Echolocation signals of wild Atlantic spotted dolphin (*Stenella frontalis*)

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An array of four hydrophones arranged in a symmetrical star configuration was used to measure the echolocation signals of the Atlantic spotted dolphin (*Stenella frontalis*) in the Bahamas. The spacing between the center hydrophone and the other hydrophones was 45.7 cm. A video camera was attached to the array and a video tape recorder was time synchronized with the computer used to digitize the acoustic signals. The echolocation signals had bi-modal frequency spectra with a low-frequency peak between 40 and 50 kHz and a high-frequency peak between 110 and 130 kHz. The low-frequency peak was dominant when the signal the source level was low and the high-frequency peak dominated when the source level was high. Peak-to-peak source levels as high as 210 dB *re* 1 μPa were measured. The source level varied in amplitude approximately as a function of the one-way transmission loss for signals traveling from the animals to the array. The characteristics of the signals were similar to those of captive *Tursiops truncatus, Delphinapterus leucas* and *Pseudorca crassidens* measured in open waters under controlled conditions. © *2003 Acoustical Society of America.* [DOI: 10.1121/1.1518980]

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I. INTRODUCTION

The Bahama Islands are an archipelago in the tropical West Atlantic east of Florida that are surrounded by deep water while the Bahamas banks are relatively shallow (<15 m). The banks are thick, submerged platforms of calcareous rock providing diverse habitats, including fringe and patch reefs, atolls, grassy flats, and ledges. Since 1985, a resident community of approximately 200 spotted and 200 bottlenose dolphins have been identified, sexed, and observed in a variety of behavioral contexts in this area (see Fig. 1). Basic life history and age class categories for the Atlantic spotted dolphin, *S. frontalis*, have been described (Herzing, 1997). Underwater behavior and correlated sound (narrow-band frequency <20 kHz) have also been described including sounds correlated with (1) contact/reunion (whistles), (2) excitement/distress (whistle-squawks), (3) pursuit/herding (buzzes), (4) aggression (burst-pulses), (5) group synchrony (synch pulses), (6) interspecific interactions (barks, screams, squawks), (7) nonvocal sounds (tail-slaps), and (8) foraging/feeding (echolocation clicks) (Herzing, 1996, 2000). Previous studies on the behavior and sound production of *S. frontalis* in captivity also exist (Wood, 1953; Caldwell and Caldwell, 1966, 1971; Caldwell *et al.*, 1973).

The echolocation signals used by *S. frontalis* in the Bahama banks, measured on a broadband basis, will be considered in this paper. The echolocation characteristics of delphinid species have been studied primarily in captivity (Au, 1993). Measurements from stationary dolphins in captivity have shown that echolocation clicks are emitted in a directional beam and signals measured off-axis are distorted with respect to the signals measured along the major axis of the beam. Therefore, it is very difficult to obtain accurate measurements of free-ranging, fast moving dolphins in the wild. Another complicating factor is associated with the broadband nature of echolocation signals and the possibility that the center frequency of echolocation clicks tends to vary with the intensity of the emitted clicks. Au *et al.* (1985) found that higher intensity clicks emitted by a beluga whale (*Delphinapterus leucas*) in Hawaii had higher frequencies than the lower intensity clicks used by the same animal in San Diego Bay. Au *et al.* (1995) also found a nearly linear relationship between the center frequency and source level of a false killer whale (*Pseudora crassidens*), i.e., the higher the source level, the higher the center frequency of the emitted clicks. Therefore, any measurements of the spectra of echolocation clicks should be accompanied by an estimate of the source levels.

