Off-axis effects on the multi-pulse structure of sperm whale coda clicks

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Sperm whale (*Physeter macrocephalus*) clicks have a multi-pulse structure, a result of the reflection of sound energy between air sacs in the spermaceti organ. Although previous research revealed that usual clicks (used for echolocation) recorded away from a vocalizing whale's longitudinal axis have waveforms with poorly defined pulse structures, it has been unknown whether sperm whale coda clicks (used for communication) show similar off-axis effects. To address this knowledge gap, a hydrophone array was used to localize vocalizing sperm whales, and the waveforms of coda clicks recorded from different aspects were examined. Coda clicks recorded close to the whale's acoustic axis showed well-defined multi-pulsed waveforms, while those recorded off-axis did not. As for usual clicks, this suggests that sound energy radiates directly into the water upon reflection off the frontal sac. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3075598]

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I. INTRODUCTION

The largest toothed whale, the sperm whale (*Physeter macrocephalus*), demonstrates extreme differences in morphology and life-history, both within the species and in comparison to other cetaceans. However, no feature of the sperm whale is perhaps as noticeably extreme and fascinating as its large nasal complex. Its large nose, which contains the spermaceti organ, junk bodies, and other organs associated with sound production (Fig. 1), makes up approximately 1/3 of the sperm whale's total body weight and body length (Rice, 1989), giving this species the claim to the "biggest nose on record" (Raven and Gregory, 1933).

Although other functions had previously been proposed for the hypertrophied nasal complex (see Clarke, 1970, 1978; Carrier *et al.*, 2002), Norris and Harvey (1972) were the first to advance a sound generating function. They suggested that an initial sound pulse generated by the forcing of air through the museau de singe (or phonic lips) (Fig. 1) is reflected between air sacs at the anterior and posterior ends of the spermaceti organ (Norris and Harvey, 1972), resulting in the observed multi-pulsed structure of sperm whale clicks. This initial theory was revised as the "bent horn" theory (Møhl *et al.*, 2003) to explain the weak initial pulse (p0) and powerful subsequent pulse (p1) obvious in the recordings of usual clicks (echolocation clicks) recorded from in front of the vocalizing whale [Fig. 2(a)].

Recent research confirms the bent-horn theory; sound in a usual click is produced at the museau de singe using a pressure differential (Madsen *et al.*, 2003), and a fraction of the initial sound energy leaks directly into the water as the weak initial pulse (Møhl, 2001). The majority of the sound energy, however, is reflected backward into the spermaceti organ (Fig. 1) (Zimmer *et al.*, 2005b) and is subsequently reflected off the air-filled frontal sac at the posterior of the spermaceti organ and focused in the junk complex before emission into the water as the powerful p1 pulse (Fig. 1; Cranford, 1999; Møhl *et al.*, 2000, 2003; Zimmer *et al.*, 2005a). The multi-pulsed structure of usual clicks is related to the two-way travel time between the air sacs (Møhl, 2001; Møhl *et al.*, 2003).

Just as sound energy is leaked at the anterior end of the spermaceti organ when the initial p0 pulse is produced, the reflection of usual click sound energy on the frontal sac at the posterior end of the nasal complex also involves the leakage of sound energy into the water, resulting in the emission of a p1/2 pulse (Zimmer *et al.*, 2005a). When a usual click is recorded on-axis directly in front of a vocalizing whale, the p1/2 pulse merges with the p1 pulse (Zimmer *et al.*, 2005a). Conversely, when a usual click is recorded on-axis directly behind the vocalizing whale, the p1/2 pulse merges with the p0 pulse [Fig. 2(b)] (Zimmer *et al.*, 2005a).

