Source levels of clicks from free-ranging white-beaked dolphins (*Lagenorhynchus albirostris* Gray 1846) recorded in Icelandic waters

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This study reports the source levels of clicks recorded from free-ranging white-beaked dolphins (*Lagenorhynchus albirostris* Gray 1846). A four-hydrophone array was used to obtain sound recordings. The hydrophone signals were digitized on-line and stored in a portable computer. An underwater video camera was used to visualize dolphins to help identify on-axis recordings. The range to a dolphin was calculated from differences in arrival times of clicks at the four hydrophones, allowing for calculations of source levels. Source levels in a single click train varied from 194 to 211 dB peak-to-peak (p-p) re: 1 μPa. The source levels varied linearly with the log of range. The maximum source levels recorded were 219 dB (p-p) re: 1 μPa. *© 2002 Acoustical Society of America.* [DOI: 10.1121/1.1433814]

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I. INTRODUCTION

The white-beaked dolphin has a black and white robust body with a short, thick, gray, white, or brown rostrum. The adult dolphins weigh between 220 and 350 kg and have lengths between 220 and 280 cm (Reeves *et al.*, 1999). They are endemic to the North Atlantic and can be found in groups along the coast of Iceland during summer. The dolphins are very curious and will often swim near boats and bow ride.

The presumed echolocation clicks from white-beaked dolphins resemble those recorded from the bottlenose dolphin (*Tursiops truncatus* Montagu 1821). Bottlenose dolphins emit short, broadband clicks with peak frequencies about 120 kHz (Au, 1980). White-beaked dolphins also emit broadband clicks 10 to 30 μs in duration with peak frequencies about 120 kHz, but some clicks from white-beaked dolphins have a secondary peak at about 250 kHz (Rasmussen and Miller, in press). In most acoustical studies, the orientation of the whale with respect to the hydrophones is unknown and source levels cannot be calculated. Thus, source levels, the sound pressure 1 m from the source recorded on the acoustic axis, are reported for only a few odontocetes in the wild. Source levels and other parameters of clicks from several odontocete species during different recording conditions are summarized in Table I.

The purpose of this study was to measure source levels of clicks from free-ranging white-beaked dolphins using a four-hydrophone array.

II. METHODS

Recordings were made in Icelandic waters not far from Keflavik (64°00.5′N, 22°33.4′W) between 22 and 26 August 1998. Water depth at the recording sites was about 35 m and the bottom was sandy.

We used a four-hydrophone array (Au *et al.*, 1998) with omnidirectional, calibrated ITC 1094 hydrophones having a flat frequency response up to 160 kHz. The same array was used to measure source levels from free-ranging spinner dolphins and spotted dolphins (Schotten *et al.*, in press; Schotten, 1997). The three hydrophones were arranged in a triangle with the fourth hydrophone in the center. The outer hydrophones were spaced 0.61 m from the center hydrophone. The angle between each pair of outer hydrophones was 120°. A small underwater video camera was attached and fixed 10 cm above the center hydrophone. The hydrophone array was mounted on a long pole that was lowered to a depth of about 2 m from the side of a 10-m motorboat. The propellers were stopped during recordings, but the engines idled. Hydrophone cables were connected to a multichannel amplifier and then to a portable computer on board. Analog-to-digital conversion (500 ksamples/s) was accomplished using two GAGE 1210 pc-boards. Dolphin signals were continuously digitized and stored in a temporary memory, but only signals where the amplitude on the center hydrophone exceeded a preset trigger Level were saved to disk. Up to 80 clicks could be stored in one data file. The clock time of the computer was synchronized with the video and a time stamp for each triggering was stored in a companion file. A computer program determined the click with the highest amplitude within the sample and used it to determine the received sound-pressure level (SPL). Clicks for calculating source level were only used if these clicks showed high-frequency components on all four hydrophones and had a click with the highest (or equally high) amplitude on the center hydrophone. Au (1993) has shown that on-axis clicks have high amplitude and low distortion, while off-axis signals are more variable. Cursors were manually set at the maximum positive peak of each click on the four channels and time of arrival

TABLE I. Characteristics of some odontocete clicks and recording conditions. The table is compiled primarily from field recordings where source levels could be calculated. Characteristics of clicks from bottlenose dolphins are shown for comparison.

