Chapter 9
Listening for Whales at the Station ALOHA Cabled Observatory

Julie N. Oswald, Helen Ou, Whitlow W.L. Au, Bruce M. Howe, and Fred Duennebier

Abstract The Station ALOHA Cabled Observatory (ACO) is an ocean-bottom observatory that allows continuous real-time monitoring of ocean processes including sounds produced by baleen whales. Baleen whales can be challenging to study using traditional visual methods due to their cryptic behavior and offshore ranges. Many baleen whales produce distinctive sounds that propagate well under water and so ocean-bottom hydrophones like the one at the ACO can be used to investigate the occurrence and acoustic behavior of these animals in locations that are difficult to access and study long-term using other methods. We examined 12 months of recordings from the ACO (February 2007–February 2008) and found that sounds produced by blue, sei, and minke whales all occurred seasonally between October and April. Low-frequency pulses produced by fin whales were detected year-round, although much less frequently during the summer months than during the winter months. These seasonal patterns matched those of humpback whales, who migrate to Hawai'ian waters to breed and give birth. Blue, minke, fin, and sei whales are probably using Hawai'ian waters for breeding, but further research is necessary to confirm this. The ACO has provided, and continues to provide, a long-term dataset for investigating seasonal and diurnal trends in the occurrence of baleen whales and other cetaceans at a location that would be difficult to study any other way.

J.N. Oswald (✉)
Bio-Waves, Inc., 364 2nd Street, Suite #3, Encinitas, CA 92024, USA
e-mail: julie.oswald@bio-waves.net

H. Ou
Hawaii Institute of Marine Biology, University of Hawaii,
46-007 Lilipuna Road, Kaneohe, HI 96744, USA

W.W.L. Au
Hawaii Institute of Marine Biology, Kaneohe, HI 96744, USA

B.M. Howe
Department of Ocean and Resources Engineering, University of Hawaii,
2540 Dole St, Holmes Hall 402, Honolulu, HI 96822, USA

F. Duennebier
Department of Geology and Geophysics, University of Hawaii,
680 East-west Road, Honolulu, HI 96822, USA

W.W.L. Au, M.O. Lammers (eds.), *Listening in the Ocean*, Modern Acoustics and Signal Processing, DOI 10.1007/978-1-4939-3176-7_9

9.1 Station ALOHA

9.1.1 What Is the Station ALOHA Cabled Observatory?

The University of Hawaii's Station *ALOHA* Cabled Observatory (ACO) is a seafloor oceanographic observatory that is linked to shore by a fiber-optic cable, which allows continuous, real-time monitoring of ocean processes. To quote the ACO website, it is "one of but a handful of seafloor observatories worldwide connecting deep-sea science directly to the researchers who are working to understand the complex processes that occur there" (http://aco-ssds.soest.hawaii.edu/ALOHA/ACO.html). The ACO is located 100 km north of Oahu, Hawaii (22 45′N 158 W) as shown in Fig. 9.1 and is also the site of the long-term Hawaii Ocean Time-series (HOT) open ocean measurement program. As part of the HOT program, research vessels visit Station ALOHA 10–12 times each year to study physical and biogeochemical properties of the North Pacific Ocean (Karl and Lukas 1996). ALOHA stands for "A Long-term

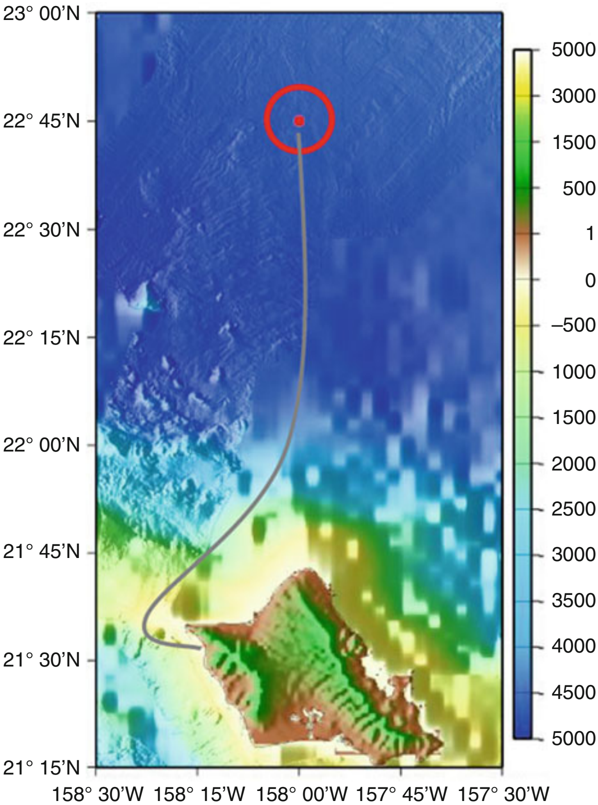

Fig. 9.1 A map showing the location of the Station ALOHA Cabled Observatory and the fiber optic cable connecting the ACO to the AT&T cable station at Makaha, Oahu

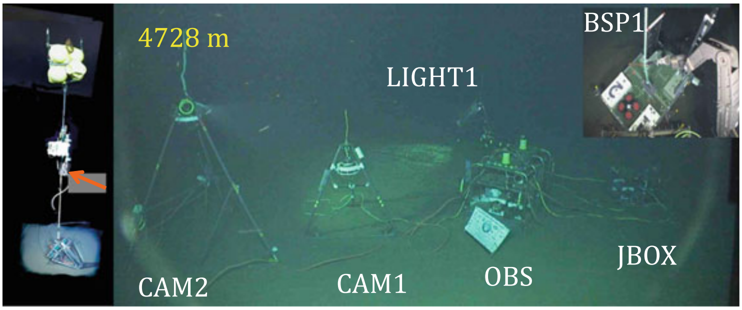

Fig. 9.2 The ACO seafloor system at 4728 m water depth. (*left*) the proof module; the hydrophone is within a PVC vented shroud 10 m above the *bottom*, indicated by the *red arrow*. The *white rectangular* structure just above and to the left is the sea water return electrode, covered with aragonite. Glass ball floats in protective hardhats above keep the mooring line taut. (*right*) the configuration of the seafloor system after the November 2014 service, showing the new camera and lights (CAM2, LIGHT1) and basic sensor package with modem and CTD (BSP1), as well as the JBOX, OBS, and CAM1 deployed in June 2011

Oligotrophic Habitat Assessment"; the ocean here is a "desert" (oligotrophic) and is representative of 70 % of the world's ocean. Because the ACO sits on the seafloor at approximately 4800 m depth, it provides researchers with the opportunity to study deep-sea processes in conjunction with ship-board observations, resulting in the ability to examine this location at all depths (Howe et al. 2015).

