Critical areas for future research described in other chapters in this volume include (1) measurement of echolocation signals, especially high-frequency clicks, in free-ranging dolphins (Schotten et al., chapter 54; Lammers et al., chapter 58); (2) social and nonsocial uses of echolocation both in captivity (Blomquist and Amundin, chapter 60; Moreno, Kamminga, and Stuart, chapter 59) and in the wild (Herzing, chapter 56); (3) signal propagation (Watkins and Daher, chapter 57); passive versus active use (dos Santos and Almada, chapter 55); and (4) cross-modal studies of echolocation (Pack, Herman, and Hoffman-Kuhnt, chapter 41). Continued research is needed in these areas to ensure the future understanding of the function of dolphin echolocation in the wild.

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Echolocation Recordings and Localization of Wild Spinner Dolphins (*Stenella longirostris*) and Pantropical Spotted Dolphins (*S. attenuata*) Using a Four-Hydrophone Array

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Introduction

Despite the large amount of data, derived from captive odontocetes, on the capabilities of the active dolphin echolocation system (see Au 1993 for an overview), virtually nothing is known about the actual use of echolocation in the wild and its ecological significance. The most important questions needing answers are from which distances dolphins usually echolocate, to what extent the use of echolocation is dependent on the type of environment and time of the day (e.g., the light-dark cycle), whether members of a dolphin school echolocate simultaneously or eavesdrop on the echolocation of one animal, and how often echolocation is used (Au 1993, 271). However, before such questions can be addressed, it is first necessary to describe the characteristics of echolocation clicks emitted by free-ranging odontocetes.

Odontocetes can be divided into two acoustic categories (Au, introduction to this volume). The first comprises all species that can produce both long-duration, frequency-modulated tonal sounds (known as whistles) as well as pulsed sounds (echolocation clicks and burst-pulses). Clicks can extend to frequencies >150 kHz, are broadband, and have a duration of 50–100 μs; while whistles are frequency-modulated tones up to 20 kHz with harmonics up to around 70 kHz (Lammers et al. 1997), lasting 0.1 to several seconds. The odontocetes in the second acoustic category are known to produce only pulsed sounds. These pulsed sounds are narrowband, generally around a high peak frequency of up to 140 kHz, with durations in the order of 100–200 μs.

Because the proposed division of odontocetes into two acoustic categories might have implications concerning the different uses of clicks, it would be worthwhile to determine whether the division holds for all odontocete species, and to which category each species belongs. For this purpose, it is necessary to record and analyze echolocation clicks from all odontocete species using similar, high-frequency (up to 200 kHz) broadband equipment. No such click descriptions were found in the literature for either spinner dolphins (*Stenella longirostris*) or pantropical spotted dolphins (*S. attenuata*). Both species, like all species from the genus *Stenella,* are known to produce whistles (Norris et al. 1994) and therefore are expected to belong to the first acoustic category.

When recording echolocation clicks from wild dolphins at sea, there are a number of problems: (1) it is generally unknown which dolphin is producing the recorded clicks and how many animals are echolocating; (2) the peak-to-peak source level (SL) of clicks cannot be estimated with accuracy because the distance from the dolphin to the hydrophone is unknown; (3) terminations of clicks are often lost in reverberation and reflections from the water surface; and (4) the orientation of the dolphin's head with respect to the hydrophone is generally unknown, so that it cannot be ascertained whether clicks are from the main axis of the echolocation beam (Au 1993).

An array of hydrophones can be used to determine

the distance of an echolocating dolphin and whether the measured signals propagated along the animal's beam axis. By using a line array of three or more hydrophones spaced equal distances apart, such as in the study of Møhl, Surlykke, and Miller (1990), it is possible to determine the distance to the sound source but not the direction. However, with four hydrophones arranged in a configuration other than a line, it is possible to determine the exact position of the sound source to one of two points. W. A. Watkins and Schevill (1974) used an array of four hydrophones spaced 30 m apart at the vortices of a tetrahedron to localize spinner dolphins (*S. longirostris*). Due to the large size of the array, however, the directional echolocation clicks were seldom recorded at all four hydrophones. To localize dolphins by their echolocation clicks, an array would need to be small, rigid, and portable. Furthermore, by attaching an underwater camera to the array, connected to a VCR synchronized with the click recording device, the orientation of echolocating dolphins can be ascertained. In the present study, an array of four hydrophones arranged in a symmetrical star configuration, with one center hydrophone and three extending arms spaced 120° apart (adopted from Aubauer 1995), was used to measure the echolocation signals of wild spinner dolphins (*S. longirostris*) and pantropical spotted dolphins (*S. attenuata*).

