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Sperm whale clicks: Directionality and source level revisited

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In sperm whales (*Physeter catodon* L. 1758) the nose is vastly hypertrophied, accounting for about one-third of the length or weight of an adult male. Norris and Harvey [in *Animal Orientation and Navigation*, NASA SP-262 (1972), pp. 397–417] ascribed a sound-generating function to this organ complex. A sound generator weighing upward of 10 tons and with a cross-section of 1 m is expected to generate high-intensity, directional sounds. This prediction from the Norris and Harvey theory is not supported by published data for sperm whale clicks (source levels of 180 dB *re* 1 μ Pa and little, if any, directionality). Either the theory is not borne out or the data is not representative for the capabilities of the sound-generating mechanism. To increase the amount of relevant data, a five-hydrophone array, suspended from three platforms separated by 1 km and linked by radio, was deployed at the slope of the continental shelf off Andenes, Norway, in the summers of 1997 and 1998. With this system, source levels up to 223 dB *re* 1 μ Pa *per* RMS were recorded. Also, source level differences of 35 dB for the same click at different directions were seen, which are interpreted as evidence for high directionality. This implicates sonar as a possible function of the clicks. Thus, previously published properties of sperm whale clicks underestimate the capabilities of the sound generator and therefore cannot falsify the Norris and Harvey theory. © 2000 Acoustical Society of America. [S0001-4966(00)03301-4]

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INTRODUCTION

In 1972, Norris and Harvey presented a seminal paper on the possible function of the nasal structures of the sperm whale as a gigantic generator of sound. To appreciate the boldness of this proposal, one should keep in mind the unique size and proportions of this Odontocete. Old males can weigh upwards of 50 tons (Berzin, 1971), 1000 times more than the smallest member of the suborder, *Phocoena*. About $\frac{1}{3}$ of total body weight—and body length—is allocated for the soft structures of the nose, which is aptly coined the “biggest nose on record” (Raven and Gregory, 1933). Apart from its scale, the “design” of this nose is quite unlike that of other Odontocetes. The spermaceti case is an elongated, horn-shaped structure of connective tissue containing up to 2 tons of liquid wax and extending throughout the length of the nose. It is bound in the front and rear by air sacs. The case rests on a similarly sized structure (the “junk” in whaling parlance), a longitudinally, stacked series of lens-shaped bodies of spermaceti, each surrounded by connective tissue.

At the time of publication of the Norris and Harvey theory (1972), the basic properties of sperm whale clicks were known from several papers, notably the one by Backus and Schevill (1966). The trademark of clicks from this species is a multi-pulsed structure, in which pulses are spaced at fixed intervals and with decaying amplitude (Fig. 1). The Norris and Harvey theory (1972) explains this pattern by proposing a single pulse being generated at one end of the spermaceti sac, traveling down the sac, and being reflected at the air sac at the other end. On return, part of the energy is

intercepted by the opposing sac, giving rise to the next pulse. Thus each trailing pulse is derived from the preceeding pulse as a diverted fraction of the energy of the former. The authors’ prime suspected location of click generation is the “monkey muzzle,” a structure of tough, connective tissue surrounding the distal end of the right nasal passage at the anterior termination of the spermaceti organ.

Norris and Harvey (1972) also performed experiments with a multiple reflection model that generated trains of decaying pulses from single clicks. They published the first measurement of velocity of sound in spermaceti and combined this knowledge with their theory and with the measured value of the pulse interval from recordings of a subadult sperm whale of known length. A “remarkable correspondence” between the observed length of the animal and the prediction from their theory was obtained.¹

Overall, they made a pretty good case for the proposal that the nose of the sperm whale is a generator of sound. However, a rather basic question was not dealt with at the time: What is the survival value of investing so much of the whale’s developmental resources just to make sound? This question was subsequently addressed in a paper by Norris and Møhl (1983), in which a number of observations were presented to illuminate the hypothesis that Odontocetes—and sperm whales in particular—could use intense sound to debilitate prey.