In either case, the recorded waveform contains distinct and regular inter-pulse intervals (IPIs) that can be measured to estimate the length of the vocalizing whale (Gordon, 1991b; Rhinelander and Dawson, 2004). However, when usual clicks are recorded off-axis, the p1/2 pulse will appear in the far-field with a delay between 0 and the two-way travel time of the spermaceti organ, sometimes resulting in IPIs that cannot be distinguished [see Fig. 2(c)] and thus the incorrect or impossible estimation of whale length (Zimmer *et al.*, 2005a).

Unlike usual clicks, which exhibit a highly directional p1 pulse with relatively few and weak subsequent pulses [Figs. 2(a) and 2(b)], clicks produced in short stereotyped communication patterns termed "codas" (Watkins and Schevill, 1977) typically exhibit many successive pulses

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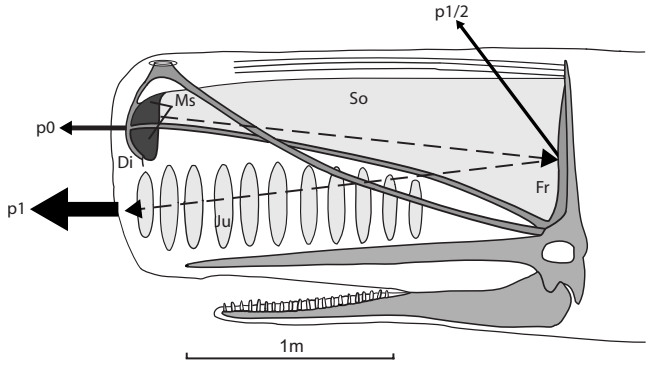

FIG. 1. Schematic view of the head of a sperm whale depicting the bent-horn model of usual click sound generation (adapted from Zimmer *et al.*, 2005a). The dashed arrows indicate the primary sound path within the nasal complex according to the modified Norris and Harvey (1972) theory. The solid arrows indicate the emission of the weak pulse (**p0**) from the phonic lips/museau de singe (**Ms**), the emission of the highly directional sonar pulse (**p1**) from the junk (**Ju**), and the leakage of sound energy as the p1/2 pulse (**p1/2**) from the frontal air sac (**Fr**). **D**, distal air sac; **So**, spermaceti organ.

(Fig. 3) and thus a longer overall click duration (Madsen *et al.*, 2002). The lower decay rate of coda clicks suggests that coda click sound energy is retained within the spermaceti organ to reverberate repeatedly between the air sacs rather than redirected into the junk complex to be released as a powerful and directional pulse (Madsen *et al.*, 2002).

The observed differences in pulse structure between usual and coda clicks must result from internal differences in the structure of the sound production apparatus. One obvious way this could be achieved is through changes in the amount of air in the frontal and distal air sacs; for example, the introduction of air into the frontal air sac could keep higher levels of energy reverberating within the spermaceti organ, consistent with the extended pulse structure of coda clicks. If

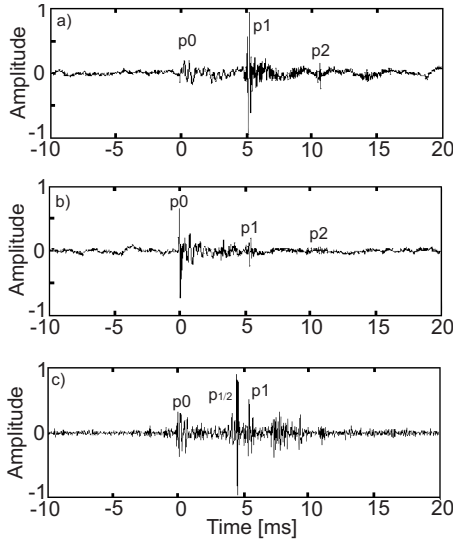

FIG. 2. Usual sperm whale clicks recorded from a remote receiver from (a) in front, (b) behind, (c) and off the acoustic axis of a vocalizing whale (adapted from Zimmer *et al.*, 2005a). The different component pulses in the clicks are denoted by p0, p1, and p2. Note that in (a) and (b), a single pulse by far dominates the energy content of the click. In the waveform recorded off-axis (c), p1/2 denotes the click energy leaked from the spermaceti organ at the frontal sac.