Materials and Methods

Let the plane of the four-hydrophone array be the *y*-*z* plane of a Cartesian coordinate system with the center hydrophone (H_0) at the origin. The coordinates of an echolocating dolphin can be expressed as a distance from H_0 to the dolphin (range R), a horizontal angle φ, and a vertical angle θ, as follows (see fig. 54.1):

$$x = R \cdot \cos\varphi \cdot \cos\theta \tag{54.1}$$

$$y = R \cdot \sin\varphi \cdot \cos\theta \tag{54.2}$$

$$z = R \cdot \sin\theta \tag{54.3}$$

To localize the dolphin it is sufficient to know R, φ, and θ. If the coordinate system is defined as in fig. 54.1, these values can be derived using the above expressions and Pythagoras's theorem to be (Aubauer 1995):

$$R = \frac{c^2(\tau_{01}^2 + \tau_{02}^2 + \tau_{03}^2) - 3a^2}{2c(\tau_{01} + \tau_{02} + \tau_{03})} \tag{54.4}$$

$$\varphi = 90° \pm \arccos\left(\frac{2cR(\tau_{02} - \tau_{01}) + c^2(\tau_{01}^2 - \tau_{02}^2)}{2\sqrt{3a^2R^2 - 0.75(2Rc\tau_{03} - c^2\tau_{03}^2 + a^2)^2}}\right) \tag{54.5}$$

$$\theta = -\arcsin\left(\frac{2Rc\tau_{03} - c^2\tau_{03}^2 + a^2}{2AR}\right) \tag{54.6}$$

where

$-180° < \varphi < 180°$

$-90° < \theta < 90°$

c = speed of sound in water ≈ 1500 m/s

a = distance between center hydrophone (H_0) and outer hydrophones (H_1, H_2, and H_3) = 0.61 m

τ_{01} = time of click arrival at H_0 − time of click arrival at H_1 (expressed in s)

τ_{02} = time of click arrival at H_0 − time of click arrival at H_2

τ_{03} = time of click arrival at H_0 − time of click arrival at H_3

The ± sign in eq. 54.5 represents the ambiguity in localization, and translates in either a positive or negative

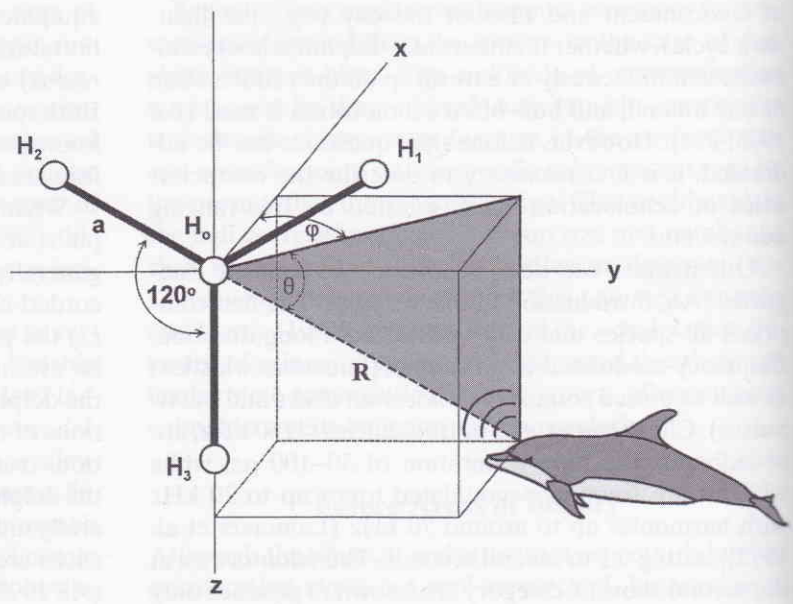

Fig. 54.1. In a three-dimensional Cartesian coordinate system, the position of a dolphin echolocating on a four-hydrophone symmetrical star array in one plane can be expressed as a range R to the center hydrophone H_0, a horizontal angle φ, and a vertical angle θ. Distance a between H_0 and each of the outer hydrophones H_1, H_2, and H_3 is 0.61 m. In this coordinate system, the echolocating dolphin has a positive x-coordinate, but negative y- and z-coordinates. Therefore, both φ and θ have negative values as well.

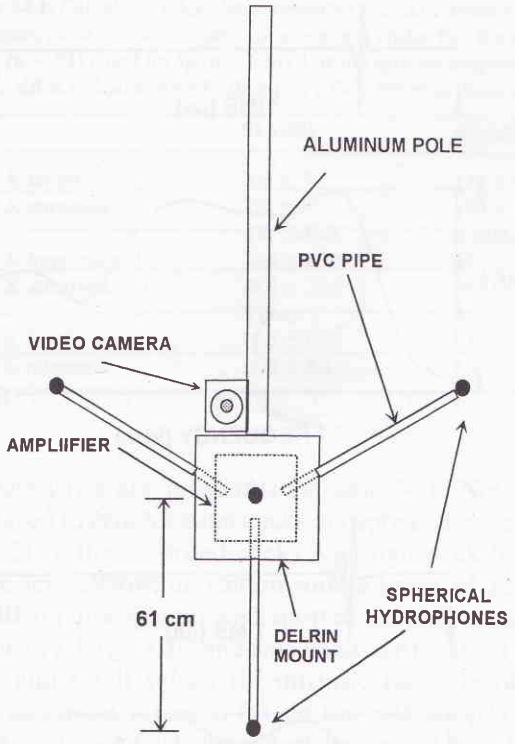

Fig. 54.2. The hydrophone array that was used for data acquisition

x-coordinate in fig. 54.1. Furthermore, eq. 54.4 shows that as the sum of time-of-arrival differences ($\tau_{01} + \tau_{02} + \tau_{03}$) approaches 0 μs, range R (as well as the range estimation error ΔR) increases to infinity. Therefore, only ranges up to an arbitrary value of 30 m ($\tau_{01} + \tau_{02} + \tau_{03} \leq -11$ μs) were reliable, and calculated positions with $R > 30$ m were rejected beforehand.