This hypothesis has problems of its own. While peak pressures in clicks of Bottlenose dolphins (*Tursiops truncatus* M.) were known to be just high enough (Au *et al.*, 1974)

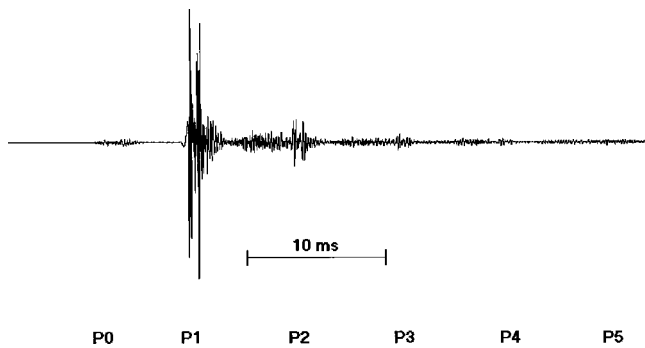


FIG. 1. Waveform of sperm whale click, selected to illustrate the multi-pulse pattern. Pulses are labeled P0–P5. Note the constant interpulse interval between pulses $P_n - P_{n+1}$ for $n > 0$, which is the essence of the Norris and Harvey theory (1972). The low-amplitude P0 pulse precedes the P1 pulse with a slightly shorter interpulse interval than found for the remaining intervals. The doublet pattern is caused by surface reflection.

to have debilitating effects on fish (see Zagaesky, 1987), the most commonly cited source level (SL) for sperm whale clicks of 180 dB *re* 1 μ Pa (Watkins, 1980) is about 40 dB below debilitating levels.

Another observation of Watkins (1980) is that sperm whale clicks lack directionality. This counter-indicates bio-sonar as a function of the clicks. Additionally, it is not supportive of the hypothesis of the sperm whale nose as being the largest biological generator of sound, since directionality generally follows the ratio of transmitter cross section to wavelength (Urlick, 1983). With an aperture on the order of 1 m and wavelengths on the order of 0.1 m, directionality in sperm whales should be as good as, or better than, that of dolphins, which have a pronounced directionality (Au *et al.*, 1986, 1987). Instead, Watkins' observation implicates a smallish generator. And smallish is definitely not a property of the nose of sperm whales.

Thus, either the Norris and Harvey theory (1972) of sperm whale click generation is not realized, or the reported properties of clicks are not fully representative.

This paper deals with the latter alternative. To obtain measures of the properties of sperm whale clicks beyond waveform and repetition rates is not a trivial matter. The species is found at the slope of the continental shelves, where they habitually dive to depths of 1000 m or more. To get recordings near the whales requires deep water hydrophones, which are costly and difficult to handle. Once recordings have been made, source level determination involves a series of processes: deriving the received sound pressure, measuring the sound velocity profile (SVP) of the medium, and positioning the whale. The positioning process dictates the use of an array of hydrophones. The spacing of the latter is a compromise. They have to be sufficiently widely spaced to

yield a proper position and to present a set of significantly different angles to the whale. Yet, the hydrophones must also be sufficiently close to each other so that they can all pick up signals from the same source. A special problem is to know the relative locations of the hydrophones. Above all, the whale should comply and direct its clicks towards one of the hydrophones (if directionality is indeed present). This can never be ascertained, but the probability that it occurs can be increased with the number of hydrophones deployed, and by increasing the time spent recording.

Here, we report our attempts to meet the above requirements. The data obtained shows several properties expected from high directionality, as well as extremely high peak pressures in certain sperm whale clicks, which presumably were recorded close to the acoustic axis of the source.

I. METHODS

Recordings were made between 14 and 28 July 1997, and between 8 and 24 July 1998, in an area about 10 NM (nautical miles) northwest of Andenes, Northern Norway. Geographical coordinates of the center of the area of operations are 69°25'N, 15°45'E. Here, an undersea canyon brings the slope of the continental shelf to within 8 NM of the coast. The depth drops rapidly from about 130 to 1000 m. In this area solitary, presumably foraging male sperm whales are found and usually spaced some kilometers apart when surfaced. The water is part of the Gulf Stream and the Norwegian Coastal Current, running NE at an average speed of 1 knot (Johannesen, 1986). Recordings were made at sea state 2 or below.

