Source parameter estimates of echolocation clicks from wild pygmy killer whales (*Feresa attenuata*) (L)

P. T. Madsen[a)]
Ocean Alliance, 191 Western Rd., Lincoln, Massachusetts 01773; and Department of Zoophysiology, Institute of Biological Sciences, University of Aarhus, DK-8000 Aarhus C, Denmark

I. Kerr and R. Payne
Ocean Alliance, 191 Western Rd., Lincoln, Massachusetts 01773

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Pods of the little known pygmy killer whale (*Feresa attenuata*) in the northern Indian Ocean were recorded with a vertical hydrophone array connected to a digital recorder sampling at 320 kHz. Recorded clicks were directional, short (25 μs) transients with estimated source levels between 197 and 223 dB *re*. 1 μPa (pp). Spectra of clicks recorded close to or on the acoustic axis were bimodal with peak frequencies between 45 and 117 kHz, and with centroid frequencies between 70 and 85 kHz. The clicks share characteristics of echolocation clicks from similar sized, whistling delphinids, and have properties suited for the detection and classification of prey targeted by this odontocete.
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I. INTRODUCTION

Most of the knowledge on odontocete biosonars stems from an intense research on a few delphinid species. It has been demonstrated that dolphins use biosonar to probe their environment, and their sonar system has, at ranges up to 100 m, detection and discrimination capabilities surpassing the performance of manmade analogs (Au, 1993). While such investigations have shed essential light on the basic performance of odontocete biosonar systems, it is not clear if data on the transmission system from trained animals studied in captivity are representative of the signals free ranging animals produce while using their biosonar for orientation and food finding in natural habitats (Au, 1993; Au and Herzing, 2003).

In this paper we report the first data on source properties of clicks from free ranging pygmy killer whales (*Feresa attenuata*). The pygmy killer whale (Feresa) among the smaller dolphins with a body length of around 2.3 m and a weight around 150 kg. They are usually found in off-shore tropical waters in groups of 5–30 animals, where they forage on a variety of food items including, fish, cephalopods and apparently also other small delphinids (Ross and Leatherwood, 1994). Most of the knowledge on Feresa is limited to morphometrics and stomach contents collected from stranded specimens, and there is little or no data on the ecology, behavior, life history and acoustics of this odontocete species (for a review, see Ross and Leatherwood, 1994).

We quantify and discuss characteristics of Feresa clicks and compare them to the properties of clicks of other odontocetes with biosonar recorded in captivity and in natural habitats.

[a)]Present address: Woods Hole Oceanographic Institution, Wood Hole, Massachusetts 02543. Electronic mail: pmadsen@whoi.edu

II. MATERIALS AND METHODS

A. Platform and recording gear

The recording gear consisted of a vertical array of three hydrophones deployed 5–7 m from the research vessel (for details see Madsen *et al.*, 2004).

Signals were digitized with a Wavebook 512 (IOtech), 12 bit ADC, sampling at 320 kHz on each of the three channels. Each recording session lasted 20 s with an additional 5 s of off-load time from the WBK30 memory. The LP filter, acting as an analog anti-alias filter, was compensated for during analysis yielding a flat (± 2 dB) frequency response of the recording system between 1 and 160 kHz.

B. Signal analysis

Analysis was performed with Cool Edit Pro (*Syntrillium*) and custom written routines in Matlab 6.0 (*Mathworks*) (for details see Madsen *et al.*, 2004). Signal duration (τ, μs) was determined by 97% the relative signal energy derived by integrating the squared pressure over an interpolated (10 steps) 64 point window symmetrical around the peak of the signal envelope (Fig. 1). Received rms sound pressure level (dB *re*. 1 μPa rms) was calculated by integrating the square of the instantaneous pressure as a function of time over the time window τ relative to the same integral over the same time τ of a calibration signal. Energy flux density (dB *re*. 1 $\mu\mathrm{Pa}^2$ s) was defined as the rms sound pressure level $+10\log(\tau)$ (*sensu* Au, 1993).

