Feasibility of using acoustic DIFAR technology to localize and estimate Hawai`ian humpback whale population

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This report is used for documentation and timely communication of preliminary results. While the report has not undergone complete formal review and editing, it reflects sound professional work and may be referenced in scientific and technical literature.

ABSTRACT

The objective of this project was to determine if the DIFAR (directional frequency analyses and recording) sonobuoy technology could be applied to estimate the population size of humpback whales singing in chorus. In order to accomplish this objective, the project was divided into two phases. The first phase consisted of obtaining high quality recordings of singing humpback whales at close ranges to determine the characteristics of their songs. The second phase consisted of deploying two DIFAR sensors to obtain directional information from chorusing humpback whales. Eight different singers were recorded at ranges from 20 to 40 m. The songs consisted of burst of sounds called units, and units were organized into phrases. Some of the units had higher order harmonics that extended to 15 kHz. The amplitudes of the higher frequency harmonics of some units were within 18 to 24 dB of the fundamental or highest level harmonics up to a frequency of 13.5 kHz. These results indicate a broadband quality of humpback whale songs that has not been previously reported. The source levels were based on the rms value of the maximum level for each different phrases used by each whale. Source levels varied between 171 to 189 dB re 1 μPa.

Two DIFAR sensors, each coupled to a microcontroller for remote recording of the acoustic information, were deployed in the waters outside of the Hawai`ian Humpback Whale National Marine Sanctuary office in Kihei, Maui. Unfortunately, the DIFAR system did not function properly. One unit flooded, destroying the electronics and microcontroller. The other unit had a hard disk crash. However, the analysis of the humpback whale songs provided strong evidence that the DIFAR would probably not have accurately localized humpback whales singing in chorus since the likelihood of finding short intervals of time during which only the sound from one whale was received while the other whales were silent would be extremely small. Therefore, with chorusing humpback whales, a DIFAR sensor would probably provide erroneous information. A better acoustic localization technique would be to use two beam-steerable arrays of hydrophones.

I INTRODUCTION

One of the interesting and outstanding characteristics of male humpback whales (*Megaptera novaeangliae*) is the complex songs that they sing while wintering at lower latitudes. Humpback whales typically winter in the waters of the Hawai`ian islands to reproduce and give birth. Over the recent years the number of whales in Hawai`ian waters have steadily increased (Mobley et al., 1999) to the point that the background ambient noise environment of waters off west Maui, and probably the waters of other Hawaiian islands, is dominated by songs of humpback whales singing in chorus (Au and Green, 2000; Au et al., 2000). During the 1998 humpback whale season, Au et al. (2000) used a portable acoustic data acqusition system (DAS) that was laid on the ocean bottom (40 ft depth) to record the background humpback whale chorusing sounds from January through April. The DAS was controlled by a microcontroller that turned the system on and acquired sound recordings for four minutes every half hour on the hour and half hour. Recordings were made in near-shore waters off Puamana Beach Park (lat: 20^{o}21', long: 156^{o}39.5') adjacent to the town of Lahaina, Maui. They found that during all hours of the day and night, there were always a number of humpback whales singing in chorus at the peak of the season.

An important issue in understanding the population dynamics of the humpback whales wintering in Hawai`i is the number of whales in a given body of water at any given time. So the obvious question is whether the chorusing sounds can be used to estimate the population of male singers in a body of water. An acoustic technique that may provide a way to localize humpback whales and therefore, obtain information on population density. The U.S. Navy has been using DIFAR (directional frequency analyses and recording) sonobuoys for several decades. These sonobuoys can determine the azimuth of low frequency sounds below 2 kHz. This technique has only recently being used for scientific purposes (D'Spain, et al., 1991). A DIFAR system consists of two orthogonal pair of directional acoustic paritcle velocity sensors, a magnetic compass and an omnidirectional pressure sensor (hydrophone). The north-south (NS) and east-west (EW) components of particle motions are computed within the sensor package at the hydrophone resulting in three signals (the hydrophone and the NS and EW component signals) from which the magnetic azimuth of a sound source can be determined. By using two or more

DIFAR sensor arranged along a line, one can resort to a triangulation process to determine the exact location of a sound source relative to the position of the DIFAR sensors.

Despite the obvious potential of localizing singing humpback whales with a pair of DIFAR sensors, there are some technical issues that must be taken in consideration. There is no question that a DIFAR sensor can unambiguously determine the direction from which the sounds of a singing whale are coming from. However, it is not certain how well DIFAR sensors may work in an environment where several humpback whales are singing or chorusing together. Having sounds from several locations arrive at a DIFAR sensor at the same time will cause the sensor to sum the acoustic energy as coming from a single source and provide a false indication of the azimuth of this single source. Humpback whales sing in chorus, which mean that a number of whales are singing simultaneously. So an important question is whether or not there are breaks or silent periods within a humpback whale song that would allow the a DIFAR sensor to unambiguously detect sounds from another or even several other whales.

Humpback whale songs consist of sequences of burst of sounds, with silent periods between each burst. A burst of song is typically referred to as a unit. Units produced repeatedly in a pattern are referred to as phrases, and phrases repeated in a particular pattern are referred to as theme. A complete song is a sequence of a number of theme. An important issue is whether or not a DIFAR sensor can detect many whales that are not singing in synchrony by taking advantage of the silent periods between units in each individual's song. Therefore, in order to address this issue the temporal structure of humpback whale songs needs to be understood as much as possible.

This project was divided into two parts, the first part involving close range (< 50 m) recording of humpback whale singing in order to understand the temporal structure of songs and to obtain source level information. The second part involved the installation of two DIFAR sensor units on the bottom of the ocean and the collection of humpback whale chorusing sounds.

II APPROACH

Phase 1

Humpback whale songs were recorded with a Sony DAC recorder and a wideband hydrophone (flat to at least 150 kHz). Before going into the field, the gain of the DAT was calibrated as a function of its gain-knob for the two input modes. A 2 v peak-to-peak 500 Hz pure tone calibration signal was also recorded at the beginning of the DAT tape. The calibration signal was used to obtain the appropriate scale factor after the data tape was digitized and saved on a PC. Therefore, the sound recording system was calibrated so that absolute values of sound pressure levels could be measured.

Measurements of humpback whale songs were done in conjunction with Dr. James Darling of the West Coast Whale Research Foundation. Singing humpback whales were approached with a 17-foot Boston whaler and when the whale dove to assume its singing position, the tail fluke was photographed. When a singer submerges a visible "slick" is left on the ocean surface. Immediately after the whale dove, we approach to within 20 to 40 m of the whale. The boat engine was then turned off, the hydrophone was deployed overboard to a depth of 12 m and the DAT was turned on. A total of two days were spent recording the songs of 8 male humpback whales.