The hydrophone array consisted of four omnidirectional ITC 1094 A elements. Hydrophones, with a flat frequency response up to 160 kHz, were attached to a rectangular block of delrin mounted via PVC pipes as shown in fig. 54.2. The four hydrophones were connected to a rechargeable battery-driven, multichannel preamplifier/linedriver with an 18 dB gain, housed in a watertight box attached to the delrin block. The preamplifier was connected via cables feeding back to the boat to a rechargeable battery-driven, multichannel amplifier with an adjustable gain for each channel. An aluminum pole with a small video camera in a watertight transparent container was attached to the array to stick it into the water. The camera was connected to a VCR on board, synchronized with the click recording device.

The hydrophone outputs were amplified by either 36 or 42 dB and fed into a four-channel, 12-bit simultaneous analog-to-digital (A/D) converter system sampling at 500 kHz. The A/D cards were housed in a transportable "lunch-box" type personal computer. The data acquisition program was written in Qbasic 4.5. Data acquisition was triggered by the input of H_0, which caused the transfer of 200 pretrigger points and 200 posttrigger points (800 μs) per channel to the board's memory. A maximum of 80 consecutive clicks, with the accompanying interclick intervals and times of recording, could be stored in one file each time.

The array was calibrated by transmitting trains of simulated *Tursiops* clicks under water and recording them with the hydrophone array at different distances from the transmitter. The array was held so that H_0 was at the same depth as the transmitter (thus, $\theta \approx 0°$), and the plane of the array was parallel to the plane of the transmitter (thus, $\varphi \approx 0°$). Calculations of R best resembled the actual ranges when the point of the maximum amplitude of the recorded click was taken as the arrival time on each channel, under the restriction that the same excursion within the click was used on each of the four channels (for that purpose, excursions could be selected manually by means of a built-in cursor option). Additionally, the best results were obtained when a three-point parabolic curve was fitted through the point of maximum amplitude and the points preceding and succeeding that point, for an exact estimate of the time of click arrival on a channel. The calculated mean ranges were plotted against the actual ranges, expressed in units of the center/outer hydrophone distance "a" (which was 0.61 m in this case). Localization was highly accurate for ranges smaller than 15 m, and sufficiently accurate for ranges up to 25 m (fig. 54.3). Standard deviations increased with range, but remained very small (<0.7 a).

Echolocation recordings from wild spinner dolphins and pantropical spotted dolphins were obtained at the Waianae coast of Oahu, Hawaii, aboard a 5.2 m Boston Whaler during four days from February to April 1997. While spinner dolphins frequently visit two sandy bottom areas of this coast, spotted dolphins are only encountered on rare occasions, and only on one occasion could their clicks be recorded. The measured water depth was 40 m, while depth varied from 6 to 21 m for the spinner dolphin click recordings. The subsequent analysis of each click was performed on the channel with the highest recorded amplitude, to increase the chance that the analyzed click was recorded from the center of the echolocation transmission beam. First, the click was manually selected on that channel by using the built-in cursor option, to separate the actual click from reverberation and from its reflection from the water surface, which often overlapped with the click itself. Because of this overlap, a subjective decision was made in differentiating the actual click from surface reflection. This was facilitated by comparing the four channels: the elapsed time (Δt) between the click and its surface reflection should be different on each channel, with the largest Δt on the channel of the deepest hydrophone H_3. To get a rough estimate of Δt, equations were derived for Δt on each channel, as specified in the appendix. After manual selection of a recorded click on the channel with the highest amplitude,

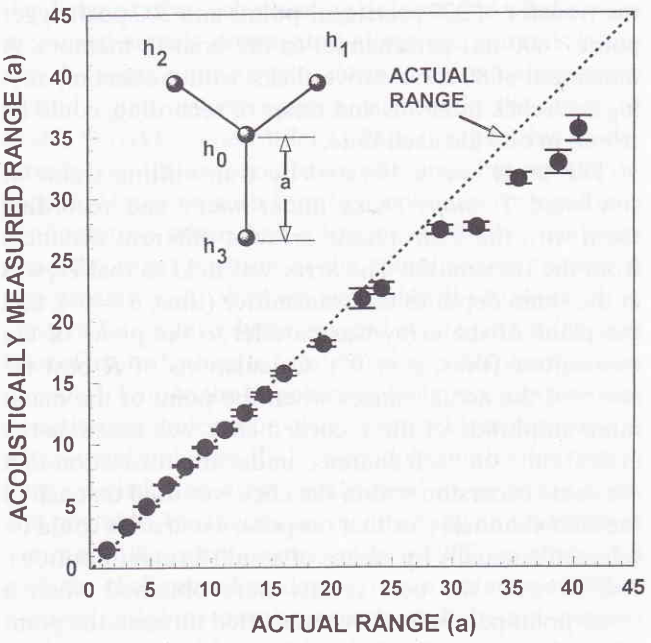

Fig. 54.3. Array calibration for calculations of R (means and standard deviations), expressed in units of a (a = 0.61 m)

