," *Mar. Mamm. Sci.* **15**, 102-122.

## Humpback calf hydrophone array recordings

- McCowan, B. (1995). "A new quantitative technique for categorizing whistles using simulated signals and whistles from captive bottlenose dolphins (Delphinidae, *Tursiops truncatus*)," *Ethology* **100**, 177–193.
- McCowan, B., and Reiss, D. (1995). "Quantitative comparison of whistle repertoires from captive adult bottlenose dolphins (Delphinidae: *Tursiops truncatus*): A re-evaluation of the signature whistle hypothesis," *Ethology* **100**, 193–209.
- Norris, T. F., McDonald, M., and Barlow, J. (1999). "Acoustic detections of singing humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific during their northbound migration," *J. Acoust. Soc. Am.* **106**, 506-514.
- Pack, A. A., Herman, L. M., Deakos, M. H., Hakala, S., Craig, A. S., Olson, J. R., Spitz, S. S., Herman, E., Goetschius, K., and Lammers, M. O. (2005). "First report of sounds recorded from individual humpback whale calves on the Hawaiian wintering grounds," *Abstracts, 16<sup>th</sup> Biennial Conference on the Biology of Marine Mammals*, San Diego, CA, p. 216.
- Parks, S. E., and Clark, C. W. (2007). "Acoustic communication: social sounds and the potential impacts of noise," in *The urban whale: North Atlantic right whales at the crossroads*, edited by S. D. Kraus and R. M. Rolland, Harvard University Press, Cambridge, MA, pp. 310-332.
- Parks, S. E., and Tyack, P. L. (2005). "Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups," *J. Acoust. Soc. Am.* **117**, 3297–3306.
- Payne, R. S. (1978). "Behavior and vocalizations of humpback whales (*Megaptera* sp.)," in *Report on a workshop on problems related to humpback whales (Megaptera novaeangliae) in Hawaii*, edited by K. S. Norris and R. R. Reeves, U. S. Dep. Commer. NTIS PB-280, **794**, 56-78.
- Payne, R. S. (ed.). (1983). *Communication and Behavior of Whales* (Westview Press, Inc., Boulder, Colorado), pp. 643.
- Payne, R. S., and McVay, S. (1971). Songs of humpback whales. *Science* **173**, 585-597.
- Potter, J. R., Deakos, M. H., Koay, T. B., Durville, C., and Pack, A. A. (2003). "Up close and personal: Recording humpback whale song at close ranges (10-50m)," *Proceedings, Oceans 2003 MTS/IEEE Conference*, San Diego, CA, p. 472.
- Robinson, J. G. (1982). "Vocal systems regulating within-group spacing," in *Primate Communication*, edited by C. T. Snowdon, C. H. Brown, and M. R. Petersen (Cambridge University Press, Cambridge), pp. 94-116.