The tape of the whale songs was digitized and analyzed using CoolEdit. The amplitude of the largest unit in a phrase was measured along with the time duration of each unit and the silent time between successive units. The spectrograms of the songs were also observed visually on a PC monitor.

Phase 2

Two DIFAR sensors were deployed in the waters immediately in front of the Hawai`ian Humpback Whale National Marine Sanctuary office in Kihei, Maui. Each DIFAR sensor was suspended from a section of 7.25" OD PVC pipe by four bungee chords as shown in Figure 1a. The unit shown in Figure 1a was then mounted on a four legged structure constructed of PVC pipes that was driven into the bottom. The support structure and DIFAR unit standing on the bottom of the ocean at a depth of approximately 12 m is shown in Figure 1b. The original plan was to have a cable from each unit run back to the Sanctuary's office for acquisition of the data. However, after an inspection of the field site in mid-January immediately after the project started, we found that the bottom depth did not change drastically with distance from shore so that the cable run would have had to be much too long (several km). Therefore, a decision to go to a

(a) (b)

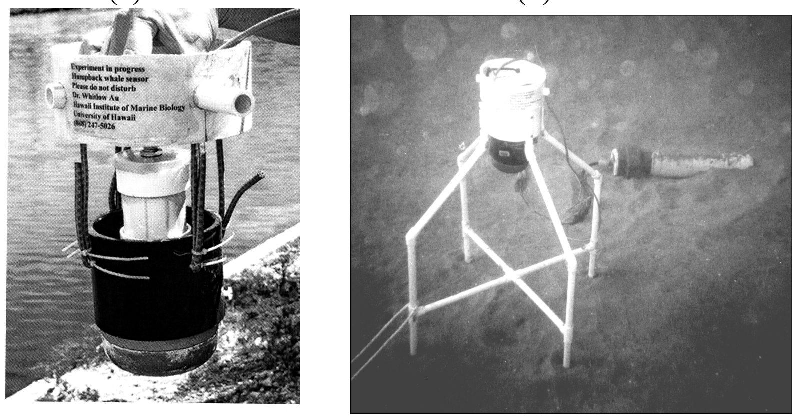

Figure 1. (a) DIFAR sensor supported by 4 bungee cords suspended from a section of 7.25" PVC pipe. (b) The DIFAR sensor mounted on a PVC support structure which was in turn embedded into the ocean bottom.

remote microprocessor controlled unit despite the short time frame before the end of the

The Persistor microcontroller with a multi-channel analog-to-digital converter was selected to perform the remote sensing task. Special power up and power down ciru-cits and anti-aliasing filters were designed, tested and fabricated. A schematic of the electronic circuit is included in Appendix A. A power-up and power-down sequence controlled by the microcontroller is necessary to conserve battery power. The electronic and battery packages are shown in Figure 2. The assembly was housed in a 4" PVC pipe having the proper removable end-cap with an O-ring seal. The housing is on the right side of Figure 1b laying on the bottom of the ocean.

Two DIFAR units were deployed in the third week of March, towards the tail end of the humpback whale season. Because of the rush to deploy the unit before too many whales departed for northern waters, we were not able to test the complete system as a whole but only as individual components. The DIFARS sensors were deployed at a depth of approximately 40 ft.

III Results

Phase 1

It is important to consider the structure of a portion of a humpback whale song in order to understand the data obtained in this phase. Humpback whale songs consist of an orderly alphabetic pointing out specific sound burst. This system of classification can be