the following click characteristics were calculated (defined as in Au 1993, 137, 216–24): normalized energy (E_N), peak frequency (f_p), center frequency (f_0), 3 dB bandwidth (BW), root mean square (rms) bandwidth (β), signal duration (τ), rms signal duration (τ_d), time bandwidth product ($\tau_d\beta$), centroid of the time waveform (t_0), Woodward time resolution constant ($\Delta\tau$), and intrinsic range resolution ($\Delta r = \frac{1}{2} \cdot c \cdot \Delta\tau$). The click characteristics were fed into a spreadsheet program, together with the coordinates of that click, the peak-to-peak source level SL (level referenced to 1 m from the source with units of dB re 1 μPa), and the source energy flux density SE (referenced to 1 m from the source with units of dB re 1 μPa^{2}s).

Results

A total of 851 spinner dolphin clicks and 340 spotted dolphin clicks were recorded and analyzed. Of these clicks, only 131 spinner dolphin clicks and 196 spotted dolphin clicks were recorded on all four channels. The remaining click recordings suffered from a loose connection between the preamplifier and amplifier, causing a loss of one or more channels for those recordings, which therefore could not be localized. Also, the video equipment malfunctioned, so that the orientation of echolocating dolphins could not be ascertained. However, if the center hydrophone recorded the highest signal, then in all probability the animal was directing its beam toward the array.

A typical spinner dolphin click is shown in fig. 54.4A. It was recorded from a distance of 13 m, with the highest amplitude recorded by the center hydrophone, H_0. The

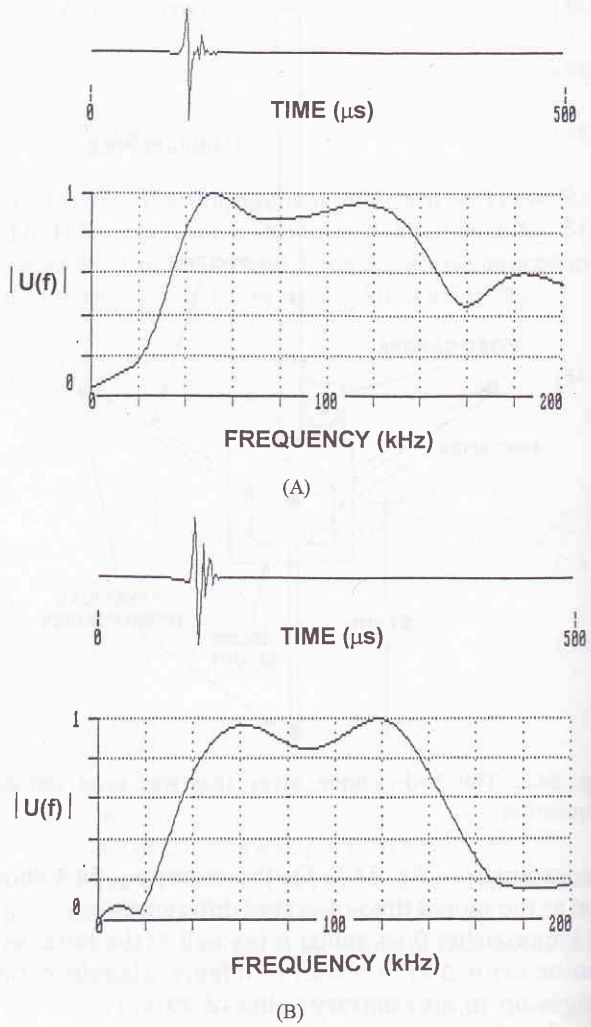

Fig. 54.4. Normalized time domain waveform $s(t)$ and frequency spectrum $S(f)$ of a typical spinner dolphin click (A) and spotted dolphin click (B)

waveform of the recorded click was a 36 μs transient signal with two main excursions and some minor excursions; most of the energy of its bimodal broadband frequency spectrum fell between 40 and 140 kHz. The calculated peak-to-peak source level was 214 dB. A typical spotted dolphin click, recorded from a distance of 12 m with the highest amplitude on the center channel, is shown in fig. 54.4B. For this click, SL = 218 dB. Generally, clicks recorded from spinner dolphins and from spotted dolphins were similar, although the waveforms of spotted dolphin clicks had minor excursions that were larger in amplitude than those of the spinner dolphin clicks. Also, there was more variation in spotted dolphin clicks. For both species, medium- to high-amplitude clicks had predominantly bimodal frequency spectra, with a low-frequency peak at 40–60 kHz and a high-frequency peak at 120–140 kHz. Clicks that were among the highest in amplitude had only a single peak in frequency, either at the low- or high-frequency peak.