## Humpback calf hydrophone array recordings

- Sharpe, F. A., Dill, L. M., Beaver, V., and Spellman, B. (1998). "Killing me softly: Feeding calls of the Alaskan humpback whale," *Abstracts, World Marine Mammal Science Conference*, Monaco, January, pp. 20–24.
- Silber, G. K. (1986). "The relationship of social vocalizations to surface behavior and aggression in the Hawaiian humpback whale (*Megaptera novaeangliae*)," *Can. J. Zool.* **64**, 2075-2080.
- Spitz, S., Herman, L. M., and Pack, A. A. (2000). "Measuring sizes of humpback whales (*Megaptera novaeangliae*) by underwater videogrammetry," *Mar. Mamm. Sci.* **16**, 664-767.
- Thompson, P. O. W., Cummings, W. C., and Kennison, S. J. (1977). "Sound production of humpback whales, *Megaptera novaeangliae*, in Alaskan waters" *J. Acoust. Soc. Am.* **62** (3), S89.
- Torianni, V. G., Vannoni, E., and McElligott, A. G. (2006). "Mother-young recognition in an ungulate hider species: A unidirectional process," *Amer. Natural.*, **168**, 412–420.
- True, F. W. (1904). "The whalebone whales of the western North Atlantic compared with those occurring in European waters with some observations on the species of the North Pacific," *Smithsonian Contributions to Knowledge* **33**, 1-332.
- Tyack, P. (1981). "Interactions between singing Hawaiian humpback whales and conspecifics nearby", *Behav. Ecol. Sociobiol.* **8**, 105-116.
- Tyack, P. L. (1982). "Humpback whales respond to sounds of their neighbors" Ph.D. diss., Rockefeller University, pp. 207.
- Tyack, P. (1983). "Differential response of humpback whales, *Megaptera novaeangliae*, to playback of song or social sounds," *Behav. Ecol. Sociobiol.* **13**, 49–55.
- Tyack, P. L. (2000). "Functional aspects of cetacean communication," in *Cetacean Societies: Field Studies of Dolphins and Whales*, edited by J. Mann, R. C. Connor, P. L. Tyack, and H. Whitehead (University of Chicago Press, Chicago), pp. 270–307.
- Tyack, P. and Whitehead, H. (1983). "Male competition in large groups of wintering humpback whales", *Behaviour* **83**, 132-154.
- Winn, H. E., Bischoff, W. L., and Taruski, A. G. (1973). "Cytological sexing of cetaceans," *Mar. Biol. (Berlin)* **23**, 343-346.
- Winn, H. E., and Winn, L. K. (1978). "The song of the humpback whale (*Megaptera novaeangliae*) in the West Indies", *Mar. Biol. (Berlin)* **47**, 97-114.

## Humpback calf hydrophone array recordings

Wisdom, S., Bowles, A. E., and Anderson, K. E. (2001). "Development of behavior and sound repertoire of a rehabilitating gray whale calf," *Aquat. Mamm.* **27**,239-255.

Zoidis, A. M., and Green, M. (2001). "Relationship of social vocalizations to pod size, composition and behavior in the Hawaiian humpback whale," *Abstracts, 15th Biennial Conference of the Biology of Marine Mammals*, Vancouver, B.C., p. 243. <http://www.cetosresearch.org/main.htm> Last viewed 9/21/07.

Zoidis, A. M., Smultea, M. A., Fertl, D., Day, A. J., DenDanto, D., Ertl, A. S., Hayes, J., and Whitt, A. D. (2005). "Can you hear me now? Social sounds and underwater behavior of Hawaiian humpback whale (*Megaptera novaeangliae*) calves," *Abstracts, 16<sup>th</sup> Biennial Conference of the Biology of Marine Mammals*, San Diego, CA, p. 315.

## Humpback calf hydrophone array recordings

TABLE I. Distribution of signal types recorded from the one humpback whale calf with the two-element array and attributed to 28 humpback whale calves recorded with the single hydrophone. No significant differences were found between sounds recorded with the two-element array vs. the single hydrophone for the three signal types based on lowest frequency, bandwidth and duration parameters as indicated below. AM = amplitude-modulated, FM = frequency-modulated.

Signal Type	Two-element Array (2006) (n = 1)	Single Hydrophone (2001-06) (n = 28) <sup>a</sup>	Total n (%)	MANOVA Statistics
AM	2	12	14 (17)	F(2,1) = 0.1285, p = 0.8919
FM	4	30	34 (42)	F(2,4) = 0.2483, p = 0.7914
Pulsed	15	18	33 (41)	F(2,3) = 1.7988, P = 0.3066
Total # signals	n = 21	n = 60	n = 81	

<sup>a</sup> Excludes duplicative sounds recorded by a single hydrophone simultaneous to the two-element array for the one calf recorded with the two-element array in 2006.

## Humpback calf hydrophone array recordings

TABLE II. Summary statistics for the amplitude-modulated (AM), frequency-modulated (FM) and pulsed signals for a male humpback whale calf recorded with the two-element (T) hydrophone array (n = 21 signals) and 60 signals attributed to 28 humpback calves recorded with the single hydrophone (S). The mean value is provided for each measure with the standard deviation in parentheses. AM = amplitude-modulated, FM = frequency-modulated, Hz = Hertz, ms= milliseconds.