The ACO consists of a number of modules (Howe, et al. 2011; Howe 2015), including:

1. Video cameras with lights to record the behavior of deep water animals such as shrimp and sea cucumbers.
2. A thermistor array and acoustic modem to collect temperature profiles of the bottom 200 m of the ocean (deployed 2011–2012).
3. Acoustic Doppler profilers to measure ocean currents.
4. Temperature and conductivity sensors (MicroCat CTD) for continuous observations of temperature, salinity, and dissolved oxygen.
5. Several hydrophones for continuous acoustic monitoring.
6. A pressure sensor (Howe et al. 2011).

Several pictures of the underwater unit of the ACO are shown in Fig. 9.2. The ACO modules are connected to shore via a retired AT&T HAW-4 electro-optical cable (Duennebier et al. 2012), which allows continuous, real-time oceanographic observations. A junction box (JBOX) at the termination point of the cable converts fiber-optic communication signals to Ethernet signals, which are then distributed by the observatory module (OBS) with low voltage power to eight user ports (Howe et al. 2011). The cable comes ashore at the AT&T station at Makaha, Oahu (Fig. 9.1). Real-time displays of temperature, salinity, currents, pressure, acoustic "seismograms," audio and video are available on the Station ALOHA website http://aco-ssds.soest.hawaii.edu/dataDisplay.php.

9.1.2 History of the ACO

In February 2007, scientists from the University of Hawaii's School of Ocean and Earth Science and Technology (SOEST) and the 513 ft Navy cable repair ship, *Zeus*, grappled a retired AT&T HAW electro-optical cable from the seafloor where it had lain for almost 20 years. They cut the cable and moved the Hawaii end to the location of Station ALOHA (Howe et al. 2011). When the cable had been relocated, the Navy ship *Zeus* lowered the "proof module" frame, which contained a hydrophone and pressure sensor. On February 16, 2007, the proof module began to send acoustic signals from the ACO back to the AT&T receiving station on Oahu. The proof module collected data nearly continuously for 20 months until it was removed in October 2008 to install more instruments and add capabilities to the observatory, e.g., user ports with power and Internet connectivity (Duennebier et al. 2012). Unfortunately, a dry-mate fiber-optic connector on this new observatory module failed, so it had to be recovered and returned to land for repair.

Repair and reinstallation of the ACO was delayed due to funding challenges. Finally, in May 2011, a redeployment mission commenced. On June 6, 2011, using the remotely operated vehicle (ROV) *Jason*, SOEST scientists successfully reinstalled the observatory at Station ALOHA. This time, the observatory contained a more extensive collection of instruments that allowed real-time visualization of the seafloor, monitoring of sound in the ocean, and measurements of temperature, salinity, and currents. The ACO has been continuously in operation since that time, and continues to evolve. In November 2014, a cruise was conducted to repair and expand the bottom instrumentation; the resulting bottom configuration is shown in Fig. 9.2. This configuration includes a new camera system with lights and hydrophone, a pumped conductivity, temperature and oxygen sensor, and an acoustic modem. The latter will serve double duty as an inverted echosounder to measure the depth averaged temperature.

9.1.3 ACO Hydrophones

The ACO is equipped with several hydrophones that detect sounds produced by marine animals, environmental processes such as rainfall and water movement, and earthquakes. One of the hydrophones (OAS Model E-2PD) has a frequency response of 0.01 Hz to 8 kHz (Howe et al. 2011). The other, uncalibrated hydrophone was home-built using a 1 cm piezoelectric ceramic element. This hydrophone has a frequency response of 0.1 kHz to 48 kHz (Ethan Roth, 2013, unpublished data). Both hydrophones are mounted 1 m off the seafloor and are spaced 1 m apart (Ethan Roth, 2013, unpublished data). Gain and filter settings for the hydrophones can be changed via an ACO user interface (Howe et al. 2011). Only data from the E-2PD hydrophone was used for the work described in this chapter.

Signals from both of the ACO hydrophones are recorded by a computer located at the AT&T Makaha cable station on Oahu using a 96 kHz sampling rate. These data are buffered at the Makaha cable station on a RAID system and are transferred in near-real time to the University of Hawaii-Manoa for archiving. The 96 kHz sample rate data are also decimated into 24 kHz datasets and are transmitted via TCP/IP to the University of Hawaii-Manoa in real-time (Duennebier et al. 2012). Real-time streaming audio and spectrographic displays are available at the ACO website (http://aco-ssds.soest.hawaii.edu/dataDisplay.php).

9.2 Baleen Whales at the ACO

Many species of baleen whales travel in small groups, exhibit cryptic behavior at the sea surface and spend a large proportion of their time under water. As a result, these animals can be challenging to study using traditional visual methods. In addition, much of the range of baleen whales includes offshore waters that are difficult to access with ships, especially for long periods of time. Fortunately, baleen whales produce low-frequency sounds that propagate well under water. In many cases, these sounds are quite distinctive and it is possible to identify them to species with a high degree of confidence. These distinctive, low-frequency sounds provide an alternative method for investigating the occurrence and behavior of elusive species and the ACO provides an excellent tool for taking advantage of these sounds. Acoustic data from the ACO are recorded continuously, providing a long-term dataset for investigating seasonal and diurnal trends in the occurrence of baleen whales at a location that would be difficult to study any other way. In the following sections, we describe our investigation of the occurrence of sounds produced by baleen whales at the ACO hydrophone.

9.2.1 Characteristics of Baleen Whale Sounds Recorded at the ACO

The baleen whale species that occur near Station ALOHA include blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), minke whales (*B. acutorostrata*), and sei whales (*B. borealis*). All of these species produce sounds that can be identified to species with a relatively high degree of confidence, although there is some uncertainty about the acoustic repertoire of Pacific sei whale. Humpback whale (*Megaptera novaeangliae*) song can also be heard on the ACO hydrophone; however, we decided to focus our attention on the other four species of baleen whales because there have been over 40 years of research on humpback whales, resulting in a tremendous amount of accumulated knowledge of this species compared with the almost nonexistent knowledge of the other species in Hawai'ian waters.