The array was deployed from three platforms and utilized four hydrophones in 1997, five in 1998. The main platform was a 41-ft auxiliary ketch ("R/V NARHVALEN") in which a Racal Store 7D instrumentation tape recorder was installed (wow and flutter specification: 0.2%–0.35%, time base error: $\pm 4 \mu$ s). This was normally operated at $7^{1/2}$ ips (inches per second), occasionally also at 30 ips. The frequency response is within ± 3 dB between 0.1 and 37.5 kHz at $7^{1/2}$ ips, 0.2 and 150 kHz at 30 ips. The tape used was Ampex 456, recorder bias being adjusted accordingly.

The dynamic range of instrumentation recorders (about 35 dB) is not sufficient to cover the range of amplitude variations in sperm whale clicks, and the most intense clicks will cause saturation. For the instrumentation recorder, an input–output function for low saturation levels was established and used to correct SL values. This extended the dynamic range by 4 dB (Weber, 1963). Filters as described in Table I largely set the limitations in frequency response.

From the main platform two B&K 8101 hydrophones were lowered, one with 30 m and one with 100 m of cable.

TABLE I. Frequency response of the hydrophone chains.

Chain	N30+N100	N460	B30+R30+M30
Recorder	Racal 7D	Racal 7D	Sony DAT
± 3 dB bandpass (kHz)	0.3–37.5	0.3–6 ^a	0.08–11.5 ^a
Filter slope (dB/oct)	HP=24, LP=30 ^b	6	6

^aEqualized to 20 kHz in analyses.

^bTape recorder gap effect.

TABLE II. Key data showing maximum level clicks from sequences selected for source positioning. From each sequence the click of max ASL was selected and its P1-component properties derived for all elements of the array. TL: transmission loss, ASL: apparent source level, ERRrms: root-mean-square error from error propagation analysis, BWrms: root-mean-square bandwidth, see Sec. I, n.a.: not available for directions towards the array with the whale in endfire position. Heading: the general heading of the whale relative to the array (A) or platform M.

Sequence	Click no.	Hydrophone	TL (dB)	ASL (dB <i>re</i> 1 μ Pa)	ERR rms, dB+, dB–		BW rms (kHz)	Heading
4t 1640	5	M30	47	175	11	n.a.	3.6	towards M
...	...	G30	61	192	5	...	2.9	...
...	...	N30	64	197	2	...	3.3	...
...	...	N100	64	197	2	...	3.2	...
4t 1659	7	M30	47	191	22	n.a.	3.1	towards M
...	...	G30	61	202	10	...	3.3	...
...	...	N30	64	190	8	...	2.7	...
...	...	N100	64	188	13	...	2.6	...
4t 1808b	2	M30	66	191	13	n.a.	8.2	n.a.
...	...	G30	62	189	16	...	7.5	...
...	...	N30	54	189	23	...	8.7	...
...	...	N100	54	188	23	...	8.5	...
4t 1817	4	M30	60	184	2	4	4.4	par. w. A.
...	...	G30	61	187	2	4	3.5	...
...	...	N30	55	195	3	2	7.4	...
...	...	N100	55	193	3	2	8.9	...
7t 898	19	N30	56	218	14	n.a.	12.4	towards A
...	...	N100	56	218	14	...	12.5	...
...	...	N460	56	192	14	...	8.3	...
...	...	B30	66	207	7	...	8.4	...
...	...	R30	66	194	7	...	6.4	...
7t 954	8	N30	65	221	5	10	7.5	towards A
...	...	N100	65	220	5	10	7.4	...
...	...	N460	65	209	5	11	7.0	...
...	...	B30	69	205	4	5	6.3	...
...	...	R30	68	193	4	7	7.0	...
7t 990	41	N30	64	223	2	3	9.7	towards A
...	...	N100	64	217	2	3	10.4	...
...	...	N460	63	192	2	3	7.8	...
...	...	B30	68	200	1	2	6.2	...
...	...	R30	66	185	1	1	6.2	...
7t 1036	17	N30	58	208	12	n.a.	11.6	towards A?
...	...	N100	58	220	12	...	8.4	...
...	...	N460	58	195	12	...	7.8	...
...	...	B30	67	204	6	...	7.3	...
...	...	R30	67	193	6	...	7.3	...