Signal Type	Lowest Freq. (Hz)	Highest Freq. (Hz)	Bandwidth (Hz) <sup>a</sup>	Starting Freq. (Hz)	Ending Freq. (Hz)	Duration (ms)	No. Pulses	Inter-Pulse Interval (ms)	n
AM (T)	140 (39)	1442 (221)	1305 (182)	NA	NA	469 (276)	NA	NA	2
AM (S)	279 (506)	4000 <sup>b</sup> (2482)	3519 (2608)	NA	NA	765 (614)	NA	NA	12
FM (T)	409 (705)	1430 (685)	1024 (395)	468 (668)	1196 (706)	253 (200)	NA	NA	4
FM (S)	405 (414)	936 (736)	531 (677)	531 (677)	583 (489)	582 (502)	NA	NA	30
Pulsed (T)	181 (315)	2536 (2115)	2359 (243)	NA	NA	164 (66)	11.3 (5.6)	14.1 (3.5)	15
Pulsed (S)	140 (244)	2948 (2118)	2808 (2136)	NA	NA	384 (237)	14.1 (11.4)	31.0 (21.8)	18

<sup>a</sup>The measured bandwidth of the AM signals is larger than that of the FM signals, as only the fundamental was measured and harmonics were excluded.

<sup>b</sup>The large AM value of the category Highest Frequency is the result of measuring all side bands of the 12 AM sounds.

## Humpback calf hydrophone array recordings

TABLE III. Comparison of vocalizations produced by young of large whale species. Age classifications are taken directly from referenced papers and may have been assessed by non-similar standards. Sample size provided when presented in literature. AM = amplitude-modulated, FM = frequency-modulated, Hz = hertz, SD = standard deviation, s = second, MSB = mean sound bandwidth.

<b>Species, Age Classification, Sample Size</b>	<b>Type: Bandwidth (Hz) MSB, SD, Range <sup>a</sup></b>	<b>Mean Duration, SD, Range (s)<sup>a</sup></b>	<b>Source</b>
Humpback whale ( <i>Megaptera novaeangliae</i> ) calf vocalizations linked with 2-element array (2006: n = 1 calf, 21 vocalizations)	Pulsed: MSB 2359, (SD 243) FM: MSB 1024, (SD 395) AM: MSB 1305, (SD 182) Overall range: 238 - 7118	Pulsed: 0.16, (SD 0.07) FM: 0.25, (SD 0.20) AM: 0.47, (SD 0.28) Overall mean: 0.21, (SD 0.15), Range: 0.01-0.66	This study
Humpback calf-attributed vocalizations recorded with single hydrophone (2001-2005: n = 28 calves, 60 vocalizations)	Pulsed: MSB 2808, (SD 2136) FM: MSB 531, (SD 677) AM: MSB 3519, (SD 2608) Overall range: 140 - 4000	Pulsed: 0.38, (SD 0.24) FM: 0.58, (SD 0.50) AM: 0.77, (SD 0.61) Overall mean: 0.56, Range: 0.08 - 2.5	This study
Humpback calf-attributed vocalizations recorded with single hydrophone (1996-2003: n = 8 calves, 49 vocalizations)	Constant rate pulse: MSB 794, Increasing or decreasing rate pulse: MSB 775, Upswept frequency tone: MSB 1297, Sound combination: MSB 1021, Median fundamental frequency 90, Overall range 30 - 3000	Mean: 0.38 Range: 0.11-0.71	Pack <i>et al.</i> , 2005
Adult humpback groups (n = 54)	Social sounds range: 50 – 10000 <sup>b</sup> , dominant frequencies < 2000, mostly FM upsweeps	Range: 0.25 - > 5	Silber, 1986
Adult male humpbacks	Song range: 20 - > 24000	Range:	Payne and