II. PROCEDURE

A. Measurement system

A four-hydrophone array with the hudrophones arranged as a symmetrical star was used to measure the echolocation signals of *S. frontalis*. Such a sensor geometry was used successfully by Aubauer (1995) in tracking echolocating bats in the field. The array structure resembled the letter "Y," with each arm being 45.7 cm in length and separated by an angle of 120 degrees as shown in Fig. 2. The arms of the

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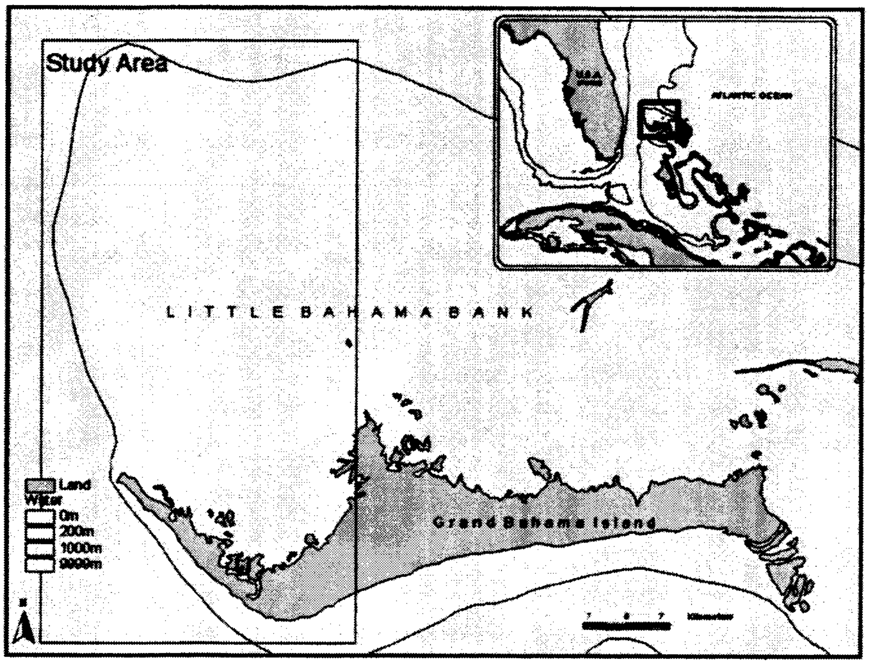

FIG. 1. Map of the study site in the banks area of the Bahama Island.

array were constructed out of 1.27-cm o.d. PVC pipe with a spherical hydrophone connected to the end of each pipe and the cable running through the center of the pipe. Another hydrophone was connected at the geometric center of the "Y." The PVC pipes fit into holes drilled into a 2.54-cm-thick delrin plate. The range of a sound source can be determined by measuring the time of arrival differences between the signal at the center and the three other hydrophones. If the arrival time difference between the center and the other hydrophones is denoted as τ_{0i}, where $i=1$, 2, and 3, then the range, R, of the source can be expressed as (see Appendix)

$$R=\frac{c^2(\tau_{01}^2+\tau_{02}^2+\tau_{03}^2)-3a^2}{2c(\tau_{01}+\tau_{02}+\tau_{03})}, \tag{1}$$

where c is the speed of sound, and a is the distance between the center and the other hydrophones.

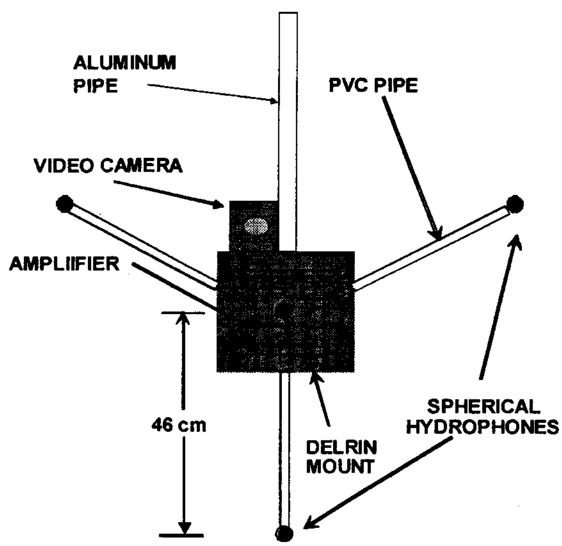

FIG. 2. Schematic diagram of the four-hydrophone symmetrical star array along with a video camera on a pole.

An underwater housing connected to the back of the hydrophone mounting plate contained an amplifier and line-driver for each of the hydrophones. A CCD video camera in an underwater housing was mounted next to the center hydrophone. A multi-conductor cable, 77 m in length, consisting of five coaxial lines and two d.c. power lines, connected the array to an adjustable amplifier-filter box containing a power supply.