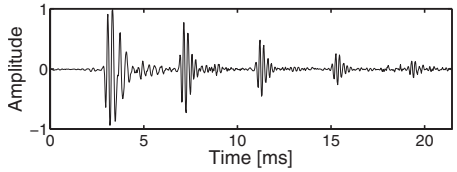

FIG. 3. Waveform of a coda click recorded from behind a vocalizing whale. Note the multiple pulses with a low rate of decay compared to the nearly mono-pulsed waveform of usual clicks [see Figs. 2(a) and 2(b)].

this were the case, we would also expect to observe significant sound leakage from the frontal sac area. Although the waveforms of usual clicks have been examined from different recording aspects (Zimmer *et al.*, 2005a; Madsen *et al.*, 2002), it is unknown whether the pulse structure of coda clicks also demonstrates off-axis effects indicative of sound energy leakage at the frontal sac. Most codas are recorded from an unknown recording aspect or from behind the vocalizing whale (see Marcoux *et al.*, 2006), prohibiting the observation of off-axis effects. To address this research gap, we inspected and compared the waveforms of coda clicks recorded on different hydrophones in a passive dynamic acoustic array.

II. METHODS

A. Field methods

We conducted fieldwork from a 40-ft sailboat, *Balaena*, between May 5 and June 20, 2004 (38 days effort) in international waters between Bermuda and the east coast of the United States in the Sargasso Sea. Encountered sperm whales were tracked visually during the day and acoustically at night using a directional hydrophone (see Whitehead and Gordon, 1986). During the day, if whales at the surface were moving slowly (<1 knot) and the weather conditions were favorable, we deployed a dynamic acoustic array.

B. Acoustic array

This localization system consisted of several small battery-powered remotely-piloted vessels (RPVs) as well as the primary research platform from which they were launched. From the side of each recording platform was suspended a hydrophone (Vemco VHLF; frequency response: 200 Hz–20 kHz $\pm$ 3 dB; midband sensitivity: 147 dB re 1 V/μPa) at approximately 80 cm below the water surface. On each RPV, acoustic signals from the hydrophone were amplified, high-pass filtered at 1 kHz, and broadcast by a FM transmitter (NRG Kits PLL PRO III). This signal was then received by a digital AM/FM PLL synthesized radio (SONY ICF-M260) onboard the deployment platform and digitally recorded on a multi-track recorder (FOSTEX VF-160; sampling rate: 44.1 kHz), which simultaneously recorded the acoustic signals detected by each of the hydrophones in the array. On each recording platform, a global positioning system (GPS) unit (Garmin GPS25-HVS) logged positional data to a flashcard. A frequency shift keying (FSK) modulator transformed the stream of ASCII sentences from the GPS unit onboard the research platform to an amplitude-modulated tonal signal (see Møhl *et al.*, 2001), which was

recorded as an acoustic track on the multi-track recorder in synchrony with the hydrophone signals. Subsequent demodulation of the FSK timestamp during analysis allowed for synchronization of the acoustic and positional data (Møhl *et al.*, 2001). The same hydrophone depth and filtering were used on the deployment platform. Recording sessions were labeled numerically according to month, day, and session of the day (e.g., 051403 was the third recording session on May 14).

During array deployment, the locations of the RPVs and whales relative to the primary research platform were recorded on a digital camcorder (SONY DCR-PC 105) from the sailboat's crow's nest. Sea surface temperature was measured using an onboard electronic thermometer, and sea salinity was estimated using a refractometer.

C. Localization analysis

The binary GPS file logged on each recording platform was converted to a RINEX file and submitted to an online Precise Point Positioning processor (Canadian Geodetic Service) to improve the accuracy of the positions. Further exclusion of erroneous noise in GPS positions was achieved by discarding fixes obtained using less than seven satellites and by smoothing the x-coordinates and y-coordinates for each GPS receiver by fitting quadratic equations to time segments spanning several seconds before and after each epoch in the record (see Christal and Whitehead, 2001).