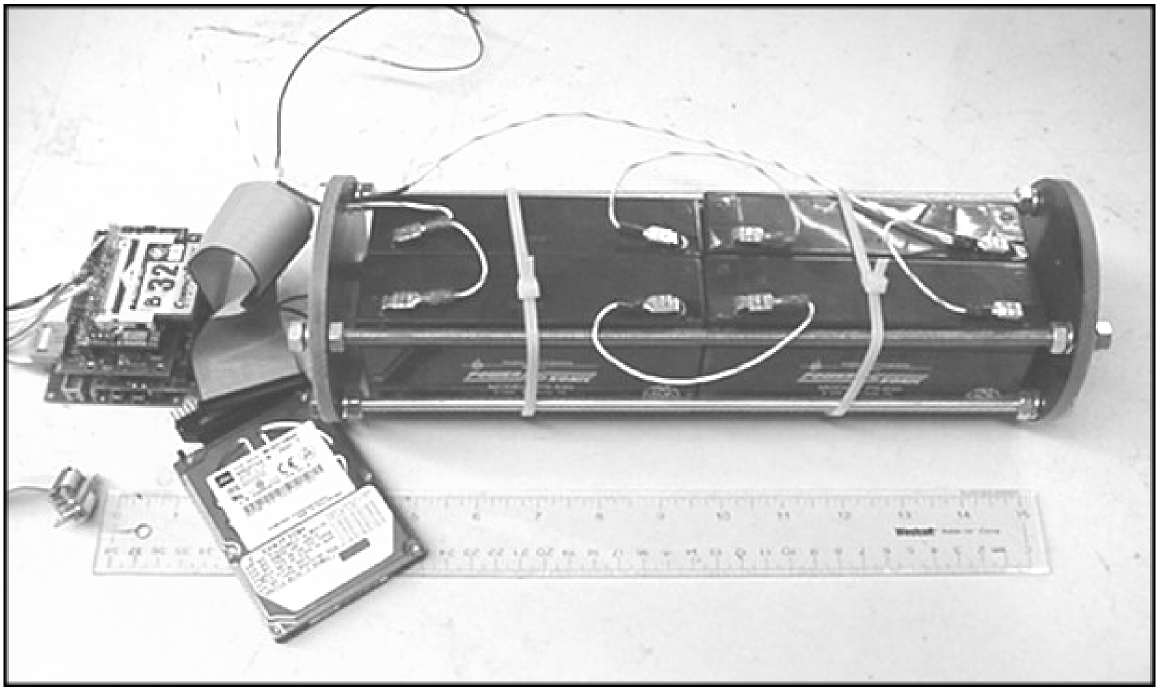

Figure 3. Electronics for the DIFAR sensor

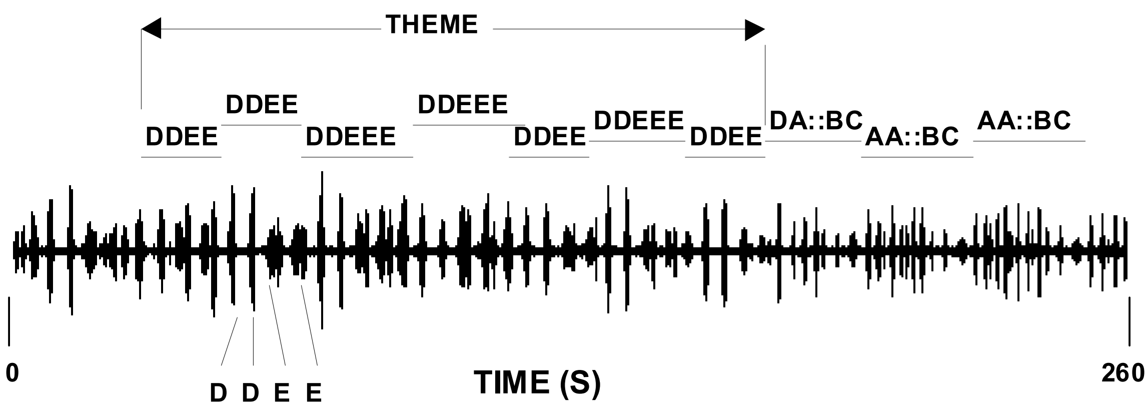

Figure 4. An example of the structure of the song of whale 8

very subjective, making it difficult to compare the results among different researchers. The units are organized in a pattern called phrases that are repeated in a sequence. Similar phrases usually contain the same number of units but can also have one or two additional units as can be seen in some of the phrases shown in Figure 4. A repeated pattern of phrases is called a theme. Several themes in a sequential pattern make up a song.

Humpback whales usually repeat the sequence of themes repeatedly from several minutes to several hours or more.

In our classification of the units in a song, the various labels or alphabets used and their associated sounds are given in Table 1.

Table 1. Classification notations and the associated sounds

A	moan (variable)
B	low moan
C	low rumble
D	high downward frequency sweeping moan
E	low upward frequency sweeping moan
F	screech
H	low frequency "rhoomp" sound
L	lion's growl
Q	squeaky hinge
R	high squeak
S	low frequency followed by high frequency squeal
T	high frequency whimper/yowl
U	upward frequency sweeping whine
W	water drop
Z	zzzzip

A total of seven specific phrases were found in the eight songs that were recorded. The waveform and spectrogram of each phrase is shown in Figures 5-11. The most unusual feature of the various phrase shown in Figures 5-11 is the high frequency components of some of the phrases. Some of the units have harmonics that extend beyond 15 kHz (see Figures 5-10). Other units have broadband energy that extends out to 15 kHz (see Figure 9 and 11). These high frequency harmonics and broadband energy have not being previously reported despite the over 30 years of research on humpback whales and their songs.

The frequency spectra of some units with high frequency harmonics extending beyond 10 kHz are shown in Figure 12. From these spectra, the relative energy in the higher order harmonics can be determined. The third harmonic in the spectrum for one of the S units in the phrase shown in figure 7 has the highest energy, and the energy at 13.5 kHz is only down by about 18 dB from the maximum level. The higher harmonics of the