Echolocation signals were digitized with two Gage-1210, 12 bit dual simultaneous sampling data acquisition boards that were connected to a "lunch box" computer via two EISA slots. The data acquisition system operated at a sample rate of 500 kHz with a pretrigger capability. When the computer signaled the Gage-1210 to collect data, four channels of acoustic signals were simultaneously and continuously digitized with the results going into separate circular memories on each Gage-1210 board. When an echolocation signal was detected by the center hydrophone, it triggered the data acquisition board. Two hundred pretriggered points and two hundred posttrigger points were collected for each channel and downloaded into the computer. A total of 80 clicks could be downloaded for each episode before the data had to be stored on the hard drive. A specially constructed ISA board was also used to measure the time interval between the clicks being acquired and to cause a light-emitting diode to flash, indicating that clicks were being captured. The interclick interval data was also downloaded and stored on the hard drive. The time of capture (to the closest 18-ms interval of the computer timing system) of each click was also saved and stored on the hard drive. The clock on a portable VCR was synchronized to the computer's clock so that the video images could be synchronized with the acoustic data.

B. Acoustic measurements

Measurement of echolocation signals was conducted from the Wild Dolphin Project's 60-ft power catamaran, *Stenella*. A map of the field site showing the Bahama bank where the study was conducted is shown in Fig. 1. All the electronics including the lunch-box computer and video tape recorder were housed on the deck of the catamaran. The field work was performed in the summers of 1996 and 1997.

The four-hydrophone array was deployed by two methods. In the first method, the array was connected to a 1-m long, 2.54-cm o.d. aluminum pipe with a handle grip at one end of the pipe. Dolphins were first located by patrolling the sandbank, an area of approximately 644 km^2. When the animals were located, the speed of the catamaran was reduced, and the dolphins were encouraged to bow ride for a short period while swimmers prepared to enter the water. The engine of the catamaran was then placed into idle and swimmers entered the water equipped with swim fins and snorkels. The array was then handed over to one of the swimmers who then swam towards the dolphins. At the same time, an operator controlled the data acquisition sequence by arming the computer to start the data acquisition process and by starting the video tape recorder.

The second method involved positioning the catamaran at night along the edge of the drop-off from the sandbank to deeper waters. A spotlight was directed into the water next to the catamaran, attracting various small fishes and squid to the surface. Spotted dolphins were also attracted by either the spotlight or the congregation of micronekton. The array was attached to a 3-m-long aluminum pole and placed in the water along side the boat close to where the spotlight intersected the water's surface. The center of the array was lowered to a depth of 1 to 1.5 m below the surface. Spotted dolphins often milled about 20–30 m from the boat foraging on prey, and also made "runs" into the lit area towards the array, continuously echolocating as they did so.

III. RESULTS

A total of 43 files of echolocation clicks were collected on three field trips. The quantity of data collected was limited by periods of equipment malfunction requiring repair. There were also occasions when a dolphin approached the array only a few degrees from the plane of the array so that one of the hydrophones would not detect the click because of the direction of the animal's beam. The number of clicks collected per file varied considerably from as low as 3 to a high of 80, the maximum number of clicks that the system could handle. Only echolocation events in which the amplitude of the signals received by the center hydrophone was either the highest or within 3 dB of the highest were accepted for analysis. This criterion was chosen to ensure that a dolphin beam was directed at the array. The beam patterns measured for three different odontocete species (Au, 1993; Au *et al.*, 1995) indicate that when the major axis of the beam is directed to within ± 5 degrees of the center hydrophone, the signal received by the center hydrophone will either have the highest or will be within 3 dB of the highest amplitude. A total of 1277 clicks met the appropriate criterion.

Three typical types of clicks are shown in Fig. 3 with the signal waveforms on the right and the frequency spectra on the left. These clicks are very brief, generally less than 70 μs in duration, with broad frequency spectra. Clicks with bimodal spectra are obvious in the spectra plots. Some of the bimodal spectra have relatively high peak frequencies (>80 kHz) whereas some have low peak frequencies (<40 kHz). The majority (~80%) of the clicks examined had bimodal spectra. The click waveforms resemble those used by other odontocetes such as *Tursiops truncatus*, *Delphinapterus leucas* (Au, 1993), *Pseudora crassidens* (Au *et al.*, 1995), and *Lagoringcus albirostris* (Rasmussen *et al.*, 2002).