All 8101 hydrophone cables were B&K AO 113 or AO 114. In 1998, an additional (spherical) hydrophone, (HS/150, Sonar Products, Ltd.) having a maximum operating depth of 1500 m was lowered to depths of between 400 and 600 m, using a 3 mm o.d., multi-stranded, nylon-insulated, single-wire cable to return the signal from a pressure-resistant canister. This housed batteries, an Etec hydrophone preamplifier, a sweep generator for calibration, and a line driver. The sea was used as the return path. The upper -3 dB cutoff was 20 kHz in most of the recordings, except for the session generating data for Table II. On this occasion, a leak in the cable reduced the upper -3 dB frequency to 6 kHz. Equalization of the response to 20 kHz was carried out during analysis. The three hydrophones and their associated electronics (chains) are referred to as N30, N100, and N460.

The two satellite platforms (in 1997 a 38-ft ketch, “Mette-Marie,” and a 12-ft Zodiac, and in 1998 two Zodiacs) were spaced 0.5 to 1 NM from each other and from the

main platform. After deployment of the hydrophones, changes in geometry occurred only passively by differential drifting. Each satellite platform had a B&K 8101 hydrophone (referred to as G30 and M30 in 1997 and B30 and R30 in 1998), powered from a B&K 2804 power supply. It was lowered with 30 m of cable. A Sony DAT recorder (TCD-D7 or D8) preceded by an antialiasing filter (1998 only) completed the chains. The recording chains were adjusted so that the tape recorders were the amplitude-limiting instruments rather than the preceding electronics in front of the recorders.

Radio links (using VHF in 1997 and UHF in 1998) relayed the signals from the hydrophones of the satellite platforms to the instrumentation recorder at the main platform. The links had limited bandwidth (0.5 to 2 kHz) and low dynamic range, but preserved the timing of the sperm whale signals.

On each of the platforms, the continuous output from a

Garmin 45 GPS (global positioning system) receiver was converted to a FSK (frequency shift keying) signal that was recorded along with the acoustic signals on the DATs and the instrumentation recorder. The latter, on the main platform, thus received simultaneous inputs from the three local hydrophones, from the two telemetry links, and from a GPS signal. The seventh channel was used to record the electrical current applied to the blasting caps, used for fine-scale positioning of the hydrophones, as described below.

All B&K hydrophones were calibrated before each session with B&K 4223 hydrophone calibrators, the calibration signal being recorded on tape. Fixed gain was used in the DAT chains. On the instrumentation recorder, step attenuators were sparsely used to adapt the limited dynamic range to the received levels, changes being annotated on the commentary channel.

The frequency responses of the various recording chains are given in Table I. Filters were present or introduced for various reasons. The high-pass filters were used to reduce hydrodynamic and electric noise. The low-pass (LP) filter of the N460 chain is an inherent property of the cable/sea water transmission path. In the DAT chains, antialiasing filters were necessary to avoid folding of high-frequency components. The effect of the LP filters on frequency response was compensated for at analyzing time by properly weighted amplification. Finally, the low-pass filter of the Racal reflects the gap effect (Weber, 1963).

Sound velocity profiles (SVP) for the top 150 m were determined only in 1998, using a custom built "sing-around-device." The SVP slope we measured was identical to those measured to a depth of 1000 m in 1997 and 1998 by the Institute of Marine Research, Bergen, Norway. The SVP profile shows a decrease from 1495 m/s at the surface to 1480 m/s at a depth of 50 m. Below 50 m, the SVP varies little from 1480 m/s. This information was used for ray tracings, which showed only minor reductions in received sound level for shallow, distant sources. There was no indication of transmission losses (TLs) less than predicted from spherical spreading. Accordingly, TL was computed as $20 \log(r)$, where r is the distance in meters from the source to the receiver.