Blue whales produce sounds that have slightly different characteristics in different oceans of the world. Two characteristics that are common to blue whales in all oceans are the low tonal fundamental frequency between about 15 and 20 Hz and the long duration between 10 and 20 s (Stafford, Chap. 2; Cummings and Thompson

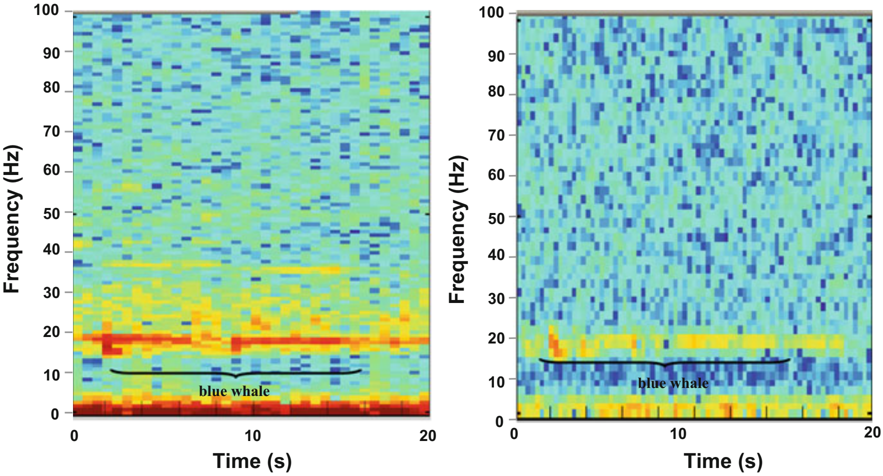

Fig. 9.3 Spectrograms of two blue whale calls recorded at the Station ALOHA hydrophone. The fundamental at 18 Hz and the 2nd harmonic at 36 Hz can be seen on the left spectrogram. The spectrogram on the right only contains the fundamental

1971, 1994; Oleson et al. 2007a, b). In addition to long duration tonal sounds, blue whales also produce stereotyped calls in two-part "AB" phrases where "A" is a series of pulses and "B" is a long, low-frequency tonal sound (see Fig. 2.2 of Stafford, Chap. 2). Spectrograms of two blue whale calls recorded at the ACO are shown in Fig. 9.3. The low-frequency (around 20 Hz and lower), tonal nature of the calls and the long duration (about 14 s) of the calls can be seen in these two examples.

Fin whales produce slowly varying, frequency modulated (FM) pulses of sound that start at approximately 25 Hz and decrease to approximately 17 Hz over a duration of 0.6–0.7 ms (Fig. 9.4). These sounds are known as "20 Hz" pulses. Fin whales produce 20 Hz pulses singly, in irregular series and as stereotyped bouts of repetitive sequences (Watkins et al. 1987). Fin whales also produce steeper FM downsweep pulses that start between 30 and 40 Hz and sweep down to slightly below 20 Hz over a duration of approximately 1 s (Cummings and Thompson 1994).

Very few recordings of sei whales exist. Thompson et al. (1979) reported that sei whales produced a sonic burst of 7–10 metallic-like sounding pulses with energy at peak frequency of 3 kHz. The train of pulses lasted 0.7 s with each pulse being about 4 ms in duration. Knowlton et al. (1991) reported sei whale sounds that consisted of two phrases of 0.5–0.8 s duration spaced about 0.4–1 s apart. Each phrase was composed of a series of 10–20 FM sweeps in the range of 1.5–3.5 kHz and lasting about 30–40 ms/sweep. However, later studies indicated that one of the predominant calls produced by sei whales is a downswept FM signal starting around 100 Hz and decreasing almost linearly to about 38 Hz (Rankin and Barlow 2007; Baumgartner et al. 2008). Spectrograms of two calls assumed to be produced by sei whales detected with the ACO hydrophone are shown in Fig. 9.5. The sei whale downsweep FM signals in the figure start at approximately 100 Hz and sweep down

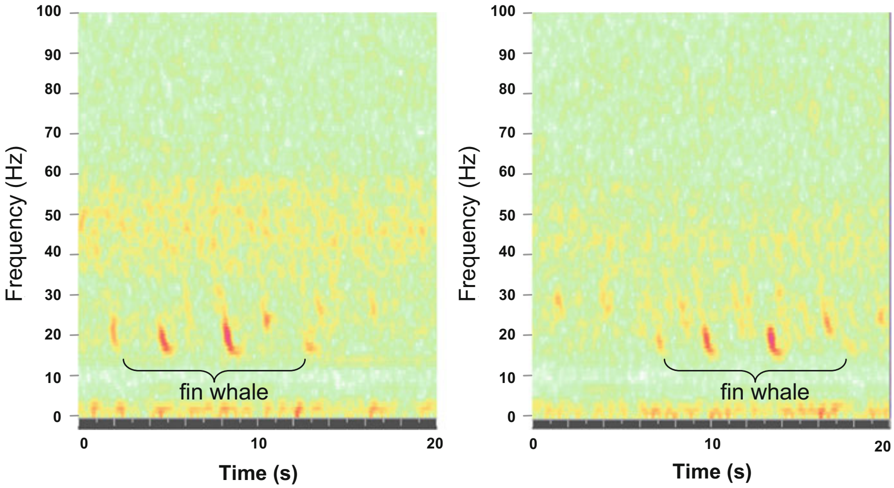

Fig. 9.4 Spectrograms of fin whale FM downsweeps recorded with the Station ALOHA hydrophone

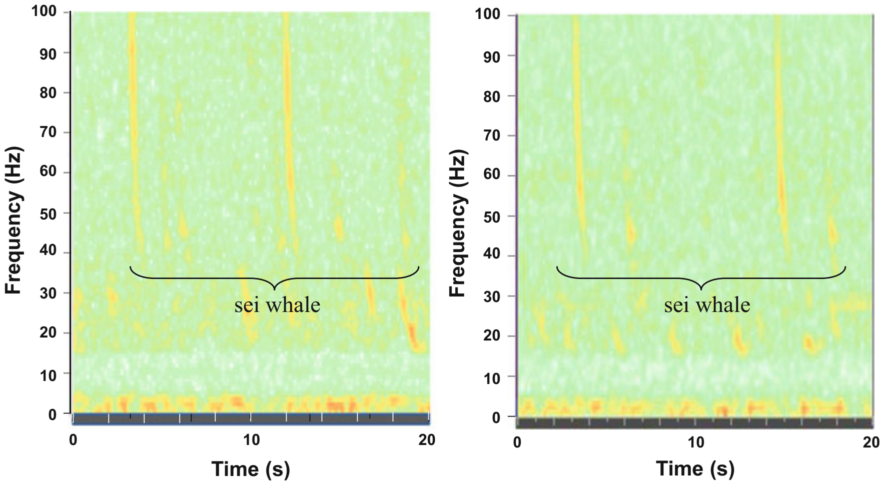

Fig. 9.5 Spectrograms of calls assumed to be produced by sei whales (based on Rankin and Barlow 2007; Baumgartner et al. 2008) detected at the Station ALOHA hydrophone. Fin whale calls can also be seen at lower frequencies

to 38–45 Hz in approximately 1 s. Sei whale downsweep FM signals can also be seen in the spectrograms in Fig. 9.5.