Means and standard deviations of the calculated click

TABLE 54.1. Calculated click characteristics ($\bar{x} \pm$ SD), defined as in Au (1993, 137, 216–24), for all the recorded spinner dolphin (*Stenella longirostris*) and spotted dolphin (*S. attenuata*) clicks. For the spinner dolphin clicks, sample size (n) = 851, except for SL and SE (n = 131), for E_N (n = 831), and for fp (n = 836). For the spotted dolphin clicks, n = 340, except for SL and SE (n = 195), and for f_p (n = 338). For SL, dB is re 1 μPa; for SE dB is re 1 μPa^{2}s; whereas E_N is unitless.

	SL (dB)	SE (dB)	E_N (dB)	f_p (kHz)	f_0 (kHz)
S. longirostris	208 ± 5	148 ± 5	−57.5 ± 2.4	69.7 ± 23.1	80.4 ± 12.1
S. attenuata	212 ± 5	150 ± 4	−56.9 ± 1.7	69.4 ± 31.3	83.4 ± 16.8
	BW (kHz)	β (kHz)	τ (μs)	τ_d (μs)	$\tau_d\beta$
S. longirostris	76.4 ± 23.4	34.1 ± 4.9	31 ± 12	4.6 ± 1.5	0.16 ± 0.06
S. attenuata	79.8 ± 35.9	38.7 ± 6.7	43 ± 15	5.3 ± 1.9	0.21 ± 0.10
	t_0 (μs)	$\Delta\tau$ (μs)	Δr (cm)		
S. longirostris	11.6 ± 6.2	9.4 ± 2.7	0.70 ± 0.20		
S. attenuata	15.8 ± 8.2	8.9 ± 3.0	0.67 ± 0.23		

characteristics are presented in table 54.1. Note that, compared to echolocation clicks of captive *Tursiops* (Au 1993, 217), the recorded clicks had high peak-to-peak source levels (with maximum source levels of 222 and 220 dB for the spinner and spotted dolphin clicks, respectively), large 3 dB and rms bandwidths, short durations, and small values for intrinsic range resolution (with minimum values of 0.4 cm for both species). The variance of each click characteristic, except for SL, SE, and E_N, was significantly higher for the spotted dolphin clicks than for the spinner dolphin clicks ($p < 0.0001$, variance ratio test). For this reason, the nonparametric two-tailed Mann-Whitney test, rather than Student's t-test, was applied to test for differences between mean click characteristics. The spotted dolphin clicks had higher values for SL, SE, E_N, f_0, β, τ, τ_d, $\tau_d\beta$, and t_0 ($p < 0.0001$), while the spinner dolphin clicks had higher values for f_p ($p < 0.05$), $\Delta\tau$, and Δr ($p < 0.0001$). No significant difference in BW was found. In summary, the recorded spotted dolphin clicks were found to be louder and longer, with better intrinsic range resolution, than the spinner dolphin clicks.

Because positions of echolocating dolphins were known, it was possible to discriminate between clicks that were supposedly emitted by different dolphins. To assign the large number of recorded clicks that had one channel missing to individual animals as well, time-of-arrival differences rather than the actual positions were used—two time-of-arrival differences were in most cases already sufficient for this purpose. Successive clicks with similar coordinates were arranged into groups, each of which was considered as a single click train emitted by one dolphin. Next, click trains that had similar coordinates but were separated in time by one or more other trains were linked and assigned to one animal, taking into account the time interval between these trains and the animal's direction of movement.

After all clicks were assigned to individual animals, a linear discriminant analysis was applied (as in Lindeman, Merenda, and Gold 1980, 183–96, 221) to test whether the division could be supported by differences in click characteristics among presumed individual dolphins. Ten click characteristics (E_N, f_p, f_0, BW, β, τ, τ_d, $\tau_d\beta$, t_0, and $\Delta\tau$) were fed into the analysis. For the 48 presumed spinner dolphin individuals, this resulted in nine significant discriminant functions ($p < 0.05$), with which the SPSS program was able to assign 44% of all clicks to the correct (i.e., previously assigned) individuals. For the 13 presumed spotted dolphin individuals, it resulted in four significant discriminant functions ($p < 0.05$), with which 40% of the clicks could be assigned to the correct individuals. Therefore, the discriminant analysis supported the performed division of clicks. However, the discriminant functions were not consistent in the weights that they assigned to each of the 10 click characteristics, so the relative importance of each click characteristic in discriminating individuals remains unclear.

For three click trains of an individual spinner dolphin and one long click train of an individual spotted dolphin (all recorded at a distance of 10–15 m, at about the same depth as the hydrophone array), several click characteristics were plotted as a function of click number (fig. 54.5). SL, SE, f_0, f_p, and BW were generally smaller at the beginning and end of a click train than in the middle part, while β remained more or less constant. There was much more variation within the spotted dolphin click train than in the spinner dolphin click trains, and the spotted dolphin click train had larger maximum values.