The spectral characteristics of the signals were quantified from a 256 point Fast Fourier Transform (FFT) on Hanning windowed data symmetrical around the peak of the signal envelopes. The peak frequency (f_p, kHz), centroid frequency (f_0, kHz), -3 dB BW (kHz), -10 dB BW (kHz), and centralized root mean square bandwidth (rms-BW, kHz) [Fig. 1(c)] were derived *sensu* Au (1993).

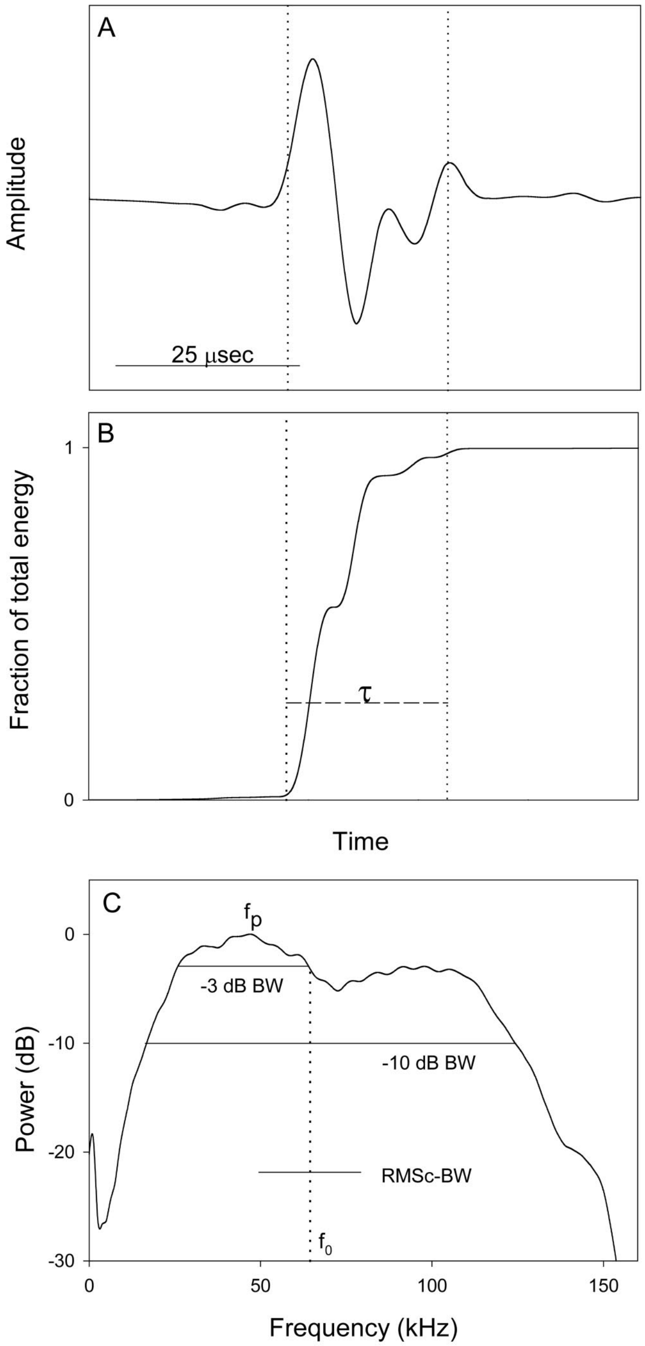

FIG. 1. (a) The waveform of the ultra-short waveform of a Feresa click. (b) The relative energy in a 64-point frame as a function of time derived as the cumulative squared pressure of the waveform displayed in (a). Signal duration, τ, is defined as the window (indicated by the dashed lines) containing 97% of the energy in the 64-point window. (c) Power spectrum of the click in (a) calculated with a 256-point FFT on Hanning windowed data. The bin width is 1.25 kHz. The relevant parameters describing the properties of the spectrum are displayed.

C. Sound source localization and estimation of source parameters

The location of the sound source was estimated from time of arrival differences (TOAD) at the three receivers by using a trigonometric approach (see, e.g., Lammers and Au, 2003). The range between the source and the receivers was calculated from the Pythagorean theorem in a localization routine implemented in Matlab (courtesy of M. Wahlberg).