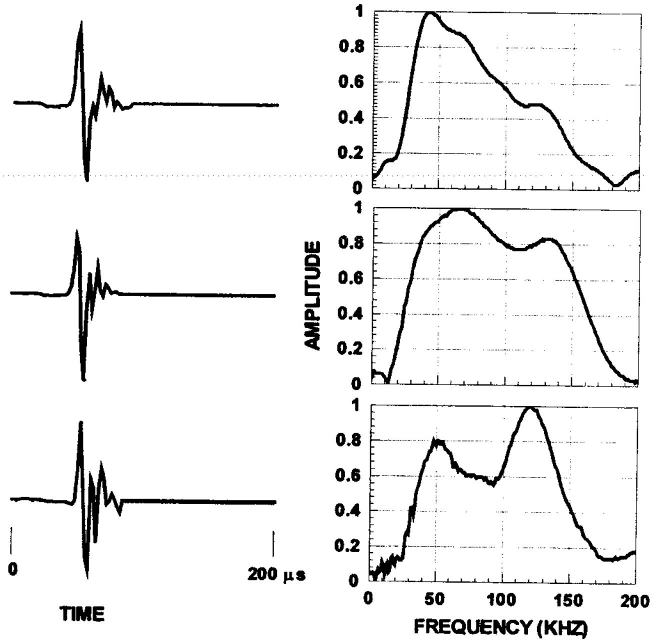

FIG. 3. Examples of the some representative waveforms and frequency spectra emitted by *Stenella frontalis* in the Bahamas banks.

The peak-to-peak source level as a function of range between an echolocating dolphin and the array is shown in Fig. 4. As the dolphin's range to the array decreased, the source level also decreased. The solid curve in Fig. 4 is a regression curve represented by the equation

$$\mathrm{SL} = 185.3 + 20\log(R) \tag{2}$$

and has an r^2 value of 0.52, where SL is the source level in dB *re* 1 μPa and R is the range in meters. The decrease in

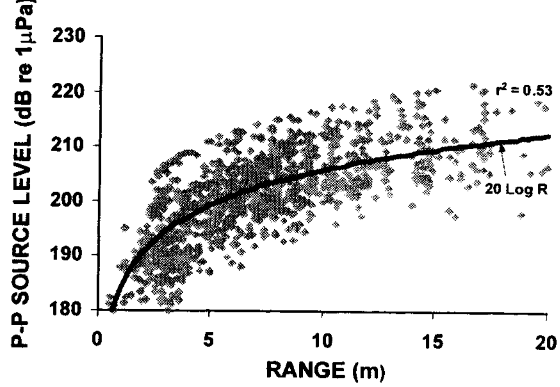

FIG. 4. Scatter plot of source level as a function of the range between an echolocating dolphin and the hydrophone array. The solid curve represents the one-way spherical spreading curve-fitted to the data in a least-square fashion with $r^2 = 0.56$.

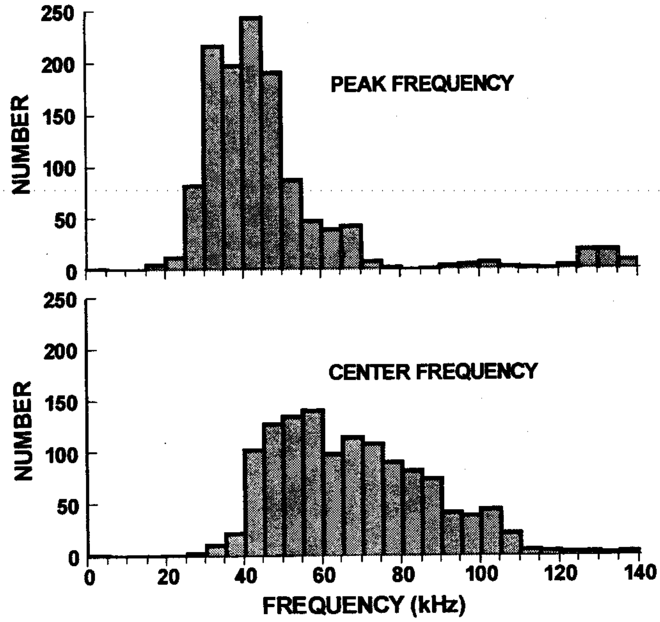

FIG. 5. Histograms of peak and center frequencies of echolocation signals.