Additionally, for the total data set several click characteristics were plotted as functions of one another (fig. 54.6). In this way, a linear relationship was found between interclick interval (ICI) and calculated range R of each click (fig. 54.6A, B). The so-called two-way transit time, which is defined as the time needed for an echolocation click to travel from the dolphin to the hydrophone array and back to the dolphin, is also indicated in these plots and can be expressed as two-wafy transit time (ms) = $1.33 \cdot R$ (m). Note that for all recorded clicks the ICIs were longer than the two-way transit times. Also, the slopes of the linear regression lines through the data were steeper than the slope of the equation for two-way transit time by about a factor of 2. This could be an indication that when the array was located farther

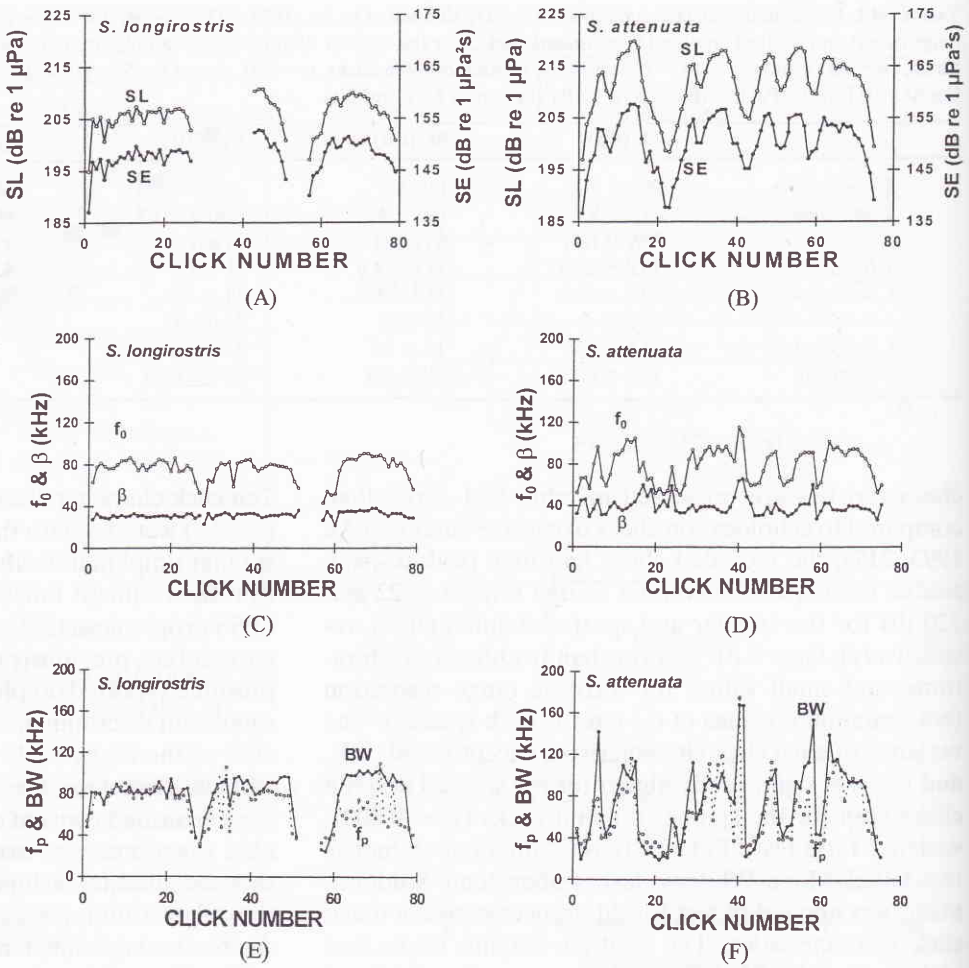

Fig. 54.5. Click trains emitted by an individual spinner dolphin (*A, C,* and *E*) and by an individual spotted dolphin (*B, D,* and *F*). SL and SE of the clicks are plotted in *A* and *B*, f_0 and β are plotted in *C* and *D*, and f_p and BW are plotted in *E* and *F*. Since the first 15 clicks of the spinner dolphin's second recorded click train were not recorded on the channel from hydrophone H_2, no ranges and therefore no values for SL and SE could be calculated for those clicks in *A*.

away, the dolphins needed a longer processing time between receiving an echo of one click and emitting the next click, assuming they were echolocating on the array. A second linear relationship was found between center frequency f_0 and peak-to-peak source level SL (fig. 54.6C, D). Equations of the linear regression lines through the data were similar for the spinner and spotted dolphin clicks, and also resembled the equation [f_0 (kHz) = 2.55 · SL (dB) − 456.40] found by Au et al. (1995) for a false killer whale (*Pseudorca crassidens*) performing an echolocation task. Finally, a third linear relationship was found between 3 dB bandwidth BW and center frequency f_0 (fig. 54.6E, F).

Discussion

Calibration of the four-hydrophone array indicated that it was highly accurate in localizing ranges up to 25 · *a* and sufficiently accurate for ranges up to 40 · *a*, where *a* is the distance between the center hydrophone H_0 and each of the three outer hydrophones. Therefore, increasing the size of the array would increase the distance at which dolphins could accurately be localized, but it would have the disadvantage that at close ranges the directional echolocation clicks probably would not be recorded on all four channels. Another disadvantage would be that the time-of-arrival differences would increase, thus requiring more digitized points per channel to store each click.