Minke whales in the north Pacific Ocean produce a sound known as the "boing." Boings are relatively stereotyped sounds that usually begin with a brief pulse followed by a longer, frequency and amplitude modulated component centered at approximately 1.4 kHz (Fig. 9.6). Based on the pulse repetition rate in the amplitude modulated component, Rankin and Barlow (2005) reported two types of boings. The "eastern

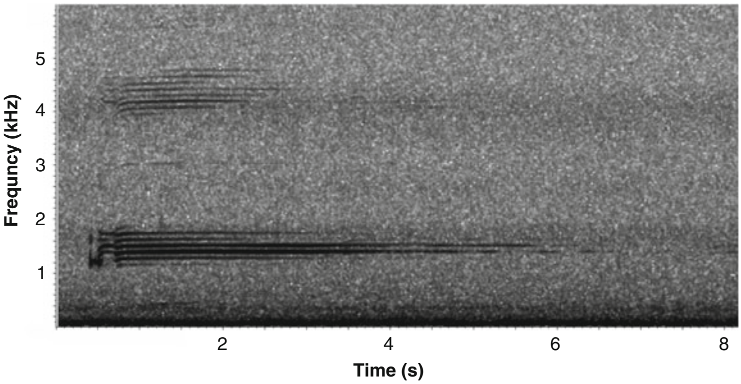

Fig. 9.6 Spectrogram of a minke whale boing detected at the Station ALOHA hydrophone

boing," which has a pulse repetition rate of 91–93 pulses/s and a mean duration of 3.6 s, was recorded east of 138° west latitude. The "central" boing has a pulse repetition rate of 114–118 pulses/s and was recorded west of 135° west latitude.

9.2.2 Automatic Detection of Sounds Produced by Baleen Whales

Matlab scripts were used in the acoustic analysis of the ACO data. The hydrophone data were digitized at a sample rate of 24 kHz, which is much higher than necessary for working with low-frequency baleen whale calls. For a standard spectrogram determination, the frequency bin size is equal to the sample rate divided by the number of points in the Fourier transform window, so for a given window size, the higher the sampling rate, the larger the frequency bins. For low-frequency baleen whale calls, bin sizes should be on the order of several Hz. The automated detectors for low-frequency blue, fin, and sei whale signals decimated the hydrophone data by a factor of 24, making the effective sampling rate equal to 1 kHz. The automated detectors for higher frequency minke whale signals decimated the hydrophone data by a factor of 6 making the effective sampling rate equal to 4 kHz.

The acoustic data were first analyzed using a bandpass filter to obtain signals in the appropriate frequency range of the species of interest. An envelope detector was applied to each file being analyzed and the average value of the ambient noise was determined. The threshold was adaptively determined by choosing a value that represented an intensity that was 3-dB higher than the averaged ambient noise intensity. The blue whale detector examined potential blue whale calls by calculating the spectra of consecutive ½ second windows using a fast Fourier transform algorithm in Matlab. If a signal was in the appropriate blue whale frequency range and had a continuous duration between 11 and 18 s, the signal would be designated as a blue whale signal. If at least three signals had the appropriate frequency range and duration in the 5-min .wav file being examined, that file would be designated as a blue whale file. Extra caution was taken when including potential blue whale signals due to non-blue whale low-frequency long-duration tones that have been recorded in the area, probably from distant shipping.

Calls produced by fin and sei whales were detected by first processing the data in each file with a bandpass filter followed by an envelope detector and establishing a threshold in a similar manner as was done for the blue whale detector. A spectrogram similar to those shown in Figs. 9.4 and 9.5 was calculated for each file and the beginning and ending frequencies along with slope of each supra-threshold signal were determined. Signals that had beginning frequencies between 80 and 100 Hz and ending frequencies between 40 and 50 Hz and had durations between 0.5 and 1 s were designated as sei whale signals. Signals that had beginning frequencies between 40 and 60 kHz and ending frequencies between 18 and 30 Hz and had duration between 0.5 and 1 s were designated as fin whale signals. At least 5 signals with the appropriate characteristics had to occur in a single 5-min .wav file before that file was designated as a fin or sei whale file.

Matlab blue, fin, and sei whale detector scripts were developed specifically for the ACO data. An interactive procedure was used in which a test data set containing about 20 5-min files with manually confirmed calls from the three species was created. A detector for a specific baleen whale species was initially created and used to analyze the files in this test set to determine how well the algorithm performed. Each detector algorithm was fined-tuned until it worked almost perfectly with the data in the test set. In addition, an informal ground-truth or validation process was conducted after all the ACO data from the time period of 17 February 2007 until 18 February 2008 were analyzed using the blue, fin, and sei whale detectors. For each species, one hundred randomly chosen files that were labeled by the detector as containing that species were examined. The spectrogram for each file was visually examined and if at least five signals that exhibited characteristics associated with fin and sei whale calls were found, then the label was considered to be correct. The correct classification rate was very high, greater than 97 % for fin whales and 98 % for sei whales. Because the detector performed so well for fin and sei whales, a validation test for blue whales was not conducted.