## Humpback calf hydrophone array recordings

(>100)		300 - 1980	McVay, 1971; Helweg <i>et al.</i> , 1992; Au <i>et al.</i> , 2000, 2001, 2005, 2006; Fristrup <i>et al.</i> , 2003; Potter <i>et al.</i> , 2003
Gray whale ( <i>Eschrichtius robustus</i> ) female calf, 1.5 – 7 mo old (n = 1 calf) <sup>c</sup> (240 h of recordings)	Ranges: Type 1a “croak” pulses <sup>d</sup> : 70 - 4000 Type 1b “pop” pulses <sup>e</sup> : 70 – 4000 Type 3 “moan” <sup>d</sup> : 80 – 2120 Type 4 “grunt” <sup>d</sup> : 70 - 5000	Type 1a: 0.039, SD 0.012 Type 1b: 0.072, SD 0.027 Type 3: 0.44, SD 0.20 Type 4: 0.34, SD 0.090	Wisdom <i>et al.</i> , 1991
North Atlantic right whale ( <i>Eubalaena glacialis</i> ) female calf (n = 1 calf, 9 calls)	Warble range: 470 - 8410	Range: 0.43 - 4.77	Parks and Tyack, 2005
Bryde’s whale ( <i>Balaenoptera edeni</i> ) juvenile (n = 1 calf, 233 vocalizations) <sup>c,f,g</sup>	Discrete pulse range: 400 – 610 Pulsed moan range: 200 – 900	Discrete pulse range: 0.010 <sup>g</sup> , Pulsed moan range: 0.5 – 51	Edds <i>et al.</i> , 1993
Bryde’s whale calf (n = 1 calf, 36 calls) <sup>h</sup>	Discrete pulse series range: 700 - 900	Discrete pulse range: 0.025 – 0.040,	Edds <i>et al.</i> , 1993

<sup>a</sup> Mean, MSB, Median, SD, and/or range are reported if available. Studies did not always report the same units and parameters.

<sup>b</sup> Maximum recording equipment frequency was 10 kHz.

<sup>c</sup> Captive animal.

<sup>d</sup> Produced by 1.5 mo of age.

<sup>e</sup> Produced at 7 mo of age.

<sup>f</sup> 1-2 year old animal

<sup>g</sup> 10 was indicated simply as “duration” in Edds *et al.* (1993) and appears to be a range compared to other numbers presented in the original document table.

<sup>h</sup> Recorded with an omnidirectional hydrophone on two occasions when only first-year free-ranging calves were present at the surface while an adult companion was diving. The discrete pulses were loudest when a calf was close to the hydrophone and thus may have been produced by a calf (Edds *et al.*, 1993). Discrete pulses were recorded only near these individual calves during opportunistic studies of free-ranging Bryde’s whale vocalizations.

**Figure captions:**

Figure 1. Spectrograms of typical signal types attributed to a humpback whale calf based on sounds recorded with the two-element array. Five pulses are seen between 0.7 and 1.7 s. These are followed by a long tonal (or slight frequency-modulated (FM)) signal starting at 2.1 s. Above each spectrogram is a representation of the signal waveform (i.e., the recorded time series of voltages from the hydrophone shown on the y axis; time on the x axis).

Figure 2. Spectrogram of an amplitude-modulated “*grunt*” signal produced by the humpback whale calf recorded by the two-element array.