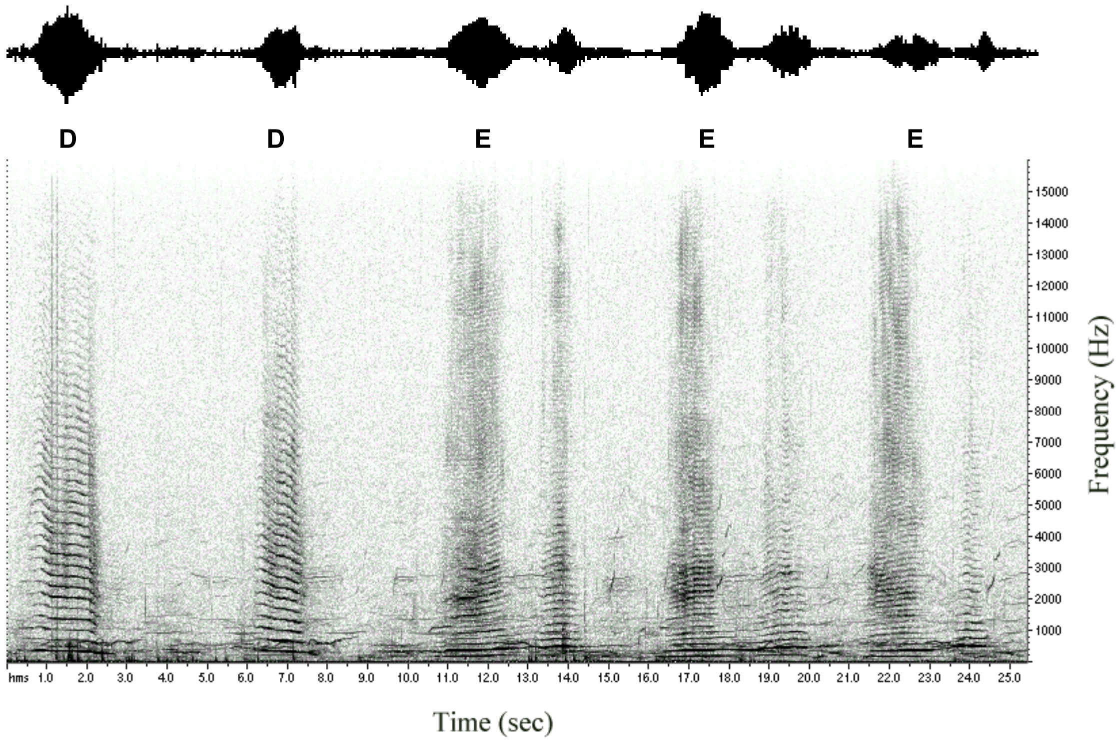

Figure 5. Phrase DDEEE from Whale 6

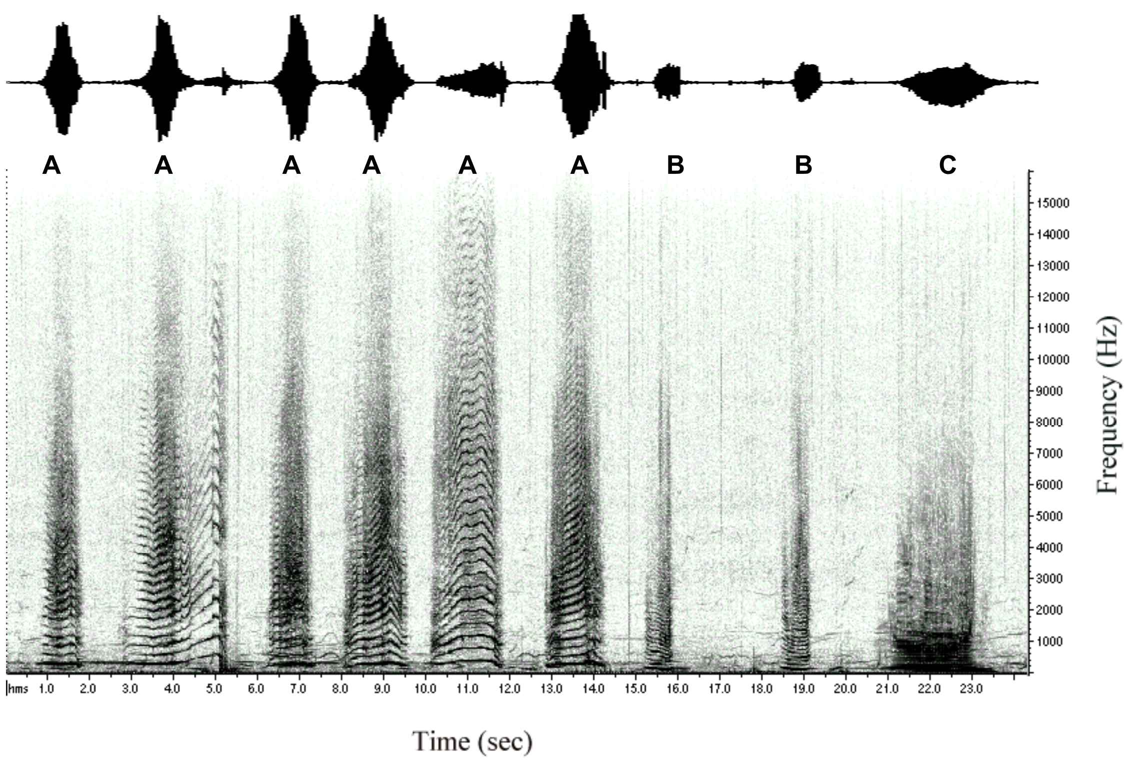

Figure 6. Phrase AAAAAABBC from Whale 2

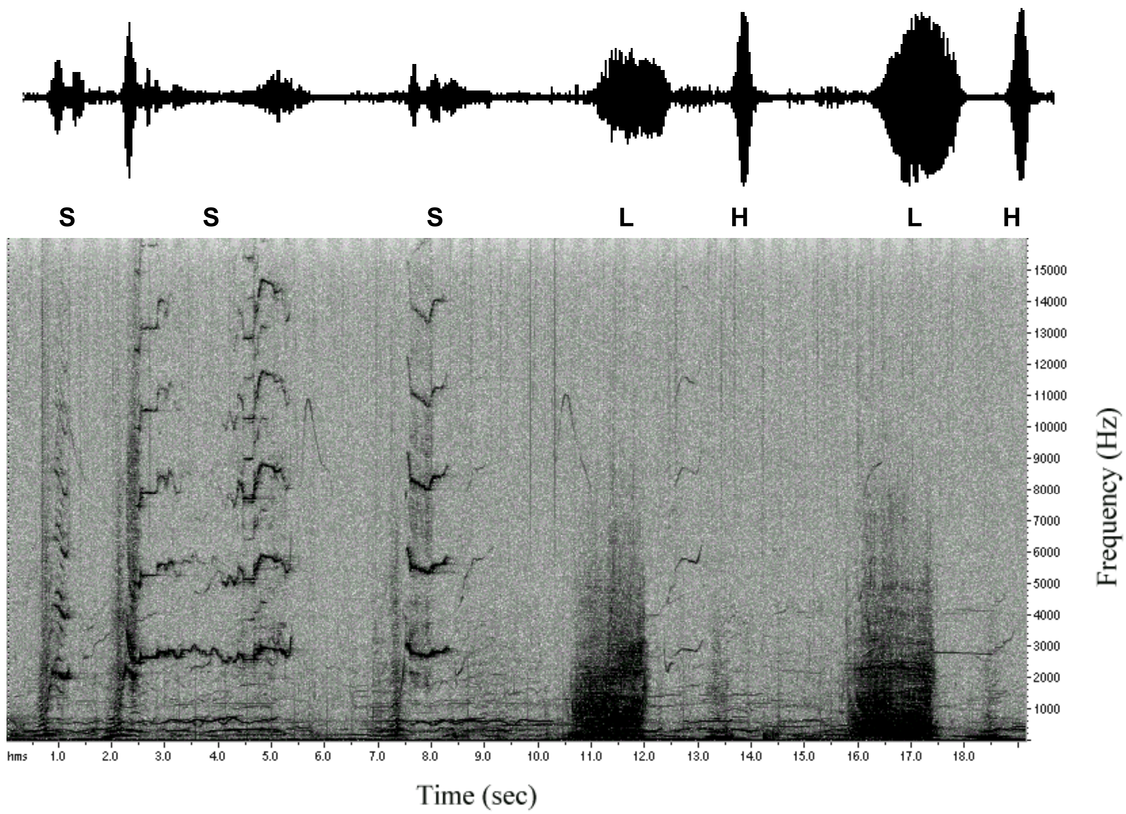

Figure 7. Phrase SSLHLH from Whale 3

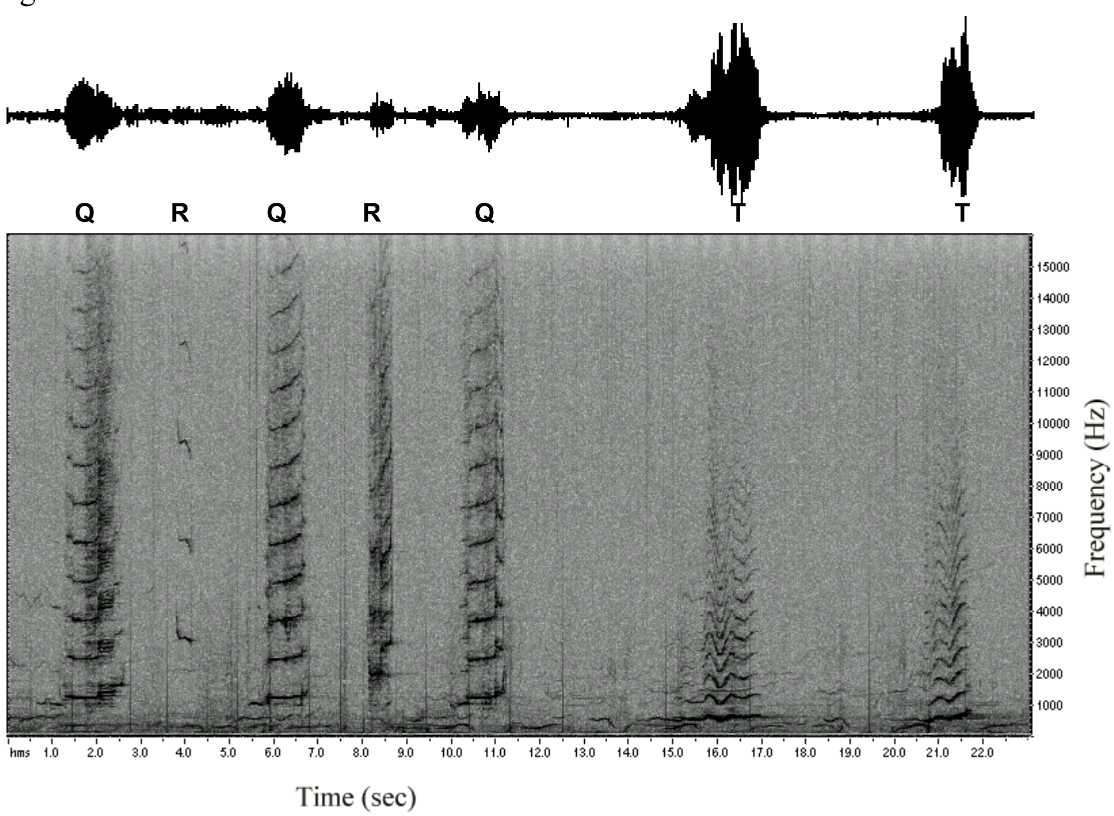

Figure 8. Phrase QRQRT from Whale 3

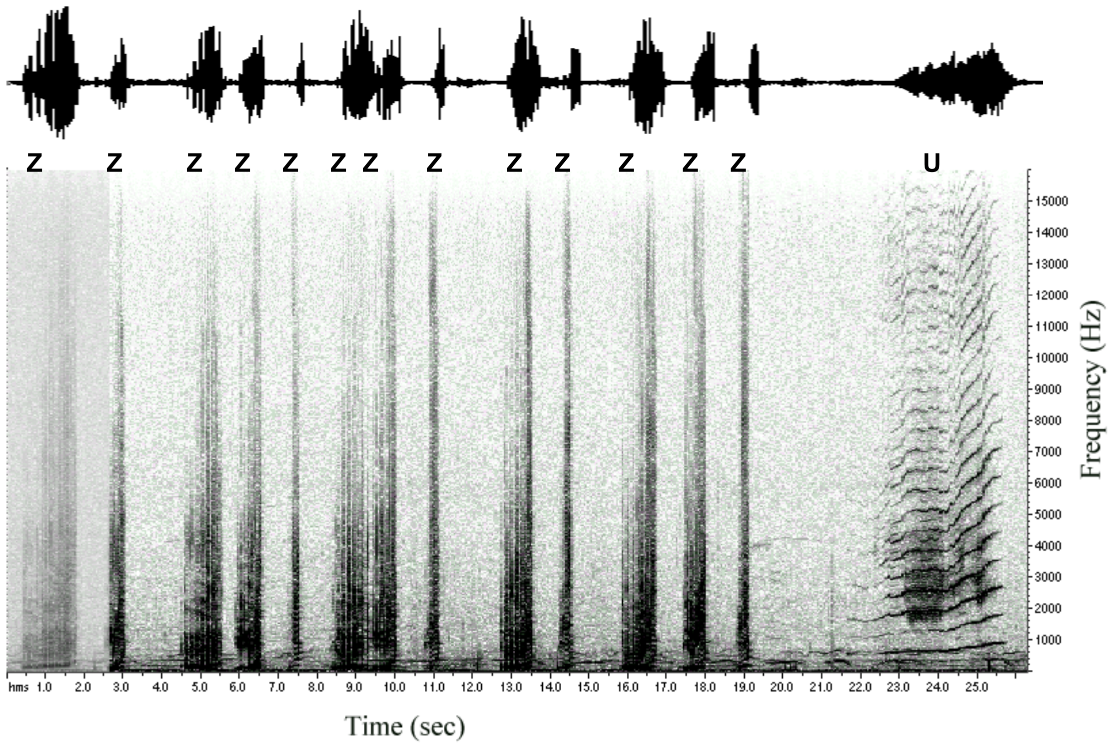

Figure 9. Phrase ZZZZZZU from Whale 4

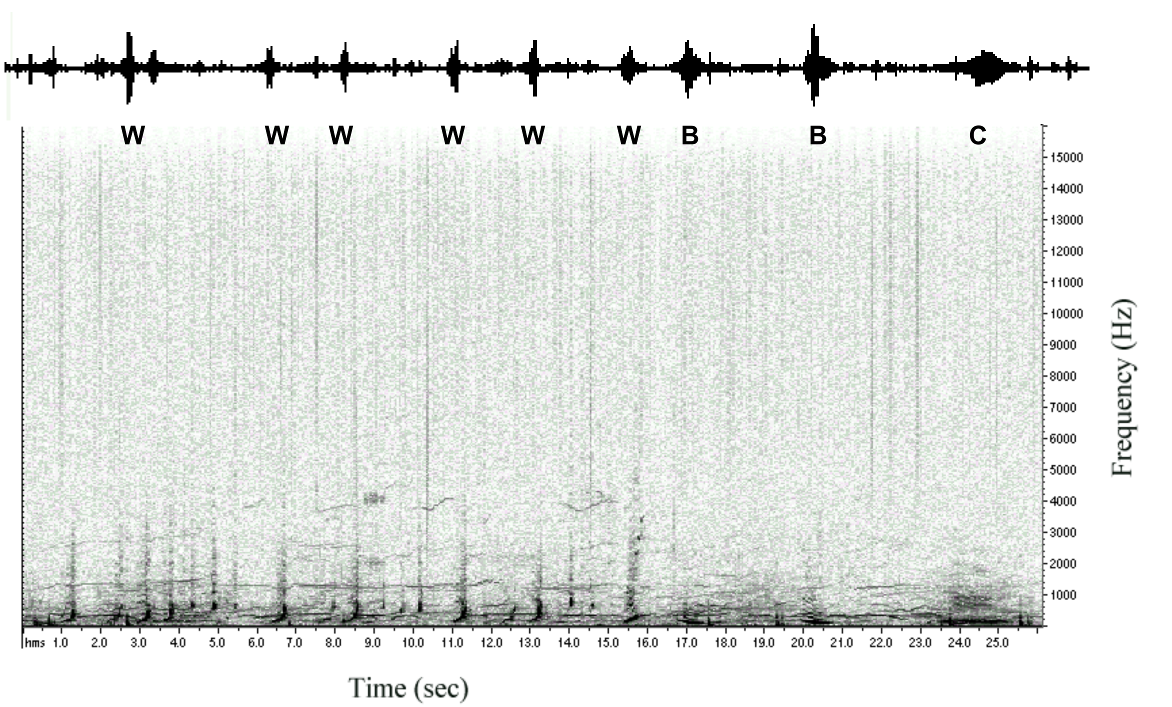

Figure 10. Phrase WWWWWWWBBC from Whale 5

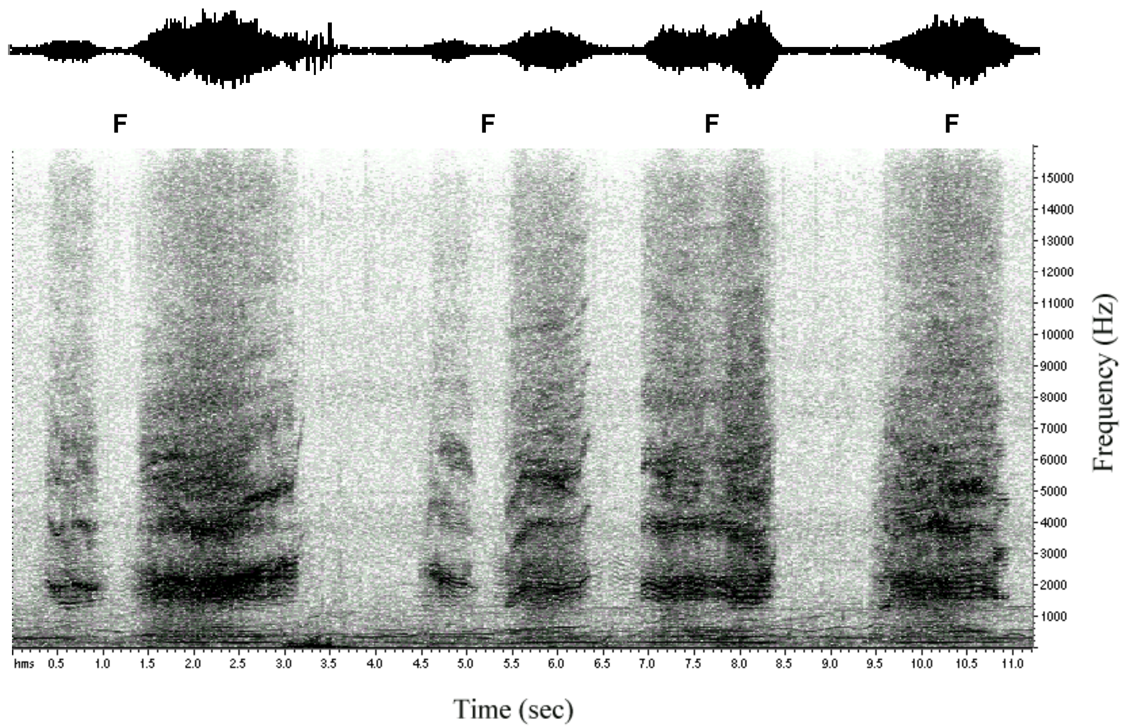

Figure 11. Phrase FFF from Whale 8

unit Q is the QRQRTT phrase shown in Figure 8 are only about 18 dB below the level of the fundamental frequency out to 8 kHz. Finally, the spectrum for unit Z show that the harmonic at about 2.5 kHz has the highest level. These types of high frequency harmonics and the levels of these harmonics have never been reported in the literature.

The means and standard deviations of the duration of the different units composing the different phrases are shown in the top panel of Figure 12. Although the number of units involved in calculating the standard deviation was rather low, as low as 2, use of standard deviations provides a way to keep track of the variations in the duration of the different units. The mean duration for the various units varied from about 0.5 to 3 s, with most of the units having an average duration between 1 and 2 s.

The means and standard deviations of the silent periods for the various phrases are shown in the bottom panel of Figure 12. The mean silent period for the various phrase varied from about 0.8 to 2.9 s, with the most between 1 and 2 s. The duration of the units and the length of the silent periods between units are important factors in using