Species	Peak-frequency kHz	Click duration μs	Maximum source level (p-p) dB *re*: 1 μPa	Number of hydrophones	Recording condition
White-beaked dolphin, *Lagenorhynchus albirostris*	120[a]	10–30[a]	219[b]	4	Wild
Pacific white-sided dolphin, *Lagenorhynchus obliquidens*	59	34–52	170	1	Captive, tank[c]
Bottlenose dolphin, *Tursiops truncatus*	52	50–250	170	1	Captive, tank[d]
Bottlenose dolphin, *Tursiops truncatus*	117	40–70	220	1	Captive, open waters, Kaneohe Bay[e]
Long-snouted spinner dolphin, *Stenella longirostris*	70	31	222	4	Wild[f]
Pantropical spotted dolphin, *Stenella attenuata*	69	43	220	4	Wild[f]
Narwhal, *Monodon monoceros*	40	29–45[g]	227	5	Wild[h]
Sperm whale, *Physeter catodon*	20[i]	200–300	232	4–5	Wild[j]

[a]Rasmussen and Miller (in press).
[b]This study.
[c]Fahner *et al.* (in press).
[d]Evans, 1973.
[e]Au *et al.*, 1980.
[f]Schotten, 1997.
[g]Miller *et al.*, 1995.
[h]Møhl *et al.*, 1990.
[i]Wahlberg (personal communication, 2001).
[j]Møhl *et al.*, 2000.

differences were measured. These differences were then used to calculate the range to the dolphin from which source levels could be determined, taking into account the transmission loss due to spherical spreading but ignoring the frequency-dependent attenuation due to the short distances (Urick, 1983). The accuracy for calculating ranges extended up to 30 m when using this array (Schotten, 1997). Source levels are expressed in dB (p-p) *re*: 1 μPa and the trigger setting allowed for the calculation of source levels (SL) greater than about 180 dB.

III. RESULTS

Only files consisting of clicks on all four hydrophones were analyzed and in these cases we assume the dolphins were interrogating our array. A total of 1718 source levels was calculated. The maximum recorded source level was 219 dB measured at a range of 22 m and the minimum recorded source level was 189 dB measured at a distance of 1.5 m from the dolphin. Figure 1 shows that source levels increase with the log of range (R) ($\mathrm{SL}=16\log R+192$), giving a correlation coefficient (r^2) of 0.69, which is significant [$n=1648$, one-way Anova, $p<0.01$ (Zar, 1996)]. The $20\log(R)$ and $40\log(R)$ lines, which are the one-way transmission loss and two-way transmission loss, respectively, are included in Fig. 1.

Figure 2 shows an example where one dolphin pointed its rostrum straight at the video camera during one second. This example contained 14 clicks from a sequence with good video recordings and many clicks. Source levels remain fairly constant at 204 to 206 dB at ranges of 3.5 to 6.5 m, but the source levels decrease to less than 200 dB at about a range of 2.7 m. The results from this individual dolphin reflect the tendency that source level increases with range as shown in Fig. 1.

Because of the way we selected clicks for source level analysis and for other reasons, interclick intervals could not be correlated with range.

IV. DISCUSSION

Source levels from free-ranging white-beaked dolphins are similar to those reported from trained bottlenose dolphins in open waters (Au, 1993). Source levels for the bottlenose dolphin varied from 208 dB at a range of 6 m to a maximum

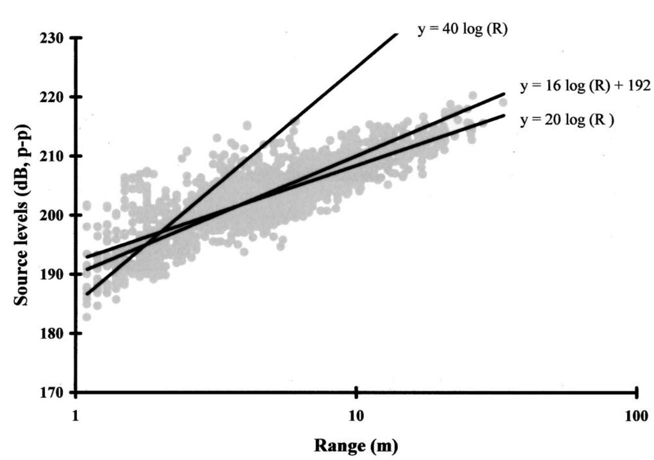

FIG. 1. Source levels in dB (p-p) *re*: 1 μPa as a function of range (m). The source levels ($n=1718$) increase with the log of range [$y=16\,\mathrm{Log}\,(R)+192$, $r^2=0.69$], which is close to the one-way transmission loss [$y=20\,\mathrm{Log}\,(R)$]. The two-way transmission loss line [$y=40\log(R)$] is also shown.