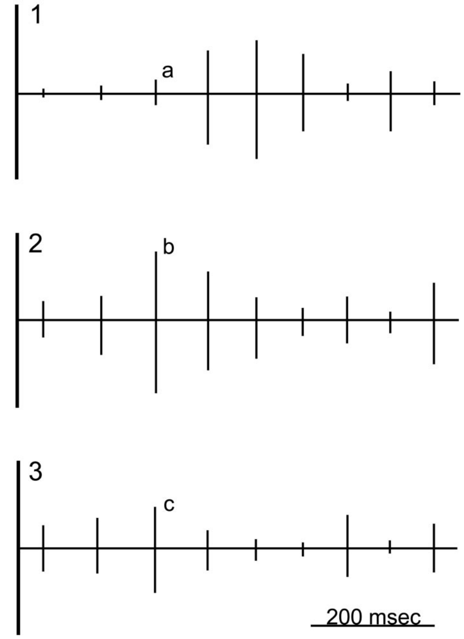

FIG. 2. Sounds tracks of the three hydrophones deployed at 4 (1), 8 (2), and 12 (3) meters depth. The same click train recorded in three different aspects is displayed in the three tracks. The full amplitude on the *y* axis corresponds to a tone with a sound pressure level of 213 dB//1 μPa (pp). Note how the ASL anomaly shifts between the receivers as the likely result of a directional sound source scanning different parts of the array. Click b is an example of a click classified as being recorded on or close to the acoustic axis of the sound beam, and (a) and (c) are recorded at angles of 15° and 7° off-axis, respectively. The tracks have been high pass filtered at 5 kHz (20 dB/octave).

Source levels (SL) were calculated from the following equation: SL=RL+TL. Transmission loss (TL) was estimated by $\mathrm{TL}=20\log(R)+R\alpha$, where α is the frequency-dependent absorption at the centroid frequency of the received click. The term apparent source level (ASL, *sensu* Møhl *et al.*, 2000) is used to emphasize that RL+TL equals the back-calculated sound pressure level one meter from a directional source of unknown orientation. The term source level (SL) can only be used where the recording aspect equals the axis of the sound beam. Source properties derived from hydrophones in a position off the acoustic axis have little relevance for the performance of the sonar system and it is therefore important to report properties measured on or close to the acoustic axis along with reliable SL estimates (Au and Herzing, 2003).

As can be seen in Fig. 2, the ASL of the same click recorded with different hydrophones from different aspects varies considerably. These profound amplitude changes over time on each of the hydrophones are presumably the result of scanning movements of a directional sound beam ensonifying the array. It is therefore clicks with the highest ASL's in such click trains that are most likely to represent the properties of sonar signals close to or on the acoustic axis of the clicking animal. All recordings were carefully examined manually, and only signals with maximal, relative amplitude on the center hydrophone compared to the other two hydrophone tracks in ensonifications were classified as being close to or on the acoustic axis of the clicking animal (e.g., see click b of Fig. 2).