Positions of the platforms were derived from the GPS signals. The specified rms error of this system is 100 m (set by US Department of Defense, DOD), which suffices for approximate fixes of favorably located sound sources and array legs of the large size used here. Some reduction of GPS error was achieved by making running averages of positions of the slowly drifting platforms. However, for whales in array end-fire directions (i.e., sources close to the line through a pair of hydrophones, outside the array), standard GPS determination of array geometry is inadequate, as, e.g., in sequence 898 (Fig. 5). Also, the sway of the cables for the deeper hydrophones, due to differential drift of the platform and the deeper layers of water, introduces an uncertainty in the position of the hydrophones. To reduce this uncertainty, a series of transients generated by blasting caps were set off in 1998 from the three platforms, and from a third, GPS-positioned dinghy. From such data the actual acoustic travel times between the various platforms and all the hydrophones

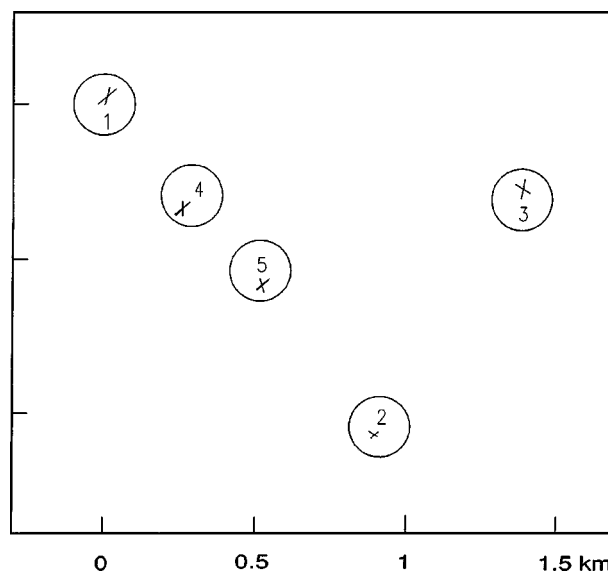


FIG. 2. Recording geometry in the 1998 recordings. Numbers refer to calibrating shots, 1 to 3 being fired from the three platforms, 4 and 5 from a GPS positioned dinghy. Circles signify GPS positions of platforms, with the centers obtained through linear regression of 5 min of continuous recordings. Diameter represents the DOD imposed RMS uncertainty. The crosses at 1 to 3 represent measured distances of travel for the transient signals to the two other platforms, assuming a sound velocity of 1490 m/s. The crosses at 4 and 5 are derived from acoustical localization of the transient and subsequent derivation of the distances to the three platforms.

were determined and used to define the residual uncertainties. The latter was then used in error propagation analysis of the acoustic localization of whales (Wahlberg, 1999a, b). However, this kind of calibration was only done in two sessions. The acoustic data from 1998 reported below was selected for being close in time (within less than 6 min) to the transient events.

In 1997, the GPS signal of the N-platform fell out in the session from which data for Table II was derived. The relative positions of platforms were instead reconstructed from the Radar log.

The recordings were subsequently digitized in stereo (using the 30-m hydrophone signals from the main platform as a reference in one channel) by standard PC sound-card-compatible hardware (digitizing rate: 44.1 kHz). This resulted in four files, describing one sequence of clicks. In addition, the DAT recordings from the satellite platforms were digitized, using the GPS timing for rough synchronization and the telemetry linked series for absolute synchronization under operator control. The precision of this process is in the order of fractions of a millisecond.

The digitized series were analyzed by commercially available sound-editing software (COOLEDIT96, SYNTRILLIUM), as well as by custom-built software (A. Heerfordt) for rms bandwidth determination. The effect of the antialiasing filters was compensated for by postrecording frequency weighting.

All levels are given in peak equivalent root-mean-square (peRMS) which is the rms sound pressure level of a continuous pure tone having the same amplitude as the transient. Traditionally, levels are given as peak-to-peak levels with the rms sensitivity of the hydrophone as the reference. This