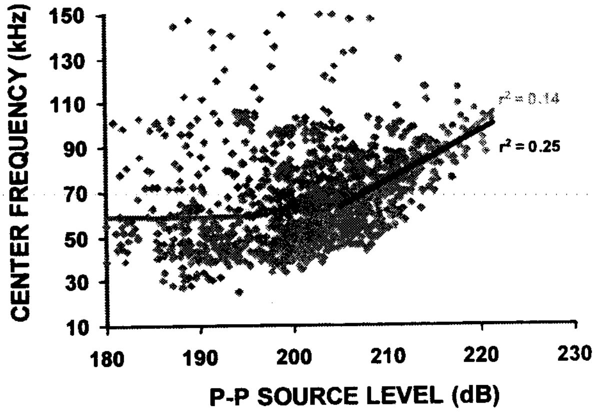

FIG. 6. Scatter plot of center frequency versus source level. A third-order polynomial is fitted for all data and has an r^2 value of 0.14 while a linear regression curve is shown for source levels greater than and equal to 205 dB with $r^2=0.25$.

SL corresponded to the decrease in the one-way spherical spreading loss. Therefore, the amplitude of the echoes returning to the dolphins increased in magnitude as the range decreased, suggesting that the dolphins prefer to receive echoes that have increasing signal-to-noise. The results also suggest that the dolphins were echolocating on the hydrophone array and not on some other objects since the source level decreased as the range to the array decreased. Also, the interclick intervals were always greater than the two-way travel time from the animals to the array and back, which is consistent with the notion that the dolphins were echolocating on the array. The fitted curve was constrained to vary as $20 \log R$, however, the "best-fit" logarithm's curve would be very similar to the $20 \log R$ fit and the difference in r^2 would be in the third decimal place.

The distributions of peak and center frequencies of the echolocation signals are shown in Fig. 5. Peak frequency is defined as the frequency at which the frequency spectrum of a signal has its maximum amplitude. Center frequency is defined as that frequency which divides the energy in a frequency spectrum into two equal parts; it is defined mathematically as

$$f_o=\frac{\int_0^\infty f|S(f)|^2 df}{\int_0^\infty |S(f)|^2 df}, \tag{3}$$

where $S(f)$ is the Fourier transform of the echolocation signal and f is the instantaneous frequency. Seventy-six percent of the signals had center frequencies greater than 50 kHz and 23% had center frequencies greater than 80 kHz. The center frequency extends to much higher frequencies than the peak frequency and this property is indicative of signals with bimodal spectra. Eighty percent of the echolocation clicks had bimodal spectra in which the amplitudes of the secondary peaks were within 50% of the amplitude of the primary peak. Therefore, center frequency is a more representative measure of signals with bimodal spectra (Au *et al.*, 1995).

The variation of the center frequency as a function of the source level is shown in Fig. 6. A third order polynomial regression with an r^2 value of 0.14 is also shown in the figure. The regression line suggests that the center frequency in independent of the source level for levels lower than 200 dB *re* 1 μPa. However, as the source level increases beyond 205 dB, the center frequency also increases. If only signals with source levels equal to or greater than 205 dB are considered, the dependence of center frequency on source level becomes stronger with an r^2 value of 0.25. The dependence of the center frequency on source level is weaker than for *Pseudora crassidens* (Au *et al.*, 1995) where a linear regression line has an r^2 value of 0.44.