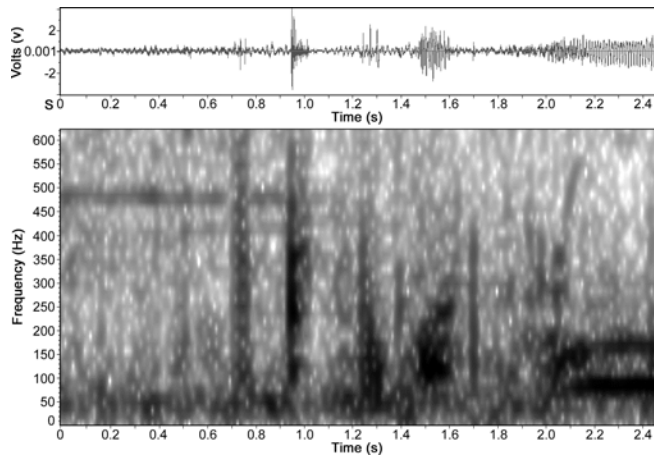


Figure 1



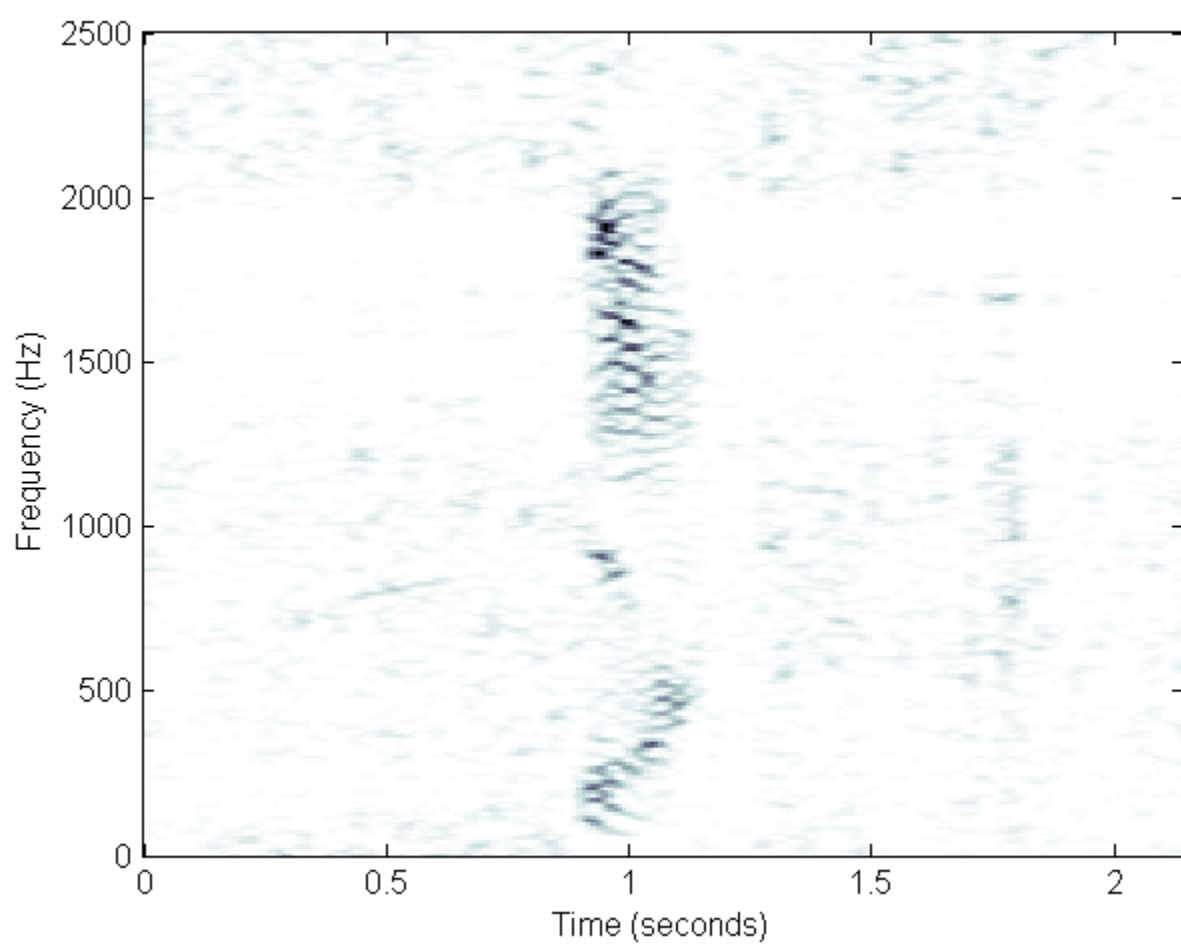


Figure 2