Two different types of minke whale detectors were used to analyze the ACO data. The first used a data template detector (Oswald et al. 2011) created with XBAT (Extensible Bioacoustic Tool) software. XBAT's data template detector is a spectrogram correlation detector that examines the time cross-correlation sequence between an example sound [in this case, both a high signal-to-noise ratio (SNR) boing and a medium SNR boing were used as example sounds] and the sound file being analyzed. Events are detected when the correlation exceeds a user-defined threshold. The XBAT detector was ground-truthed using 8 h of data recorded on 5th March, 2007. An experienced acoustician visually and aurally identified boings in a spectrogram, and ranked each boing as one of five quality categories ranging from one (audible, but barely recognizable as a boing on the spectrogram) to five (very loud and clear boing). The results of the manual examination were then compared to automated detections made using XBAT on the same section of dataset. A total of

783 boings were manually identified in the 8-h recording that was used for ground-truthing the detector. The automated detector identified 100 % of category 5 boings ($n=49$), 99 % of category 4 boings ($n=78$), 91 % of category 3 boings ($n=150$), 59 % of category 2 boings ($n=259$), and 22 % of category 1 boings ($n=247$). Only 5 % of detections made by the XBAT detector were false detections and most of these were caused by sounds produced by humpback whales.

The second minke whale boing detector utilized the same process as was used for fin, sei, and blue whales. The signals detected by the envelope detector were subsequently analyzed in the frequency domain by creating 250 ms segments, with each segment analyzed using fast Fourier transform (FFT). The peak frequency and side-band frequencies (the localized maxima if there are any) were calculated for each Fourier spectrum. The signal was classified as a boing sound if its peak frequency remained within the range of 1375–1430 Hz with less than 10 Hz fluctuation from one step to the next, and if the separation between main band and side bands was in the range of 116 ± 6.75 kHz. If a signal contained an outstanding side-frequency component (not necessarily a side band of the peak frequency), it would not be classified as a "boing" if (1) this side-frequency portion did not have time duration comparable to the peak frequency band or (2) its separation from the peak frequency did not fall into the required range. If a signal satisfied the condition on the peak frequency range and it did not contain any side frequency components in the 1–2 kHz range, it would also be classified as boing (Ou et al. 2012).

This boing detection algorithm was tested on the same data set used by Oswald et al. (2011) to test the XBAT algorithm. Out of 1447 boing sounds that were manually detected by visual inspection of the spectrograms, both of the detectors recognized more than 90 % of them, with XBAT giving slightly better results. However, the non-spectrogram method produced a lower number of false alarms, with a 0.3 % false alarm rate compared to 5 % for XBAT, indicating that the XBAT detector was more sensitive to noise caused by humpback background chorusing sounds that were also detected by the ACO hydrophone. Because of this, all analyses presented in the following sections are a result of the non-spectrogram analysis method.

9.2.3 Baleen Whales at the ACO

The detection of baleen whales in the ACO recordings is reported in terms of the number of 5-min files per day in which whales of a given species were detected. The overall results are shown in Fig. 9.7 as a function of month. One of the obvious but very important results is that whales were generally only detected during the winter and spring months. The only exception to this occurrence pattern was fin whales. Throughout the months of June–September, when there were no detections of minke, blue or sei whales, there were days in which one or two files contained fin whale downsweeps, except for September 10 and 11 in which 8 and 9 files, respectively, contained fin whale downsweeps. The actual number of files per day for a given species was not considered to be an important metric in this study because detection depends on the distance between the whale and the hydrophone, as well

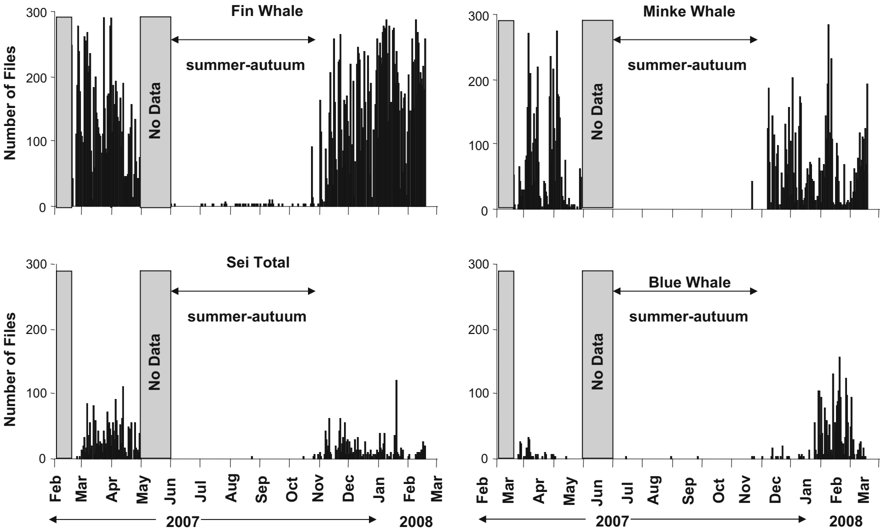

Fig. 9.7 The number of 5-min .wav files recorded at the Station ALOHA ACO that contained sounds produced by baleen whales during the period of February 17, 2007–February 18, 2008. *Grey boxes* represent time periods in which recordings were not made

as the ambient noise level for any given time and day. High winds, rain, and high sea states are some of the environmental variables that would affect the ambient noise for any given period. Fin whales were the most frequently detected species, followed by minke whales. Blue and sei whales were detected the least frequently. On several days, fin whale calls were detected in over 96 % of the files.

Based on the results in Fig. 9.7, whales do not suddenly appear but arrive in Hawai'ian waters in a gradual but somewhat sporadic manner. This can also be seen in Fig. 9.8, which is an expanded view of Fig. 9.7 to show in greater detail the beginning of the 2007–2008 baleen whale season. A small number of sounds produced by sei whales were detected as early as October 2, while a small number of sounds produced by fin whales were detected on the next day, October 3. A number of fin whale calls were detected sporadically during the October 4–28 period, after which they were detected regularly. Minke whale boing sounds were regularly detected starting on November 7. Even though sei whale calls were the first to be detected in October, calls produced by this species did not occur regularly until after October 31. The blue whale calls in the beginning of the 2007–2008 baleen whale season were fairly sporadic, making it difficult to ascribe a pattern to the occurrence of these calls. The important features in Figs. 9.7 and 9.8 can be summarized as: (1) the calls from the different species were not detected at the same time but were spaced out by days and weeks, (2) in the beginning, there were days during which a small number of calls were detected followed by days during which no calls were detected, (3) the pattern of calls on a day-to-day basis varied considerably. For example, fewer than 30 files contained fin whale calls on November 15 but the next day, the number of files with fin whale calls shot up to 258, an increase of nearly nine times over 2 consecutive days.