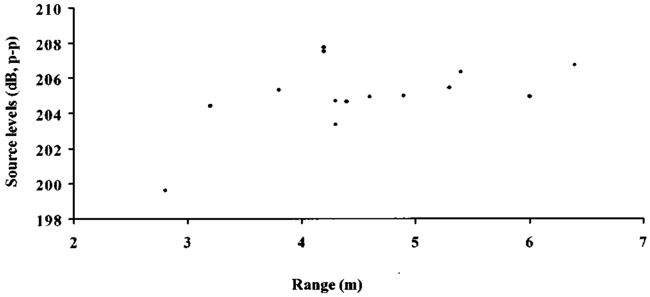

FIG. 2. An example from a file where one dolphin is looking straight towards the underwater video camera during one second. Source levels are in dB (p-p) *re*: 1 μPa.

of 230 dB at a range of 77.7 m (85 yards) to the target. The source level was 214 dB at a range of 20 m (Au, 1980). We calculated source levels of clicks from free-ranging white-beaked dolphins to 208 ± 2 dB ($n=20$) at a range of 6 m and 214 ± 2 dB ($n=20$) at a range of 20 m. Thus, source levels are essentially identical for these two species at the same target distance. We found a maximum source level of 219 dB when the dolphin was at a distance of 22 m. Our measuring system was limited at greater distances, so white-beaked dolphins can presumably produce clicks as loud as those from bottlenose dolphins. The maximum recorded source level from bottlenose dolphins (230 dB) was measured from one click in a sequence with an average source level of 220 dB (Au, 1980).

Calculated source levels from white-beaked dolphin clicks also resemble source levels from free-ranging spinner dolphins and spotted dolphins (Table I). Schotten (1997) reported source levels between 195 and 222 dB for spinner dolphins and between 197 to 220 dB for spotted dolphins. The minimum source levels in these recordings, as in our recordings, are dependent on the trigger level of the recording setup. Source levels of clicks from the Pacific white-sided dolphin (*Lagenorhynchus obliquidens* Gill 1865) measured in a tank were 170 dB (Evans, 1973); recently, Fahner (in press) measured source levels between 149 and 157 dB for the same species also in a tank. Bottlenose dolphins produce lower intensity clicks in tanks than in open waters (Au, 1993).

Our method of selecting clicks assured that these were directed toward the array and presumably on-axis, or nearly so. Assuming the array was the target, source levels increased linearly with the log of range for clicks from white-beaked dolphins (Fig. 1). Source levels also increase with range for a single dolphin looking straight towards the video camera (Fig. 2). This is the first documented case that shows a significant linear relationship between the source level and the log of range for a dolphin species. We expected the increase in click level to fall on the 40 log range line (Fig. 1), which would compensate for the two-way transmission loss for increasing distance. Had this been the case, the received echo level would be constant and independent of distance assuming no changes in target reflectivity. Surprisingly, the regression line [$16\log(R)$ in Fig. 1] is closer to the one-way transmission loss with distance [$20\log(R)$ in Fig. 1]. This implies that the sound level impinging on the target is nearly constant. Thus, as the dolphin closes on the target the received echo level increases by 6 dB for each halving of distance. In fact, this is exactly what bats do, except we know that contractions of the middle-ear muscles attenuate audition, thus compensating for the increased echo level, at least over some ranges (Henson, 1965; Hartley, 1992).

The white-beaked dolphin apparently controls the energy it puts in the outgoing signal. We found a variation in source levels of about 20 dB at any given range below 10 m (Fig. 1). At greater ranges the variation decreases. These variations are greater than we expected based on an assumed beam pattern similar to that of the bottlenosed dolphin, and on our method of selecting clicks for source level calculations. We therefore assume that the variation in source level is produced by the dolphin. Because of this, dolphins might compensate for the two-way transmission loss at ranges between 1 and about 3 m and for the one-way transmission loss at greater distances (up to about 14 m). Source levels for bottlenose dolphins can be quite variable in a click train. Au (1993) shows an example with 17-dB variation in source level in one click train produced by a dolphin during a sonar task, and variations as much as 20 to 25 dB were not uncommon.

The source levels of most odontocete echolocation signals are considerably higher than even the most intense bat signals. After converting source levels in dB (*re*: the reference Pa) to energy flux density (J/m^2) and assuming the signals are on the acoustic axis, the strongest bottlenose dolphin clicks are about 30 dB above the most intense signals recorded from a bat (*Eptesicus serotinus*, Jensen and Miller, 1999). The strongest white-beaked dolphin clicks are about 15 dB above the bat signals. However, harbor porpoise clicks (*Phocoena phocoena*, Au *et al.*, 1999) are about -26 dB relative to the strongest bat signals.

In conclusion, four dolphin species in three genera use clicks with high source levels when recorded in the wild or in open waters. Assuming our hydrophone array was the target, clicks from free-ranging white-beaked dolphins show a clear linear relationship between source level and log of range. This is the first documented case of decreasing source level with decreasing distance to target for free-ranging dolphins, but we predict this relationship will hold for other dolphin species as well.

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