Acoustic recordings were inspected for codas that were detected on at least three of the four hydrophones in the array. Clicks were marked in these codas using a dedicated software package, RAINBOW CLICK (see Gillespie, 1997; Jaquet *et al.*, 2001), and the click data from each recording were output to a custom-written routine in MATLAB® (Mathworks) for the calculation of time of arrival differences (TOADs) between each pair of hydrophone receivers (see Wahlberg *et al.*, 2001). Because sperm whales produce loud, abrupt broadband clicks, TOADs were calculated as time differences between hydrophones in the click onset. Since the sperm whales were observed from the sailboat, the whales were assumed to be at or near the surface when vocalizing, and we localized recorded clicks in two dimensions.

For each click in each analyzed coda, an equal time-difference two-dimensional hyperbola was calculated for each TOAD using the relative locations of the receivers and the speed of sound in water (calculated using sea surface temperature and salinity in the Leroy equation; Urick, 1983) (see Wahlberg *et al.*, 2001). The intersections of these hyperbolae were averaged to estimate the location of the sound source for each click. The localization method used was the same as the MINNA (minimum number of receiver array) method described by Wahlberg *et al.* (2001) except that it repeated the MINNA method for each pair of intersecting hyperbolae and averaged the intersections to give a solution that accounts for measurement error (see Janik, 2000; Laurinolli *et al.*, 2003). The location of each coda was estimated as the average of the locations of each of its clicks.

For clicks localized using four hydrophones, the error in each click's location was estimated from the standard deviation of the hyperbola intersections in the zonal (ε_x) and the meridional (ε_y) directions (as in Laurinolli *et al.*, 2003). The error bars for each coda localized with four hydrophones were then calculated by taking the mean of each of these errors (zonal and meridional) over the clicks in the coda. A calibration of this system estimated the precision of estimated locations as approximately 0.5 m within the array (Schulz *et al.*, 2006).

D. IPI assignment of codas

To estimate the recording angle between hydrophones and the acoustic axis of vocalizing whales, whale trajectories were estimated by localizing successive codas with similar IPIs. The IPIs of localized clicks were calculated using a modified version of a previously described IPI analysis method (see Schulz *et al.*, 2008). This modified method extracts the maximum cross-correlation peak, rather than the absolute cross-correlation peak (used by Gordon, 1991a), between pulses for clicks with well-defined pulse structures, allowing the user to discard clicks with distorted pulse structures (see Schulz *et al.*, 2008). The IPI for each coda was calculated by taking the mode of the clicks in that coda. Codas with modal IPIs within 0.05 ms of one another were assumed to have been produced by the same whale (Schulz *et al.*, 2008). This conservative criterion was used since other analyses indicated that within recordings, the IPIs of codas produced by the same whale (and analyzed using these methods) differ by no more than 0.05 ms (see Schulz *et al.*, 2008). Because the clarity of the pulse structure of coda clicks sometimes varied between acoustic channels, IPI analysis was repeated for each hydrophone in the array, thereby increasing the number of codas for which an IPI could be obtained. The assignment of IPI values to codas was consistent between hydrophone receivers.

E. Determination of whale trajectory and orientation relative to receivers

Successive codas likely produced by the same whale (as determined by IPI similarity) were localized and plotted to estimate the whale's approximate trajectory and orientation. We reasoned that if successive codas are produced every few seconds and are localized in a relatively straight line, fitting a line through the estimated locations should give a reasonable approximation of the vocalizing whale's acoustic axis. Using the GPS positions of the hydrophone receivers and the estimated trajectory and orientation of the vocalizing whale, the cosine rule was used to calculate the approximate angle between the whale and each hydrophone receiver relative to the whale's presumed body axis. The waveforms of clicks in these localized codas were then visually inspected in a standard sound-editing program (COOL EDIT, Syntrillium) and compared between hydrophone receivers to determine whether there were differences in pulse structure as a result of recording aspect.