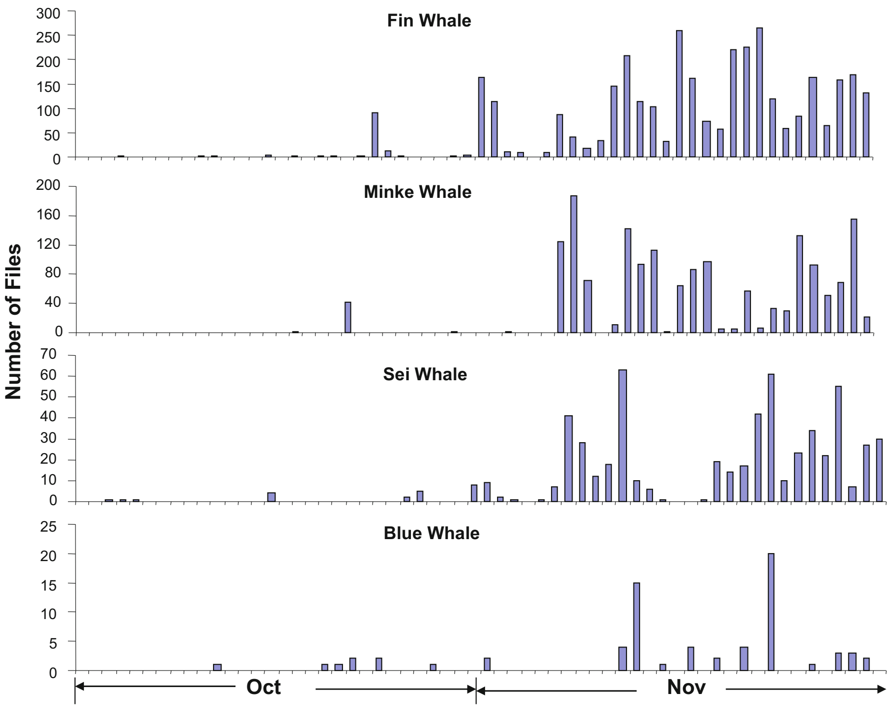

Fig. 9.8 An expanded view of the number of 5-min .wav files recorded at the Station ALOHA ACO that contained sounds produced by baleen whales at the Station ALOHA hydrophone at the beginning of the 2007–2008 baleen whale season in Hawai'i. Note that the vertical axes have different scales

An expanded view of the acoustic detection of these four species of whales at end of the 2006–2007 season is shown in Fig. 9.9. Unfortunately, the ACO hydrophone stopped functioning on April 30, 2007 for about a month so that data for the month of May, 2007 were not available. As with beginning of the baleen whale season in Hawai'i, the ending portion of the season was spaced out over about a month as the number of calls from the blue, fin, and sei whales gradually became less frequent. Blue whale calls over consecutive days dropped out on April 4, and were only detected during 2 other days in April (April 13 and 26). Consecutive days in which minke whale boings were detected ended on April 21, and boings were detected during 3 other days that month (April 25, 27 and 28). More boing sounds may have been detected if the ACO hydrophone had continued operating into May, but the pattern in April does suggest the end of the minke whale season in Hawai'i. Sei whale calls dropped off fairly steadily after April 5 with short increases on April 11, 18, and 25. Fin whale calls were detected regularly throughout April and we surmise they probably persisted into May.

The diurnal variation in baleen whale call detections over the entire baleen whale season in Hawai'i is shown in Fig. 9.10. The shaded areas on each plot approximate the twilight, night, and dawn periods. The vertical axis is the total number of files in which baleen whale calls were detected. The results indicate that the number of fin

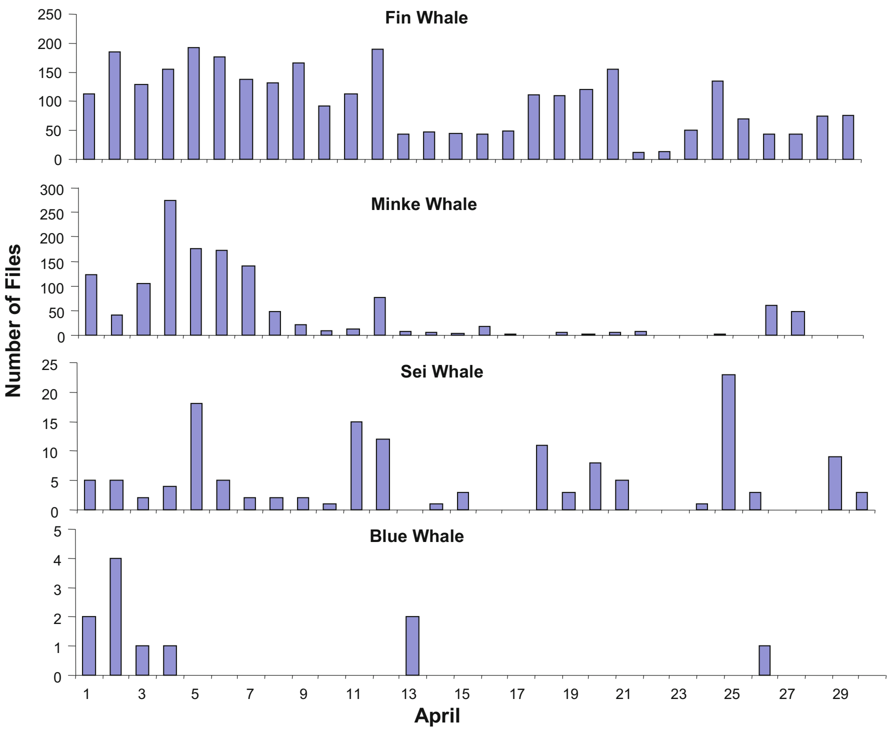

Fig. 9.9 An expanded view of the number of 5-min .wav recorded at the Station ALOHA ACO that contained sounds produced by baleen whales towards the end of the 2006–2007 baleen whale season in Hawai'i. Note that the vertical axes of the plots have different scales

and minke whale calls detected were about the same for the day and night periods. The number of sei whales calls detected was high at dawn and decreased steadily towards dusk. The number of blue whale calls detected was higher during the twilight-night hours than during the day. However, even if a pattern is shown for any of the species, the significance of the pattern is questionable. It is impossible to state whether the variability in the number of calls detected for a species was caused by a variation in the number of whales calling during a time period or if the daily movement patterns of the whales meant that the species was out of range of the ACO hydrophone, or a combination of both factors.