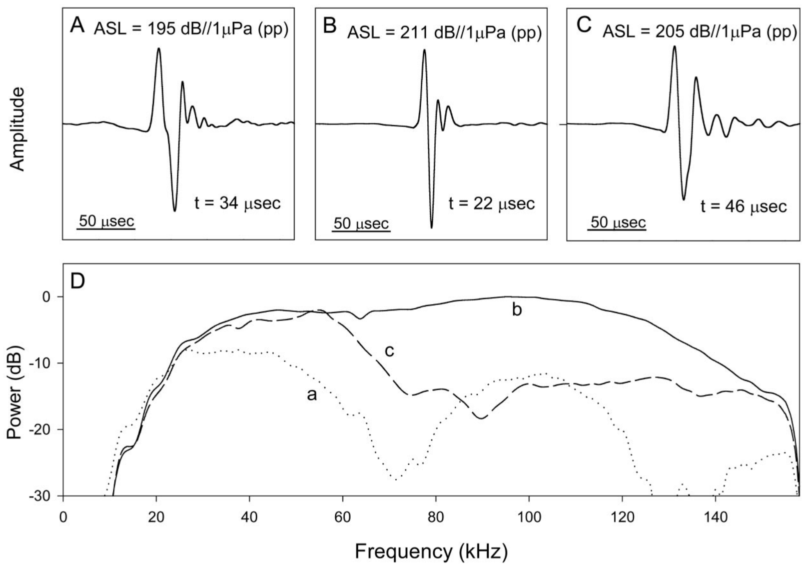

FIG. 3. Waveforms (A), (B), (C) of the click displayed as (a), (b), and (c) in Fig. 2, along with apparent source levels and durations. The ASL of (B) is likely to be the source level for that click. Figure (D) shows the power spectra of the click displayed in three different aspects in (A), (B), (C). The spectra were computed with a 256-point FFT on Hanning windowed data. The bin width is 1.25 kHz. Note that the click recorded on or close to the acoustic axis (b) is broadband with high-frequency components compared to the same click recorded at increasing angles off-axis [(c), 7°: (a), 15°], where it suffers from a low pass filter effect and notches in the spectrum.

III. RESULTS

The first of the recordings commenced on 8 March 2003, at position 1°19N/73°57E off the Huvadu Atoll in the Maldivian archipelago, where the water depth is some 1800 m. A group of 8–12 Feresa circled the research vessel and recording gear for approximately 30 min during which 49 sessions, containing more than 5000 clicks, were recorded. The second recording took place on 28 April 2003, south of Dondra head, Sri Lanka, at position 5°37N/80°43E were the water depth is roughly 2500 m. A group of 10–15 Feresa approached the research vessel, and circled it for 10 min. A total number of 18 sessions, containing some 1100 clicks, were recorded.

Using the previously outlined selection criteria, we identified a total of 26 click trains where animals ensonified the recording gear with their directional sound beams (see, e.g., Fig. 2). The clicks were part of long click trains fading in and out of the background noise with interclick intervals (ICI) between 50 and 120 ms, corresponding to instantaneous repetition rates of 8–20 click/s. On axis clicks have back-calculated source levels between 197 and 223 dB *re*. 1 μPa (pp). The rms SLs are 12–14 dB lower. The waveforms have short durations of 20–40 μs, leading to energy flux density SLs between 130–165 dB *re*. 1 μPa^2 s. Clicks recorded off the acoustic axis are of longer duration, have lower ASLs and show low-pass filtered, distorted spectra compared to the same click recorded on or close to the acoustic axis [Fig. 3].

The spectra of on-axis clicks are broadband with a -10 dB BW around 100 kHz, rms BW of around 32 kHz, and Q values between 2 and 3. Click spectra are bimodal with a stable peak around 40 kHz and a more variable peak around 100 kHz. The peaks are within ± 6 dB of each other with the high-frequency peak dominating for clicks with high source levels [Fig. 3(c)], and the low-frequency peak dominating clicks with lower source levels (Fig. 1). Therefore, peak frequency is not a good measure of the frequency emphasis of broadband spectra (Au *et al.*, 1995). The centroid frequency is a more robust measure, and it appears that Feresa clicks have centroid frequencies between 70 and 85 kHz.

IV. DISCUSSION AND CONCLUSION

A problem arising during an analysis of ultrasonic, directional clicks from free ranging odontocetes of unknown orientation in relation to the hydrophones is determining whether a signal is recorded on the acoustic axis. Since clicks recorded off the acoustic axis are distorted and not representative of the properties of the on-axis signal used by the animal for biosonar it is critical to determine if the signals have been recorded on or close to the acoustic axis of the clicking animal. As outlined previously in the materials and methods section, we have classified as the best available candidates for on-axis signals, clicks with maximum amplitudes in scans registered on the center hydrophone. When working with free-ranging animals an inherent problem with this approach is that, at least theoretically, none of the clicks may actually have been recorded on the acoustic axis. On the other hand, if an animal continuously ensonifies the recording system with a series of clicks with low source levels, they will not be classified as being on axis. The following discussion is made with these reservations since, when working with free-ranging animals, there is, as yet, no analytical method that can provide a rigid on–off classification for broadband clicks.