By using the four-hydrophone array, solutions were provided to three of the four problems of recording clicks at sea. Localizing echolocating dolphins made it possible to measure peak-to-peak source levels (SL) of the clicks (with an estimation error of less than 1.5 dB at R = 25 m in the calibration), to discriminate recorded clicks from their surface reflections, and to assign clicks to presumed individual animals. The division of clicks was supported by a linear discriminant analysis, which indicated highly significant differences in all click characteristics among presumed individual dolphins. However, due to the uncertainty of assigning multiple click trains with similar coordinates to a single dolphin (but separated in time by one or more click trains of other dolphins), it remained unclear whether each dolphin emitted its own type of click or that all click trains emitted by a single dolphin were different from one another.

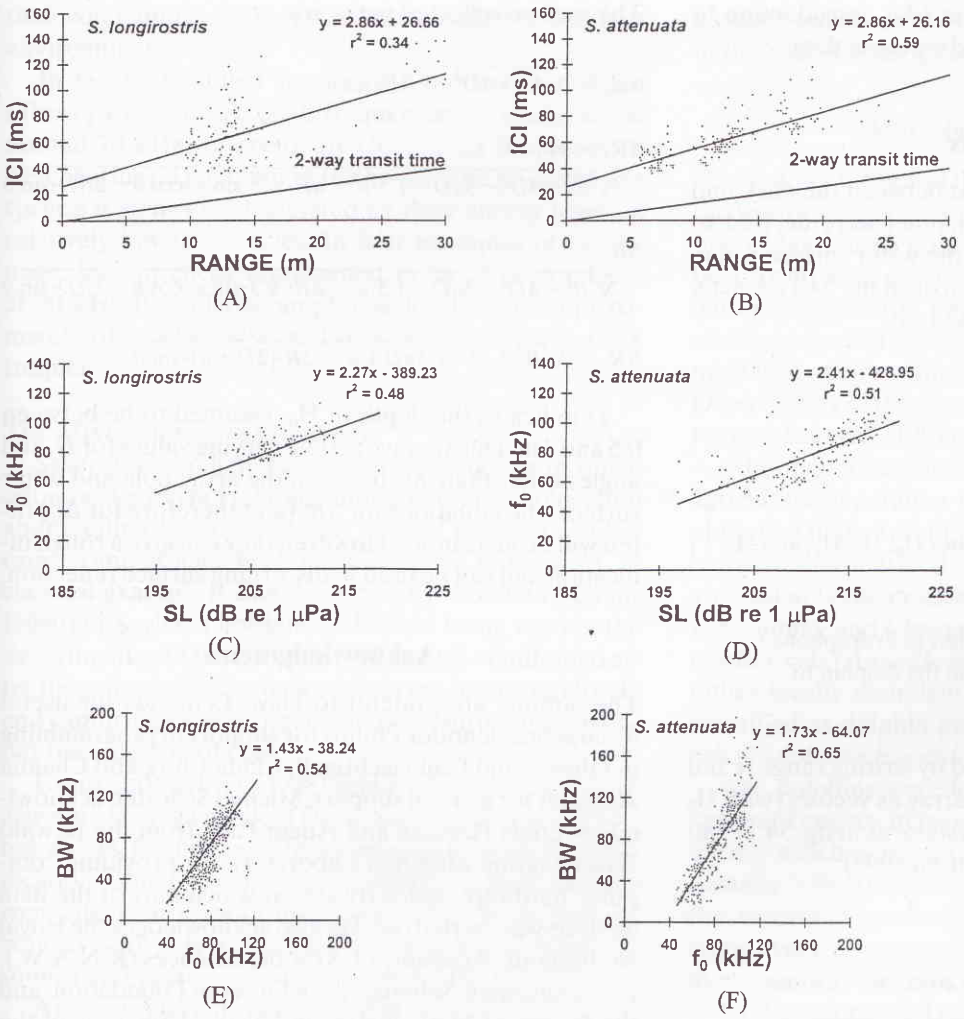

Fig. 54.6. Scatter plots of interclick interval (ICI) on range (*A* and *B*), f_0 on SL (*C* and *D*), and BW on f_0 (*E* and *F*). *A, C,* and *E* show plots for all spinner dolphin clicks, *B, D,* and *F* show plots for all spotted dolphin clicks. The equation of the least square linear regression line through the data and its correlation coefficient are indicated in the upper right corner of each plot.

To investigate this question in future research, the array recordings should be used in combination with good video recordings of known individual dolphins, such as in the populations studied by Herzing (1996).

Concerning the fourth problem of recording clicks at sea, the orientation of echolocating dolphins could not be ascertained due to malfunctioning of the video recorder. However, the use of a four-hydrophone array (as opposed to a single hydrophone) makes it easier to discriminate clicks recorded on the axis of the echolocation beam. First, it is possible to select the channel with the highest amplitude for each click. Second, one can select only those clicks with the highest amplitude recorded by the center hydrophone H_0. In this case, it is reasonable to assume that the dolphin directed its echolocation beam at or near the center of the array. Third, the linear relationship that was found between interclick interval ICI and range *R*, and the fact that ICI was larger than the calculated two-way transit time in all cases, indicate that the majority of clicks probably were recorded from dolphins that had been echolocating directly on the array. However, variations in click characteristics within one click train (such as those in fig. 54.5B, D, and F) should be treated with caution, since those variations also could result from scanning movements of the dolphin.