To quantitatively describe the clarity in the multi-pulse structure of recorded coda click waveforms, we calculated the coefficient of variation (CV) in the squared amplitude over each sample in each recorded click within a 5 ms time

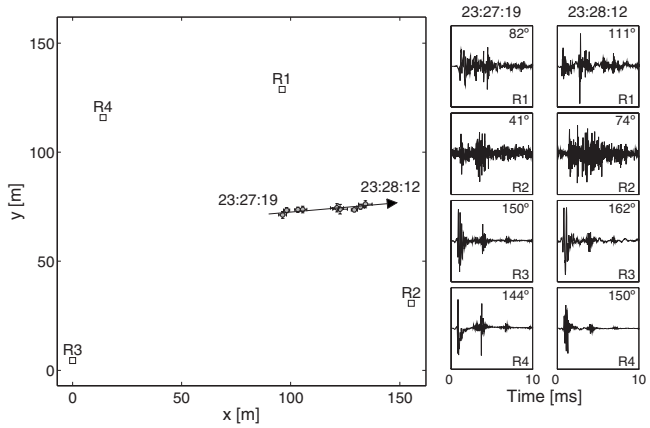

FIG. 4. The GPS positions of four hydrophone receivers (R1–R4; □) at 23:27:19 UTC and the estimated location solutions (with error bars of two standard deviations in the zonal and meridional directions) for codas with IPIs of 2.95 ms (●) produced throughout recording session 051403. The arrow indicates the estimated heading of the vocalizing whale based on codas localized between 23:27:19 and 23:28:12. The waveform of coda clicks as received on each of the four hydrophone receivers at 23:27:19 and 23:28:12 are presented along the right side of the figure together with the calculated angle between each hydrophone receiver and the estimated acoustic axis of the whale. The hydrophone deployed from the primary research platform is designated as R1. Note: the initial pulse of the click depicted in the hydrophone R4 waveform is a result of an anomalous occurrence where the FM receiver also picked up the hydrophone signal transmitted by another FM transmitter.

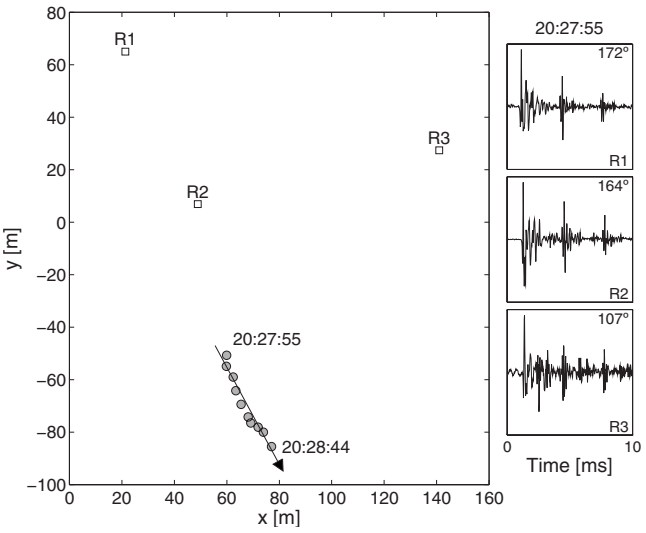

FIG. 5. The GPS positions of three hydrophone receivers (R1–R3; □) at 20:27:55 and the estimated location solutions for codas with IPIs of 3.24–3.27 ms (●) produced throughout recording session 061002. The arrow indicates the estimated heading of the vocalizing whale based on codas localized between 20:27:55 and 20:28:44. The waveform of a coda click as received on each of the three hydrophone receivers at 20:27:55 is presented along the right side of the figure together with the calculated angle between the hydrophone receiver and the estimated acoustic axis of the whale. The hydrophone deployed from the primary research platform is designated as R1.

interval beginning at click onset. A 5 ms (221 sample) time interval was used because the IPIs of all localized whales were estimated as less than 5 ms and because click durations were variable but generally longer than 5 ms. Because clicks with distinct initial pulses possessed high CVs and clicks with poorly defined pulse structures possessed low CVs, the CV provided a general measure of the clarity of the click structure while standardizing for the relative amplitude of the recorded click.