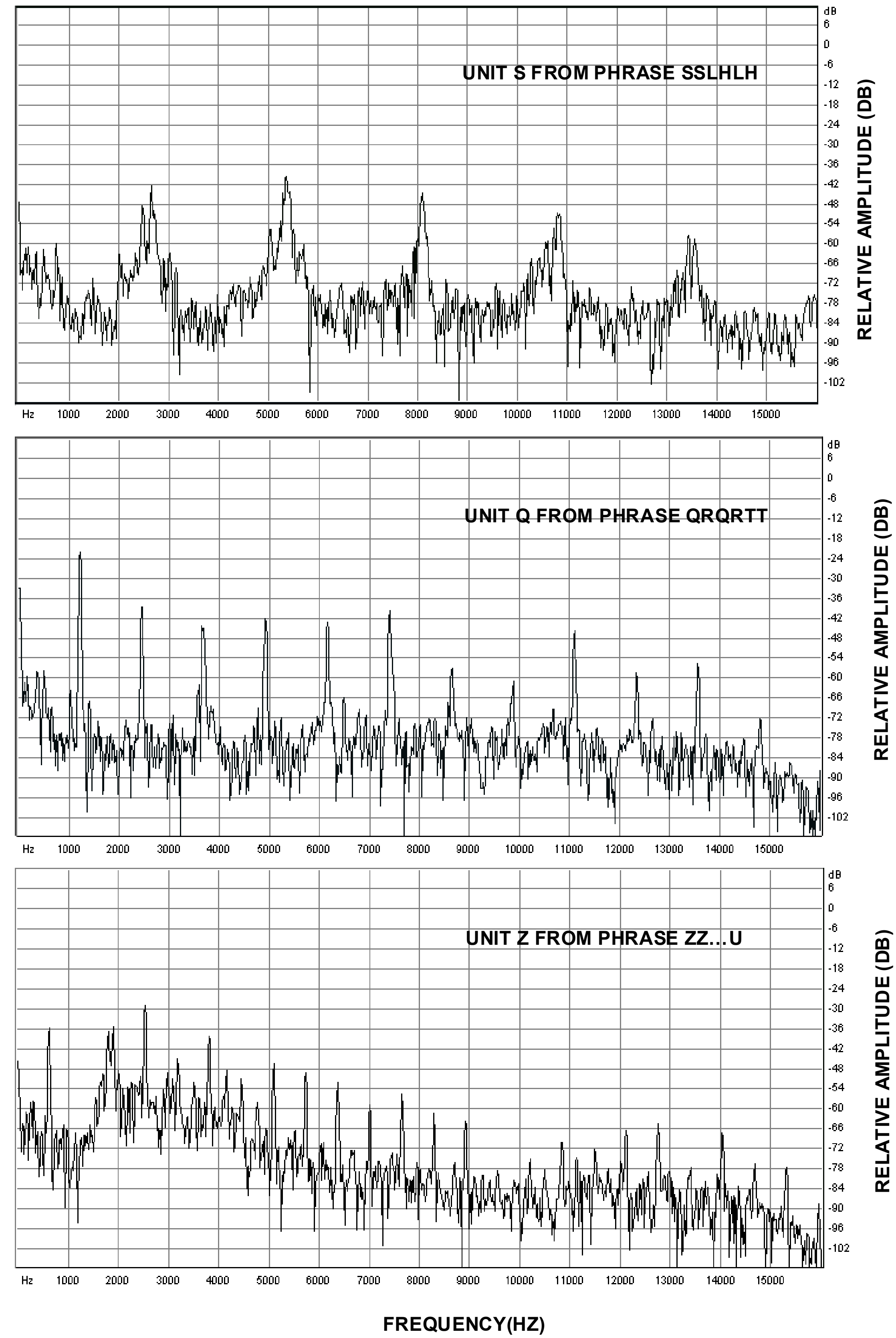

Figure 12 Spectra of selected units with very high frequency harmonics

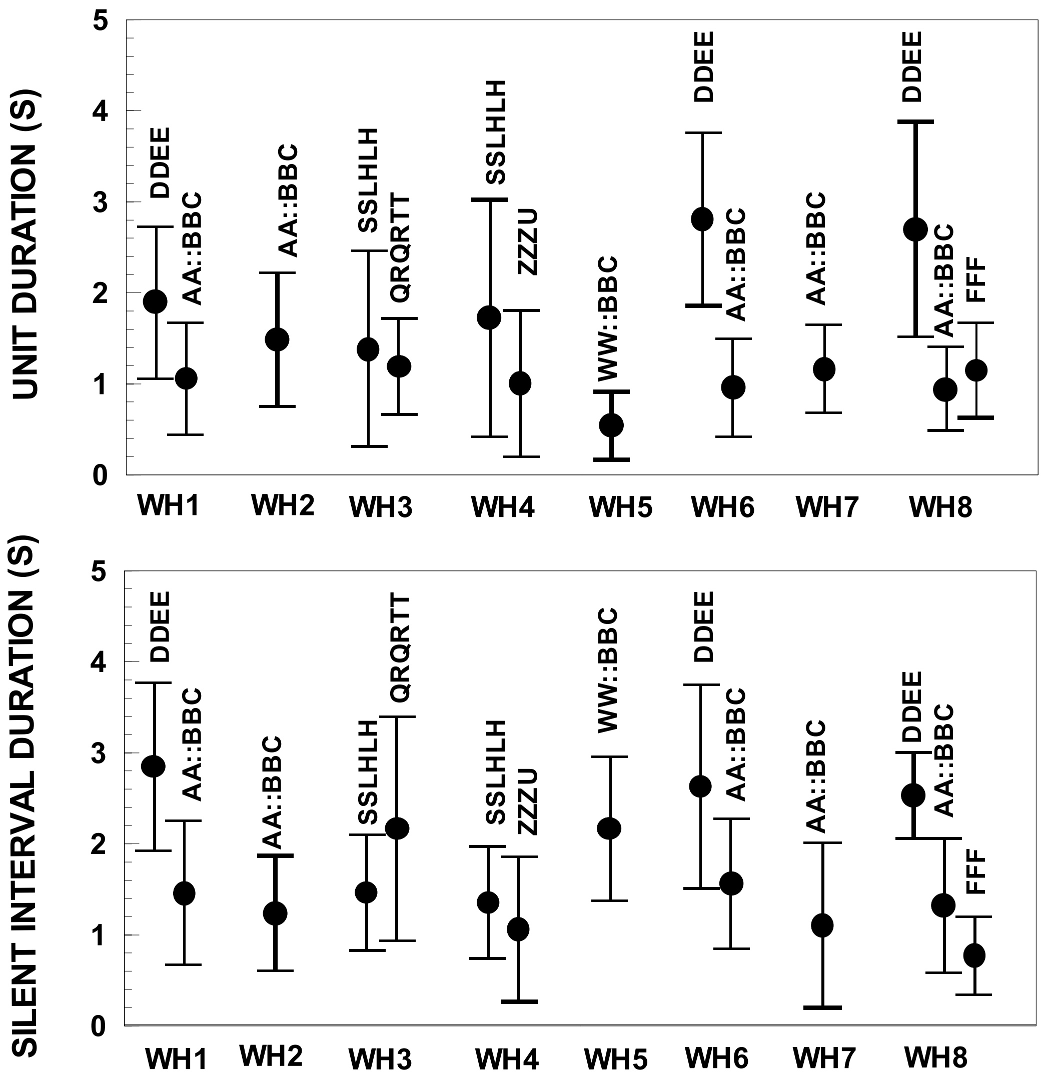

Figure 13. Top panel: the mean and standard deviation of the duration of the units in the different phrases for each whale. Bottom panel: the mean and standard deviation of the silent intervals for the different phrases for each whale.

any acoustic array to localize singing whales. If many whales are singing simultaneously as in a chorus, individual whales can only be localized if there are instances, however short, in which only the sound from one whale is detected. The probability of having an instant of time in which only one whale is producing a sound increases as the length of the silent periods become much greater than the duration of individual units.

Defining the source level of a humpback whale song is not a straightforward process because the sounds are emitted in burst, which could have different amplitudes. The

The procedure taken here is to choose the largest amplitude unit of each phrase. The source level of any specific unit is given by the equation

$$SL = |S_v| - \text{gain} + 20 \log (v_{rms}) + 20 \log R \quad (1)$$

Where SL is the source level (sound pressure level referenced to 1 m from the source), S_v is the sensitivity of the hydrophone, gain is in dB, v_{rms} is the rms (root mean square voltage), and R is the range to the whale. When a singer being observed dove to position itself in the singing position, the Boston whaler was driven to within 20 to 40 m of the slick left by the whale on the surface of the water. A conservative estimate of 20 m was used to obtain the source levels for the different whales shown in Figure 14.

The source levels of the eight whales given in Figure 14 could be an underestimate by as much as 6 dB. Nevertheless, the highest level was recorded for whale 2 at