The clicks recorded from both spinner and spotted dolphins had source levels that were 30–60 dB higher than those recorded previously from wild odontocetes (e.g., Watkins 1980). Similar click source levels, however, were recorded from wild narwhals (*Monodon monoceros*) by Møhl, Surlykke, and Miller (1990), who used a three-hydrophone line array. Therefore, more studies should use hydrophone arrays to obtain reliable source levels for other species, to close the traditionally perceived "dB gap" between wild odontocetes and captive odontocetes trained in echolocation tasks. Besides high source levels, the spinner and spotted dolphin clicks also were characterized by very broad 3 dB and rms bandwidths, short durations, and very small values for intrinsic range resolution compared to a typical *Tursiops* click. However, while closely resembling the *Tursiops* click and echolocation clicks from other whistling dolphin species, the spinner and spotted dolphin clicks were different from clicks emitted by nonwhistling dolphin species. Therefore, the hypothesized division of odonto-

cetes into two acoustic categories (Au, introduction to this volume) is further supported by these data.

Appendix

Equations of the elapsed time Δt between the click and its surface reflection on each channel were derived to obtain rough estimates of Δt. If the water surface is flat, with the pole of the array (the z-axis in fig. 54.1) exactly perpendicular, Δt can be expressed as

$$\Delta t_i = \frac{R_i - SR_i}{c}$$

where

i = 0, 1, 2, or 3, for hydrophones H_0, H_1, H_2, and H_3, respectively
$c \approx 1500$ m/s
R_i = direct path from the dolphin to hydrophone i
SR_i = surface reflected path from the dolphin to hydrophone i

Now R_i and SR_i can be derived by writing range R and the three extending arms of the array as vectors (with H_0 as the origin of the coordinate system, as in fig. 54.1) and then using the cosine rule (Schotten 1998):

$$R_0 = R$$

$$R_1 = \sqrt{R^2 + a^2 + aR \cdot \sqrt{3} \cdot \sin\varphi \cdot \cos\theta - aR \cdot \sin\theta}$$

$$R_2 = \sqrt{R^2 + a^2 - aR \cdot \sqrt{3} \cdot \sin\varphi \cdot \cos\theta - aR \cdot \sin\theta}$$

$$R_3 = \sqrt{R^2 + a^2 + 2aR \cdot \sin\theta}$$

The surface reflected paths are

$$SR_0 = \sqrt{R^2 + 4D^2 - 4RD \cdot \sin\theta}$$

$$SR_1 = \sqrt{R^2 + 4D^2 - 3aD + 1.5 \cdot a^2 + aR \cdot \sqrt{3} \cdot \sin\varphi \cdot \cos\theta - 2RD \cdot \sin\theta}$$

$$SR_2 = \sqrt{R^2 + 4D^2 - 3aD + 1.5 \cdot a^2 - aR \cdot \sqrt{3} \cdot \sin\varphi \cdot \cos\theta - 2RD \cdot \sin\theta}$$

$$SR_3 = \sqrt{R^2 + 4D^2 + 4aD + a^2 - 2R \cdot (2D + a) \cdot \sin\theta}$$

D indicates the depth of H_0, assumed to be between 0.5 and 2 m. Due to wave action, varying values for D, and angles other than 90° between the array pole and water surface, the equations for SR_i (and therefore for Δt_i) often will be inaccurate. However, they can give a rough indication and can be used in discerning surface reflection.

Acknowledgments

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A Case for Passive Sonar: Analysis of Click Train Production Patterns by Bottlenose Dolphins in a Turbid Estuary

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Introduction

The use of a sophisticated echolocation system to navigate and to discriminate prey and other targets has been demonstrated in many odontocetes (for reviews and comparisons with the bat's systems, see Au 1993, 1997, and the introduction to this volume). This active sonar capability is based on the emission of short, broadband clicks, usually in trains, and on the interpretation of their echoes, providing the echolocating animals, and also

with a powerful roaring display (Estes 1991). These displays are usually enough to discourage weaker opponents from daring a fight with them, but may not be sufficient to intimidate equally strong males. The absence of injuries after fights between the two dolphin females in this study may be due to them not really trying to bite each other, but only performing a ritualized display fight. Such ritualized fighting is found in antelope species with potentially lethal horns—for example, the impala, *A. melampus,* and the oryx antelope, *Oryx gazella* (Estes 1991). Another example is the "bite inhibition" seen in wolves, *Canis lupus,* in connection with "passive submission," where the subordinate wolf rolls onto its back, presenting its throat and abdomen, a posture that in effect prevents a dominant wolf to kill a weaker pack mate (Mech 1970).

To study these social sounds in more detail, new methods have to be adopted where free-swimming animals can interact with each other without being restricted by a narrow channel, as in this study. At present, a sound recording unit, attached by means of suction cups to the dorsal fin of our dolphins, is being tested. It will record, in any social interaction, directional pulse sounds received by the dolphin carrying the unit.

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