III. RESULTS

In recording session 051403, a whale with an IPI of 2.95 ms was localized as it moved within the array toward the periphery (Fig. 4). The structure of coda clicks produced while the whale was near the center of the array was clearly multi-pulsed in recordings made on hydrophones positioned behind the vocalizing whale (R3 and R4; Fig. 4). However, the pulse structure of the same clicks but recorded on a hydrophone receiver (R1) in an off-axis aspect was poorly defined (Fig. 4). Moreover, the pulse structure of the same clicks but recorded slightly more on-axis in front of the vocalizing whale (hydrophone receiver R2) demonstrated a clear initial pulse but a less-defined succeeding pulse (Fig. 4).

Several seconds later at 23:28:12, after the whale had moved approximately 38 m toward the periphery of the array, the waveforms of coda clicks recorded on hydrophones from behind the whale still demonstrated a clear multi-pulsed structure (Fig. 4). For hydrophone R1, which was now 111° behind the vocalizing whale, the waveforms of recorded coda clicks were slightly more multi-pulsed (Fig. 4) than for the coda clicks recorded 53 s earlier when this hydrophone was at an angle of 82° in front of the animal (Fig. 4). Conversely, for hydrophone R2, which was now 74° in front of the animal and thus at a more off-axis angle than 53 s earlier, the multi-pulsed structure of the click waveforms was much less discernible (Fig. 4).

In another recording session, 061002, a whale with an IPI of 3.24 ms was localized moving away from the 3-receiver array, nearly inline with two hydrophone receivers (R1 and R2) while off-axis to the third hydrophone receiver (R3) (Fig. 5). In the two recordings made from behind the vocalizing whale (R1: 172°; R2: 164°), the waveforms of coda clicks recorded at 20:27:55 possessed well-defined pulse structures, although the first pulse in the clicks was more elongated and less distinct than the subsequent pulses (Fig. 5). In contrast, in the recording made from an off-axis aspect (107°) to the acoustic axis of the vocalizing whale, the waveforms of the same clicks demonstrated additional pulses between the primary pulses (Fig. 5). We note, however, that since this whale was localized outside the array where errors can increase markedly (see Watkins and Schevill, 1972), these results should be considered with caution. Nonetheless, similar differences in waveforms on different hydrophone receivers were observed for another whale in session 061002 with an IPI of 3.51 ms also localized moving away from the 3-receiver array.

To examine the effect of recording angle on the clarity of pulse structure, we also plotted the CV of the squared amplitude for each localized click waveform on each hydrophone receiver against the estimated angle between the location of that hydrophone and the acoustic axis of the whale at the time at which the click was produced. Figure 6 quantitatively illustrates the qualitative observation described above

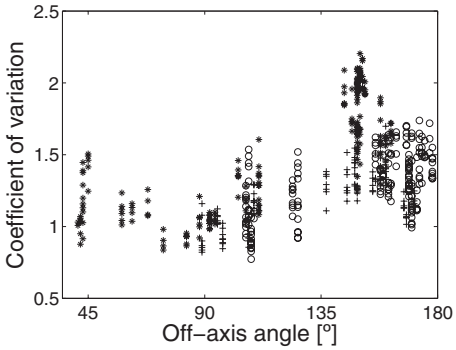

FIG. 6. Scatterplot of the CV (in the squared amplitude of the initial 221 samples) in coda click waveforms vs the estimated angle between the hydrophone receiver and the acoustic axis of the whale. The CV was calculated for 652 click waveforms from 33 different codas from three whales in two recording sessions (051403 and 061002). Each whale is represented by a different symbol.