9.3 Discussion

The distance from the ACO hydrophone at which most of the baleen whale calls were detected cannot be estimated or approximated from the results obtained from a single hydrophone. However, sound propagation characteristics of the water column in the vicinity of Station ALOHA suggest that calling animals were likely within a

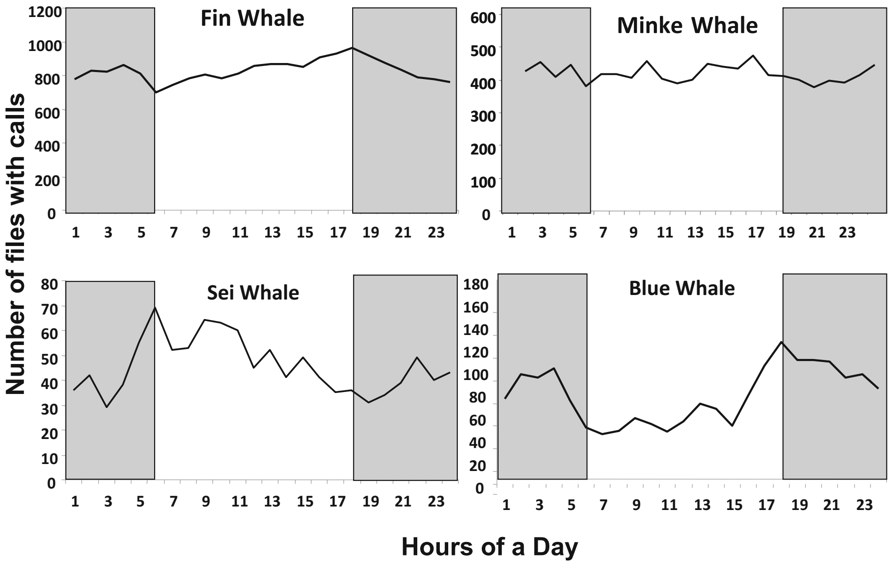

Fig. 9.10 The number of files in which baleen whale calls were detected at different hours of the day between February 17, 2007 and February 18, 2008. Shaded areas in each plot represent night time periods. Non-shaded areas represent day time

convergence zone (±30 km) of the ACO hydrophone. Long distance propagation of sound is supported by the SOFAR (Sound Fixing and Ranging) channel, which is seen at a depth of 700 m during several months at Station ALOHA (Fig. 9.11). The ACO the hydrophone is located at a depth of 4700 m, just at or slightly below the critical depth, so it is less likely to detect sound propagating from long range.

During the beginning and ending of the baleen whale season there were many days in which no whales of a given species were detected, followed by days with multiple detections. This type of variation may be attributed to the density of whales in the location of the hydrophone and to the movements of individuals. When the density of whales is relatively small and the group moves out of the detection range for the hydrophone, no calls from that species will be detected. However, as the season progresses and more whales migrate to Hawai'ian waters, animal movements have a smaller effect on acoustic detection rates since there is a higher likelihood that there will always be some whales within the detection range of the hydrophone. Therefore, as the season progressed, whales were more consistently detected.

Seasonal variation in the number of detections was not likely caused by changes in sound propagation, as the effects of the latter for an ACO hydrophone are small (Fig. 9.11).

The occurrence patterns of the four species of baleen whales included in this analysis generally corresponded with the arrival of humpback whales wintering in Hawai'ian waters. Humpback whales migrate from the waters around the Aleutian Islands and southeast Alaska to Hawai'ian waters as early as late October and leave by late April and early May (Baker and Herman 1981). One of the reasons for the humpback whale seasonal migration is for the whales to breed and give birth to their young in relatively shallow and calm inshore waters. It is not yet known why the

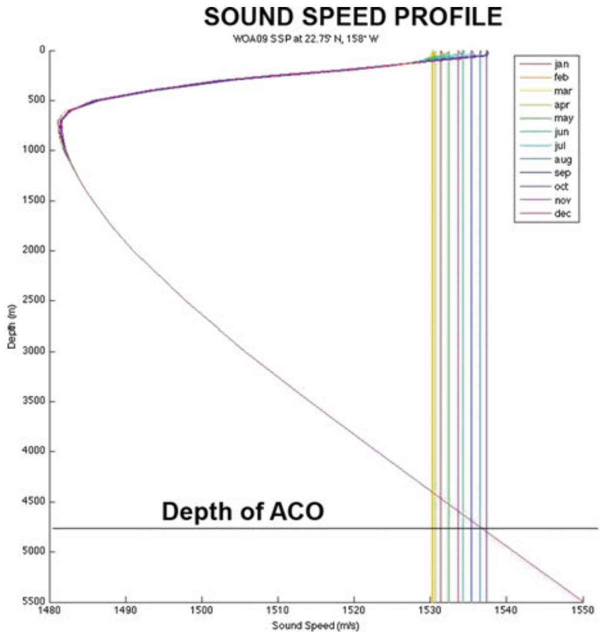

Fig. 9.11 Sound velocity profile in the vicinity of the ACO hydrophone (courtesy of L. Van Uffelen)

other species of baleen whales migrate to Hawai'ian waters. These species are not generally observed in the near shore waters frequented by humpback whales, and the waters several miles from shore are very deep and probably much rougher than inshore waters. Nevertheless, the other baleen whales may migrate to waters around Hawai'i to breed and give birth in the warm waters found at lower latitudes. We conducted a preliminary analysis to examine factors that may be related to the presence of baleen whales at Station ALOHA using oceanographic parameters measured during near monthly HOT cruises (Karl and Lukas 1996). We found no obvious correlations between the presence of baleen whales and measures of primary production, plankton community structure, and temperature. However, these were preliminary investigations and this is a topic that warrants further investigation.

The four species of baleen whales detected with the ACO hydrophone have all been observed visually in Hawai'ian waters. A NOAA cruise to estimate marine mammal abundance in Hawai'ian waters was conducted from August to November, 2002 (Barlow 2006). The four species of baleen whales detected with the ACO hydrophone were seen only late in the survey (Barlow 2006), which is consistent with our findings suggesting the arrival of these whales in October. Calls from three of the species of baleen whales discussed here (fin, blue, and minke) were also detected by Thompson and Friedl (1982) using a pair of hydrophones separated by 16 km at a depth of 731 m which was at the same depth as the SOFAR (sound fixing and ranging) axis on the north slope of Oahu. Sounds traveling in the SOFAR channel can propagate many hundreds of miles, even out to a thousand miles, making it possible to hear whales that are not in the close proximity to the hydrophone (Urick 1983), and it is not possible to determine how close the whales recorded by Thompson and Friedl (1982) were to the hydrophones that they used.