Feresa emits short duration, broadband signals similar to a large number of delphinids that have been measured in captivity (Au *et al.*, 1974) and in the wild (Rasmussen *et al.*, 2002, Au and Herzing, 2003; Schotten *et al.*, 2003; Madsen *et al.*, 2004, Au *et al.*, 2004). The centroid frequencies are higher than was has been reported for the larger, free ranging false killer whale (*Pseudorca crassidens*) (Madsen *et al.*, 2004), but are comparable to the centroid frequencies and properties of high SL clicks from similar sized dolphins such as *Tursiops*, *Lagenorhyncus*, and *Stenella*, and also the larger *Grampus*.

When recorded simultaneously on the acoustic axis and at different angles off it, the ASLs of off-axis clicks are much lower than the estimated SL defined by the on-axis version of the same clicks. This directionality is also seen in the frequency domain where the spectra of off-axis clicks are low pass filtered with increasing azimuth, and where step null regions are seen to begin forming at lower and lower frequencies (Fig. 3). This off-axis distortion is consistent with a directional signal whose transfer function is that of a broadband transient signal radiating from a piston of finite aperture. Pistons have successfully been used to model the transmitting part of the sonar systems in other odontocetes (Au, 1993), and it appears that the transmitting system of Feresa operates in a similar fashion. Given that transmitting aperture scales with the size of the nasal structures (Au *et al.*, 1999), it may be surmised that the transmitting aperture of a Feresa is larger than that of Phocoena, but smaller than that of Tursiops. If so, the equation of Au *et al.* (1999) suggests that the directionality of Feresa clicks is larger than Phocoena (DI=22 dB) but smaller than Tursiops (DI=26 dB). Hence, it can be concluded that Feresa clicks possess the needed directionality to reduce clutter, and to render generation of high source levels energetically feasible for a biological sound source.

Spectra are not only affected by directionality, but also by the acoustic output. Figure 1(a) displays an on-axis click with a source level of 203 dB *re*. 1 μPa (pp), and the computed spectrum is depicted in Fig. 1(c). It is seen that the lower-frequency peak dominates the spectrum. This is in contrast to the spectrum of a click with a source level of 212 dB *re*. 1 μPa shown in Fig. 3(b), in which the high-frequency peak dominates. The relationship is consistent with the sound production in other delphinids producing short, broadbanded clicks (Au, 1993).

Even though this study does not demonstrate echolocation, it seems reasonable to conclude that the directional, ultrasonic clicks, and the context in which they are used, is consistent with a biosonar function. The whales were localized at ranges between 13 and 52 m from the array, and under the assumption that they echolocated on the deployed recording gear, it is seen that the click intervals are in the same interval of 40–100 ms as used by trained Tursiops echolocating at similar target ranges (Au, 1993).

For prey localization during foraging it cannot be assured that the animals would use clicks with the same properties as measured when they echolocate on recording gear. Nevertheless, the broadband, powerful click properties derived in the present study should provide good temporal resolution and discrimination capabilities in detection of prey targets (Au, 1993). Assuming that the detection and signal processing of Feresa equals that of other delphinids, it can be conjectured that the source properties, including SLs up to 223 dB//1 μPa (pp), would allow for echolocation of relevant cephalopod and fish prey at ranges of 50 to 200 m, as has been estimated for other free ranging delphinids (Au *et al.*, 2004, Madsen *et al.*, 2004).

The present study, along with other array-based investigations (Møhl *et al.*, 1990; Au and Herzing, 2003; Au *et al.*, 2004; Møhl *et al.*, 2000; Rasmussen *et al.*, 2002; Schotten *et al.*, 2003; Madsen *et al.*, 2004), show that basic source parameters of clicks can be derived from free ranging odontocetes in coastal and off-shore habitats, given that the implemented on-axis selection criteria render a representative sample of clicks to be measured.

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