Histograms of the 3-dB bandwidth and the rms bandwidth are shown in Fig. 7. The 3-dB bandwidth is the width of the frequency band between the two points that are 3-dB lower than the maximum amplitude of a spectrum. The 3-dB points are also referred to as the half-power points. The rms bandwidth is a measure of the frequency width about the

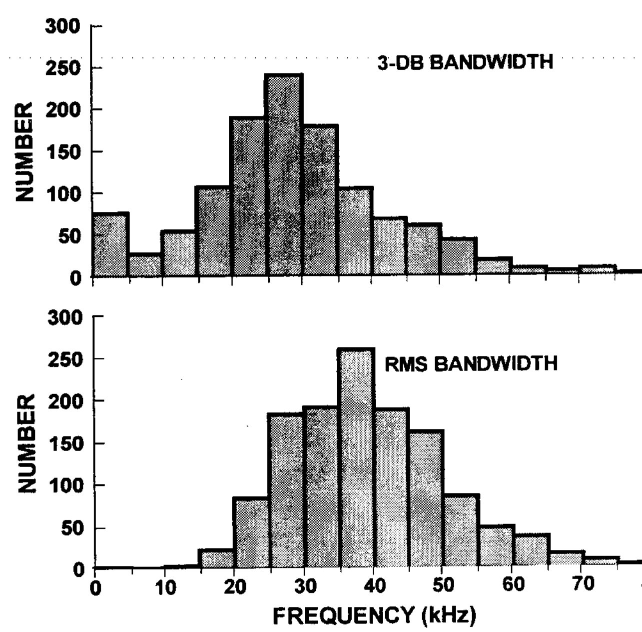

FIG. 7. Histograms of 3-dB and rms bandwidth of echolocation signals.

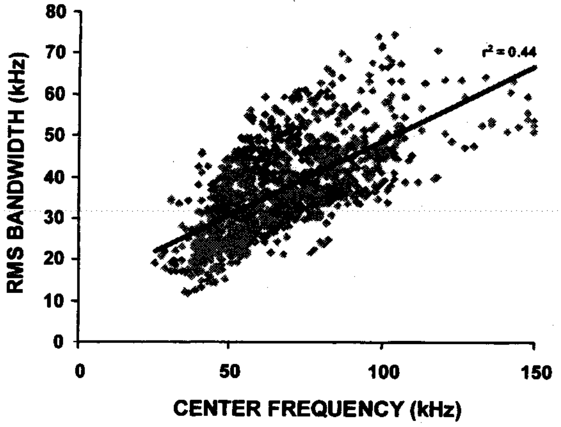

FIG. 8. Scatter plot of rms bandwidth versus center frequency. The linear regression line has an r^2 of 0.44.

center frequency. It is defined as (Rihaczek, 1969)

$$\beta = \frac{\int_0^\infty (f-f_o)^2 |S(f)|^2 df}{\int_0^\infty |S(f)|^2 df}, \tag{4}$$

where f_o is the center frequency given in Eq. (3). The 3-dB bandwidth for bimodal spectra can often provide a misrepresentation of the width of the signal since the bandwidth might cover only the frequency range about the peak frequency. The rms bandwidth is probably a better measure of the width of signals with bimodal spectra. The histograms clearly show higher values for the rms bandwidth than the 3-dB bandwidth.

A scatter plot of rms bandwidth as a function of center frequency along with a linear regression line is shown in Fig. 8. The linear regression has a relatively high r^2 value of 0.44, indicating a strong relationship between rms bandwith and center frequency. As the frequency increased, the bandwidth also increased almost linearly. The range or temporal resolution of a signal is related to the inverse of the bandwidth so that the wider the bandwidth, the smaller the temporal resolution capability of the signal (Burdic, 1969).

IV. DISCUSSION AND CONCLUSIONS

Atlantic spotted dolphin (*Stenella frontalis*) project broadband, short duration echolocation signals similar to those of other odontocetes. Most of the signals have a bimodal frequency distribution, which also contributes to the broadband nature of the signals. The broad bandwidth of the echolocation signal provides a good range resolution capability (Au, 1993) that should enable *Stenella frontalis* to be able to perform fine target discrimination in a shallow water environment where bottom reverberation can be troublesome. Spotted dolphin also project relatively high-amplitude signals with maximum source level measured about 223 dB *re* 1 μPa, although most of the source levels were between 200 and 210 dB *re* 1 μPa.