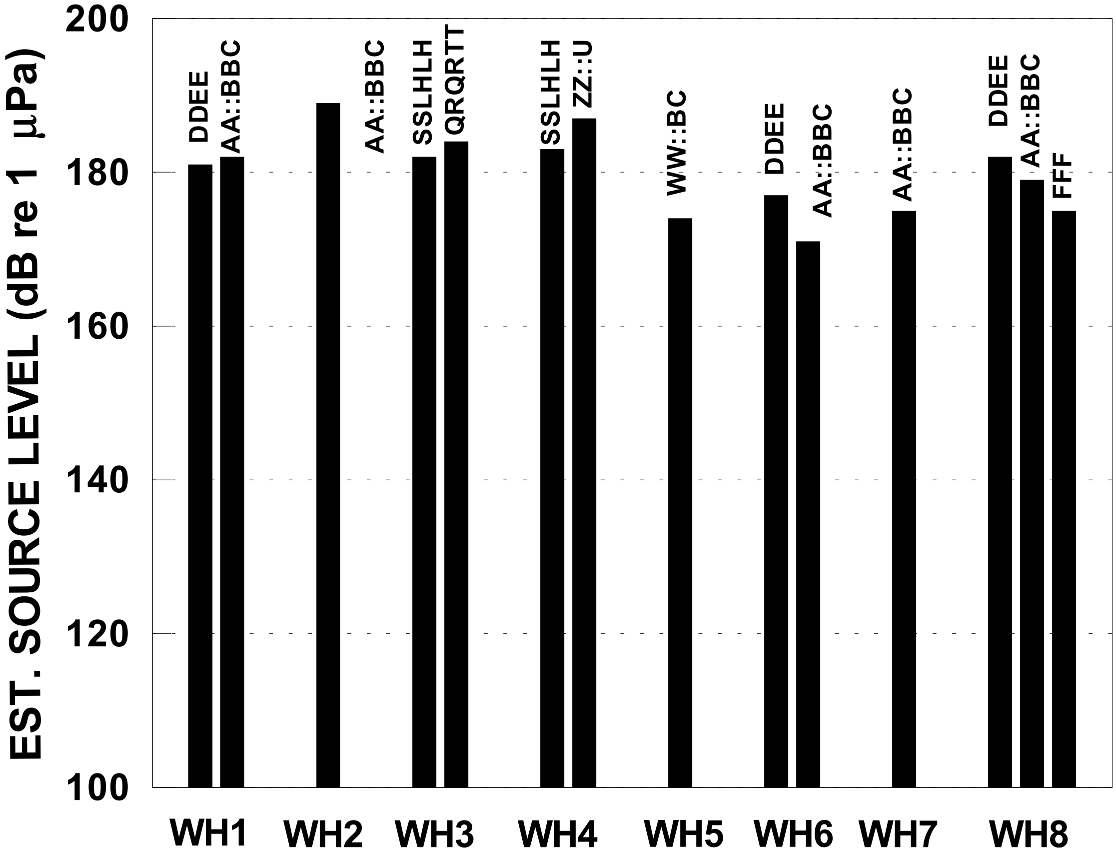

Figure 14. The average source level of the different phrases of the eight whales recorded. The source level was based on averaging the units with the highest amplitude for each phrase in the song. The specific phrases are shown above each bar in the graph.

189 dB re 1 μPa. The levels varied between 170 and 189 dB with most of the levels within ± 4 dB of 180 dB. These values are much higher than the 174 dB reported by Frankel (1994). These levels are sufficiently high that when the boat drifted close to the whale, the sounds could be heard unaided as the sound propagated through the bottom of the whaler.

Tail-fluke photographs were taken for each of the whales that was acoustically recorded. Unfortunately, the camera was jolted on the first day so that only the tail fluke of the first whale came out. The camera seemed to work normally, but when the negative was developed, the pictures were not usable. Therefore, positive proof that eight different whales were recorded does not exist, although our visual observations indicate that this was the case. It is also unfortunate that specific whales could not be identified with the sounds.

Phase 2

The use of the DIFAR sensor was a failure. One of the electronic housings leaked, destroying the microcontroller and the electronics. The hard disk of the second unit crashed, causing all data to be lost. We did not realize this disk failure since the intermediate flash memory card indicated that the unit worked. However, by the time we realized what had happened it was too late in the season to make another deployment.

IV SUMMARY AND CONCLUSION

This project has produced some very interesting data on the characteristics of humpback whale songs that have not been previously reported, or not reported with the precision herein. The broadband nature of some of the songs wsd surprising. There were many units in which harmonics extended to 15,000 Hz. Generally humpback whales are considered to be relatively low frequency sound producers. The levels of the high-frequency harmonics do not drop off significantly in some of the units. We showed one example in which the harmonic at 13.5 kHz was only 18 dB below the level of the harmonic with the maximum level. In another example the harmonic at about 11 kHz had a level that was only 24 dB below the level of the fundamental frequency.

The typical duration of a unit of sound was found to be between about 1 and 2 s. This was coupled with a typical silent interval between units which was also between about 1 and 2 s. This type of temporal pattern would have made the use of a DIFAR sensor difficult to use to obtain azimuthal information for chorusing whales. The direction of two humpback whales singing simultaneously can probably be localized since there will be many instances of time in which one whale will be silent and the other whale emit a unit. However, as the number of simultaneously singing whales in a body of water increases, the probability of the song unit from a single whale being received while all other whales are silent decreases substantially. If the typical unit duration was much smaller than the typical silent interval, the probability of a unit from one whale occurring while other whales were temporarily silent could be sufficient to obtain azimuthal information. However, given the characteristics of the songs obtained in this project it seems that a DIFAR unit would not be effective or accurate during a significant part of the humpback whale wintering season in Hawai`i. As the humpback whale season proceed s towards its peak, the number of singing whales increases steadily until there is a cacophony of sounds. For chorusing sounds, a DIFAR unit would still detect sounds, however, the azimuth information may be inaccurate since it would essentially sum up the sounds and indicate the presence of a single source when as there may be multiple sources.

It seems that a better acoustic method to obtain azimuth information on the whales participating in a chorus would be to use an electronically steerable beam from an array of hydrophones or a mechanically rotatable array. Two arrays separated in distance could then be used to triangulate the singers. However, the low fundamental frequency of most humpback whale songs would require a relatively large array. For example, at 300 Hz, the wavelength of an acoustic signal in water will be about 5 m (16 ft). For an array to have a narrow beam, its size should be several wavelengths, meaning a relatively huge structure. If we limit ourselves to detecting harmonics above 3 kHz, then the array can be reduced in size by a factor of 10.

The source levels measured in this project represent a unique set of data. Source levels for humpback whales have not been widely reported. Only two references can be found in the literature concerning the measurement of source level (Winn et al., 1970; Frankel, 1994). Winn et al. (1970) visually estimated the distance from the singer, as was done in this study. However, we approached much closer to singers and our distance estimates were probably more accurate. Frankel (1994) used a hydrophone array to localize singers off the big island of Hawi`i. The range of the whales to the array were one km and greater. Therefore, the acoustic propagation conditions were much different that the simple spherical spreading propagation condition in our study.

Despite the excellent data obtain in Phase 1, there are several cautionary considerations that should be factored in when evaluating the project. First, the unfortunate circumstance concerning the malfunction of the photo-id camera made it impossible to identify the specific whales that produced the sounds recorded. Second, the estimation of the whale's range from the boat was not as precise as one would prefer. The only practical method to obtain good range precision is to use a high frequency echo sounder to measure the singer's range as a function of time as the boat drifts.

It was truly unfortunate that the remote DIFAR units did not function properly. A series of events made this portion of the project highly problematic. The late arrival of funds made it impossible to start the project before the middle of January. The improper analysis of bottom contour plots of the water of Kihei made it necessary to switch to a remote recording technique. Because of time limitations, the remote system was not tested to the degree desired. One system apparently did function properly with the exception of a disk crash, an event that could not be predicted ahead of time. However, an earlier start would have allowed us time for another deployment after realizing the situation.

Although all the objectives of this study were not totally met, the results obtained on humpback whale songs will make a significant contribution to our understanding of humpback whales and their songs.

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