It is common knowledge that blue, fin, sei, and minke whales migrate seasonally from cooler subpolar waters at high latitudes to warmer tropical waters at low latitudes. During months when calls were not detected it may be a safe to assume that the whales have left the area on their northward migration to higher latitudes. However, in the case of fin whales, calls were still detected during the summer months, albeit at considerably lower rates than during the winter months. This suggests that at least a small number of fin whales remained in the general area of Station ALOHA all summer. Unfortunately, recordings from a single hydrophone cannot provide any information on the relative number of whales present or their distance and direction from the hydrophone.

A single hydrophone system such as the Station ALOHA ACO can provide information about the presence and temporal patterns in calling behavior for baleen whales, as well as on the relative number of calls per species. Fin whale calls were detected about ten times more frequently than blue whale calls, seven times more frequently than sei whale calls and two and a half times more frequently than minke whale calls. However, the significance of these numbers is questionable since we do not know the distances at which the whales were detected, how those distances vary among species, and how the number of calls relates to the number of animals.

Another interesting piece of information concerning the detection of baleen whale calls is that humpback chorusing sounds could be heard in the "background" of the ACO recordings during the peak of the humpback whale season in Hawai'i. Since humpback whales, to the best of our knowledge, usually inhabit in-shore waters while wintering in Hawai'i and the ACO hydrophone was about 100 km (54 nm) from shore, this suggest that some degree of long range propagation with some combination of sound channel refraction and bottom and surface scattering, and even internal wave scattering could in fact be occurring. Again, it is not possible to estimate the range at which these humpback whale chorusing sounds were detected. The addition of one or more time synchronized, and fully calibrated hydrophones to the ACO would make it possible to determine detection bearings and distances and gain more insight to the occurrence and behavior of baleen whales in this area. Nevertheless, the ACO hydrophone has provided extremely important information on the seasonality of baleen whales, their migration patterns into and out of a small area north of Oahu and the relative occurrence of different species, thus increasing our knowledge of these species in an area that is challenging to access and monitor in any other way.

References

C.S. Baker, L.M. Herman, Migration and local movement of humpback whales (*Megaptera novaeangliae*) through Hawaiian waters. Can. J. Zool. **59**, 460–469 (1981)

J. Barlow, Cetacean abundance in Hawaiian waters estimated from a summer/fall survey in 2002. Mar. Mamm. Sci. **22**, 446–464 (2006)

M.F. Baumgartner, S.M. Van Parijs, C.F. Wenzel, F.W. Tremblay, H.C. Esch, A.M. And Warde, Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*). J. Aoust. Soc. Am. **124**, 1339–1349 (2008)

W.C. Cummings, P.O. Thompson, Underwater sounds from the blue whale, *Balaenoptera musculus*. J. Acoust. Soc. Am. **50**, 1193–1198 (1971)

W.C. Cummings, P.O. Thompson, Characteristics and seasons of blue and finback whale sounds along the U.S. West Coast as recorded at SOSUS stations. J. Acoust. Soc. Am. **95**, 2853 (1994)

F.K. Duennebier, R. Lukas, E. Nosal, J. Aucan, R.A. Weller, Wind, waves and acoustic background levels at Station ALOHA. J. Geophys. Res. **117**, C03017 (2012)

B.M. Howe, A deep cabled observatory: biology and physics in the Abyss, Eos, Trans. AGU **95**(47), 429–430 (2015). doi:10.1002/2014EO470001

B.M. Howe, R. Lukas, F. Duennebier, D. Karl, ALOHA cabled observatory installation, in *Oceans*, ed. by IEEE (IEEE, Waikoloa, HI, 2011), pp. 1–11

B.M. Howe, F.K. Duennebier, R. Lukas, The ALOHA cabled observatory, in *Seafloor Observatories: A New Vision of the Earth from the Abyss*, ed. by P. Favali, L. Beranzoli, A. De Santis (Springer, New York, NY, 2015)

D.M. Karl, R. Lukas, The Hawaii Ocean Time-series (HOT) program: background, rationale, and field implementation. Deep Sea Res Part II **43**, 129–156 (1996)

A. Knowlton, C.W. Clark, S. Krause. Sounds recorded in the presence of sei whale, *Balaenoptera borealis*. J. Acoust. Soc. Am **89** 1968–1968 (1991)

E.M. Oleson, J. Calambokidis, W.C. Burgess, M.A. McDonald, A. LeDucC, J.A. Hildebrand, Behavioral context of call production by eastern North Pacific blue whales. Mar. Ecol Progr. Ser. **330**, 269–284 (2007a)

E.M. Oleson, S.M. Wiggins, J.A. Hildebrand, Temporal separation of blue whale call types on a southern California feeding ground. Anim. Behav. **74**, 881–894 (2007b)

J.N. Oswald, W.W.L. Au, F. Dunnebier, Temporal patterns in the occurrence of minke whale boings detected at the Station ALOHA Cabled Observatory. J. Acoust. Soc. Am. **129**, 3353–3360 (2011)

H. Ou, W.L. Au, J.N. Oswald, A non-spectrogram-correlation method of automatically detecting minke whale boings. J. Acoust. Soc. Am. **132**, EL317–EL322 (2012)

S. Rankin, J. Barlow, Source of the North Pacific “boing” sound attributed to minke whales. J. Acoust. Soc. Am. **118**, 3346–3351 (2005)

S. Rankin, J. Barlow, Vocalizations of the sei whale Balaenoptera borealis off the Hawaiian islands. Int. J. Anim. Sound Record **16**, 137–145 (2007)

P.O. Thompson, W.A. Friedl, A long term study of low frequency sounds from several species of whales off Oahu, Hawaii. Cetology **45**, 1–19 (1982)

T.J. Thompson, H.E. Winn, P.J. Perkins. *Mysticete Sounds*. Springer U.S. (1979)

R.J. Urick, *Principles of Underwater Sound* (McGraw Hill, New York, N. Y., 1983)

W.A. Watkins, P. Tyack, K.E. Moore, J.E. Bird, The 20-Hz signals of finback whales (Balaenoptera physalus). J. Acoust. Soc. Am. **82**, 1901–1912 (1987)