The peak-to-peak source levels measured for *Stenella frontalis* are comparable to those measured for *Tursiops truncatus* in open-water captive echolocation experiments (Au, 1980, 1993), for comparable target ranges. For target ranges between 6 and 20 m, *Tursiops* source levels varied from about 204 to 216 dB *re* 1 μPa, which are similar to that of *Stenella frontalis*. However, there is a large difference between the target strengths of targets used in the echolocation experiments for *Tursiops* and the target strength of the array assembly used to measure signals in the field. Although the target strength of the array was not measured, the theoretical target strength of an aluminum pipe, connected to a flat plexiglass container mounted on a flat delrin plate along with a camera holder, should be approximately 15–20 dB greater than the small cylinders and spheres used in the *Tursiops* experiments (Au, 1980, 1993). This comparison suggests the importance of range on the source levels utilized by dolphins. Despite the higher target strength of the array, the spotted dolphins emitted similar levels of echolocation signals as *Tursiops* echolocating on much weaker targets at similar ranges.

The variation of source level as a function of the one-way transmission loss is similar to that of the white beaked dolphin, *Lagenorhynchus albirostris* (Rasmussen *et al.*, 2002) and killer whales, *Orcinus orca* (Au *et al.*, 2001). This type of variation in source levels is also similar to variations found with captive dolphins. If the data shown in Fig. 7.14 of Au (1993) are rearranged into a plot of source level versus range, the variation with range will also be a function of the one-way transmission loss.

Our results suggest that several basic signal parameters are interrelated in a complex relationship. Source level is dependent on target range, center frequency is dependent on source level (at least for source levels greater than 205 dB), and rms bandwidth is dependent on center frequency. However, it seems that the most basic parameter in this interrelationship is target range. Therefore, it is important to be able to ascertain the range of echolocating dolphins when measuring echolocation signals, even for on-axis signals.

The results of this study also clearly demonstrate the utility of using a multi-hydrophone array to measure echolocation signals of dolphins in the wild. The symmetrical star array used in this study is relatively compact and easy to handle, and can provide information on whether a specific received echolocation signal originated in the vicinity of the major axis of the animal's transmission beam. Time of arrival differences between hydrophones were easily ascertained because of the rapid onset of the echolocation signals. Our results suggest that it is very difficult to obtain reliable data on echolocation signals without the use of some kind of array.

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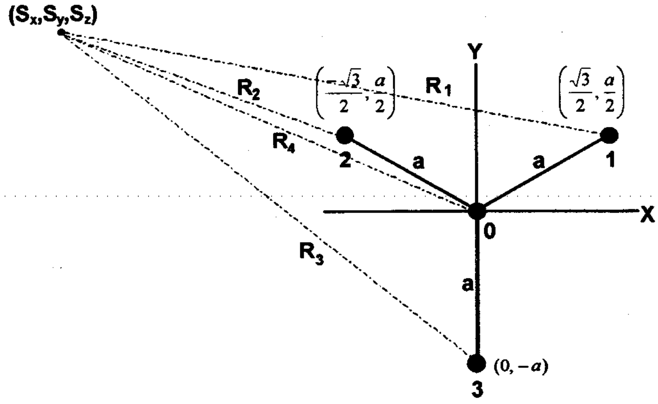

FIG. 9. Geometry for determining the location of a sound source from time of arrival difference information with a symmetrical star array.

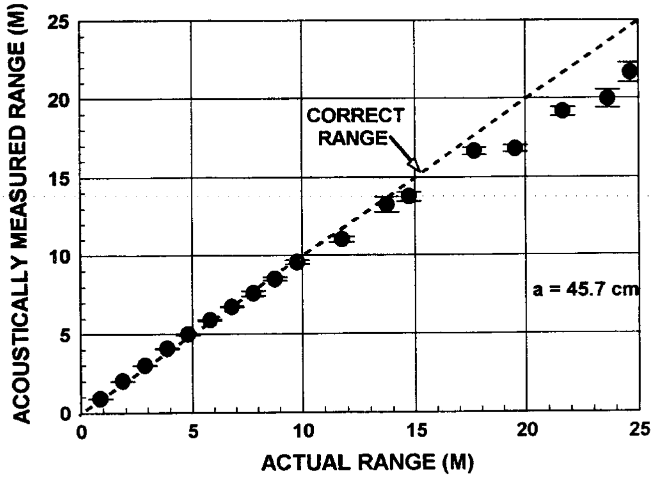

FIG. 10. Calibration measurement for the symmetrical star array used in this study. The mean and standard deviation of the estimated range from ten measures are plotted against the actual range.