that coda clicks recorded off-axis tended to possess less well-defined waveforms than those recorded closer to the acoustic axis. Although some click waveforms that were recorded on-axis possessed low CVs (see Fig. 6), such waveforms possessed clear, well-defined pulse structures but poorly defined initial pulses (e.g., see Fig. 7), thereby resulting in a low CV during the initial 5 ms of the click. Poorly defined initial pulses in otherwise well-defined clicks may have been a result of the initial release of the sound energy into the water or the distortion of the initial pulse by the p1/2 pulse.

IV. DISCUSSION

Examination of coda click waveforms recorded from different aspects indicates that sperm whale coda clicks, like usual clicks, are affected by recording orientation. For several different localized whales, waveforms of coda clicks recorded on or near the whale's estimated acoustic axis visually demonstrated a much more well-defined pulse structure than the same clicks recorded off-axis. Furthermore, plotting the CV in amplitude of localized clicks against the estimated angle of recording indicated that clicks recorded off-axis (~90°) tended to have more poorly defined pulse structures than those recorded closer to the acoustic axis.

Differences in click waveforms between hydrophones are clearly due to differences in recording aspect and not an artifact of variation in recording quality between different hydrophones since recordings from receivers R1 and R2 in session 051403 demonstrated poor click waveforms for the clicks of one whale recorded off-axis within the array (Fig. 4) but demonstrated distinct multi-pulsed waveforms for the

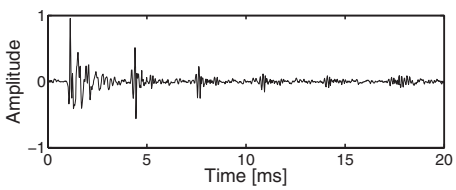

FIG. 7. Waveform of a coda click recorded at an estimated angle of 172° between the hydrophone receiver and the acoustic axis of the whale. Although the pulse structure of the waveform is well-defined, it possesses a relatively low CV in squared amplitude due to the indistinct initial pulse.

clicks of another whale recorded on-axis in session 061002 out of the array (Fig. 5). Moreover, there was also consistency within recording sessions in the clarity of pulse structure between recordings made from similar recording aspects, again indicating that the waveform of recorded coda clicks is dependent on the angle between the hydrophone receiver and the orientation of the vocalizing whale rather than the quality of the hydrophone recording.

If the sound energy of coda clicks were emitted only from the anterior end of the spermaceti organ, one would find the structure of recorded clicks to be similar at all recording aspects. The results presented here that sperm whale coda clicks recorded off-axis are much less defined in pulse structure than clicks recorded on-axis indicate that the sound energy does not exit solely from the front of the spermaceti organ and must also be leaked as a p1/2 pulse from some other point, most likely upon reflection of the frontal sac as in usual clicks.

Zimmer *et al.* (2005a) mistakenly stated that field observations by Rendell and Whitehead (2004) suggest that codas recorded in the far-field have stable IPIs. The finding here of off-axis effects clearly indicates otherwise and partially explains the considerable number of coda clicks discarded in previous IPI analyses of coda clicks (Rendell and Whitehead, 2004; Marcoux *et al.*, 2006). Moreover, the results presented here should encourage researchers to record sperm whale codas on-axis, most likely from behind the whale, and exclude from IPI analysis coda clicks recorded off-axis with poor pulse structure. Although ensuring on-axis recordings with a single hydrophone can be difficult, using a number of hydrophones in an acoustic array can increase the likelihood of recording coda clicks from an on-axis aspect and thus of obtaining clear IPIs for the estimation of body length (Marcoux *et al.*, 2006) or assignment of codas to specific whales (Schulz *et al.*, 2008).

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