APPENDIX

Let us consider the four hydrophone array with on the x-y plane and a sound source located at coordinates (S_x, S_y, S_z) as shown in Fig. 9. Let R_i be the range from the source to the ith hydrophone, where $i=1,2,3$. Then the range to each hydrophone can be expressed by the equation

$$\begin{aligned} &S_x^2+S_y^2+S_z^2=R^2=c^2t_o^2,\\ &(S_x-la)^2+(S_y-a/2)^2+S_z^2=R_1^2=c^2(t_0-\tau_{01})^2,\\ &(S_x+la)^2+(S_y-a/2)^2+S_z^2=R_2^2=c^2(t_0-\tau_{02})^2,\\ &S_x^2+(S_y+a)^2+S_z^2=R_3^2=c^2(t_0-\tau_{03})^2, \end{aligned} \tag{A1}$$

where c is the speed of sound in water, τ_{0i} is the time of arrival difference between the center hydrophone and the ith hydrophone, and $l=\sqrt{3}/2=\cos 30°$. Using the technique of Watkins and Schevill (1972), the top equation of the system of equations in (A1) is subtracted from the other equations to give (after some rearranging)

$$\begin{aligned} &-2laS_x-aS_y+2c^2\tau_{01}t_0=c^2t_{01}^2-a^2,\\ &2laS_x-aS_x+2c^2\tau_{01}t_0=c^2t_{02}^2-a^2,\\ &2aS_y+2c^2\tau_{03}t_0=c^2t_{03}^2-a^2. \end{aligned} \tag{A2}$$

This is a system of three equations with three unknowns. There are a variety of methods to solve for the unknowns S_x, S_y, and t_0. The equations of (A2) can be expressed in a matrix format as

$$\begin{pmatrix} -2la & -a & 2c^2\tau_{02} \\ 2la & -a & 2c^2\tau_{02} \\ 0 & 2a & 2c^2\tau_{03} \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ t_0 \end{pmatrix} = \begin{pmatrix} c^2\tau_{01}^2-a^2 \\ c^2\tau_{02}^2-a^2 \\ c^2\tau_{03}^2-a^2 \end{pmatrix}. \tag{A3}$$

Using Cramer's rule (Kreyszig, 1983) we can solve for t_0 by solving the determinant equation

$$t_0=\frac{\begin{vmatrix} -2la & -a & c^2\tau_{01}^2-a^2 \\ 2la & -a & c^2\tau_{02}^2-a^2 \\ 0 & 2a & c^2\tau_{03}^2-a^2 \end{vmatrix}}{\Delta}, \tag{A4}$$

where Δ is the characteristic determinant defined by

$$\Delta=\begin{vmatrix} -2la & -a & 2c^2\tau_{01} \\ 2la & -a & 2c^2\tau_{02} \\ 0 & 2a & 2c^2\tau_{31} \end{vmatrix}=8la^2c^2[\tau_{01}+\tau_2+\tau_{03}]. \tag{A5}$$

Solving the determinant in Eq. (A4) for t_0 using the relationship of $R=t_0c$, we obtain the equation for the range from the source to the center hydrophone in the array as

$$R=\frac{c^2[\tau_{01}^2+\tau_{02}^2+\tau_{03}^2]-3a^2}{2c[\tau_{01}+\tau_{02}+\tau_{03}]}. \tag{A6}$$

For a given set of delay times, solutions for S_z will have a $\pm$ ambiguity, indicating that the source can be either above or below the X-Y plane of Fig. 9.

The accuracy of using the symmetrical star array to determine the range of a sound source was measured by projecting a simulated dolphin echolocation signal at different ranges from the array and using Eq. (A6) to estimate the range. The results of the measurements shown in Fig. 10 suggest that this technique can give very accurate results out to about 17.5 m. Ten pings were measured at each range. If the purpose of estimating R is to obtain the transmission loss due to spherical spreading, then the difference in the estimated and actual ranges will result in only a 1.2-dB error for an actual range of 25 m.

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