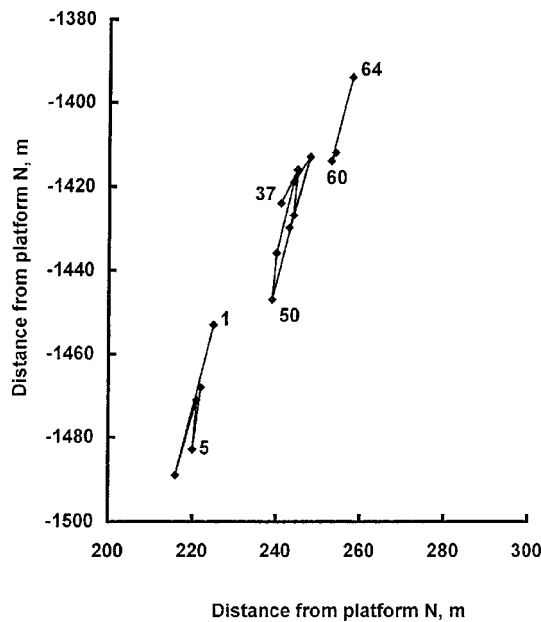
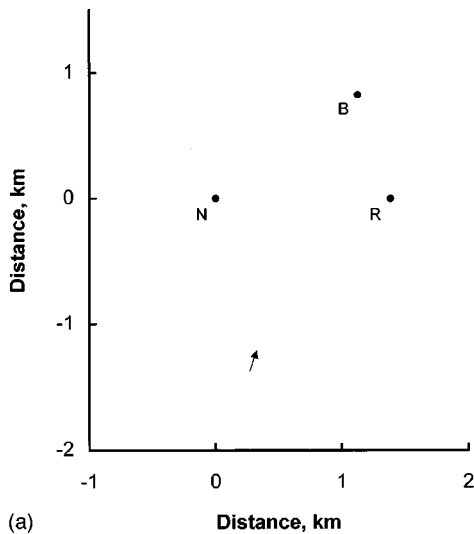
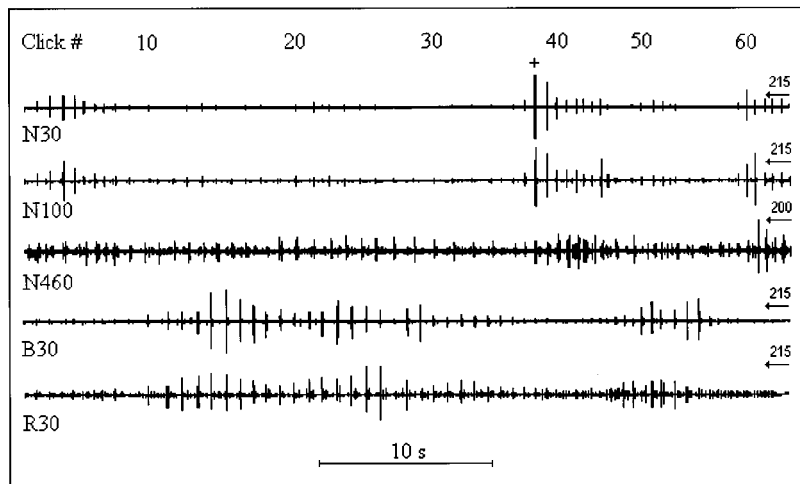


FIG. 3. Partial track of a whale. Positions from sequence 990/98, (plotted in Fig. 4). The origin refers to the location of the N-platform in Fig. 4. The first and last click in the three consecutive segments where clicks are detectable at all three platforms are identified with click numbers from Fig. 4.



(a)



(b)

method leads to 9 dB higher values than with the notation used here. For a discussion of this topic, see Møhl (1988).

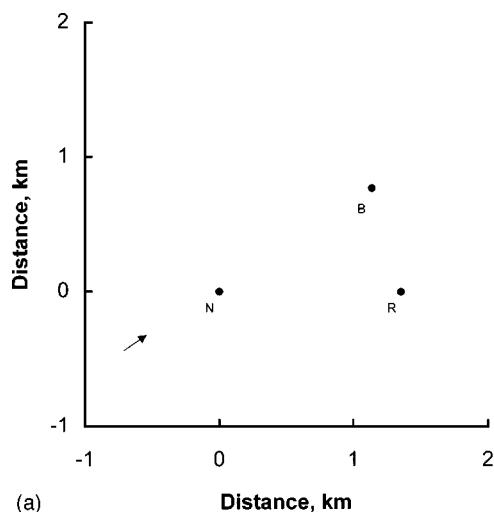
Bandwidths of isolated P1 pulses (see Fig. 1) were measured as rms bandwidth, which is a weighted distance of the frequencies in the spectrum from the frequency 0 Hz (Menne and Hackbarth, 1986):

$$\text{Brms} = \left(\frac{\int_{-\infty}^{\infty} f^2 |S(f)|^2 df}{\int_{-\infty}^{\infty} |S(f)|^2 df} \right)^{1/2}.$$

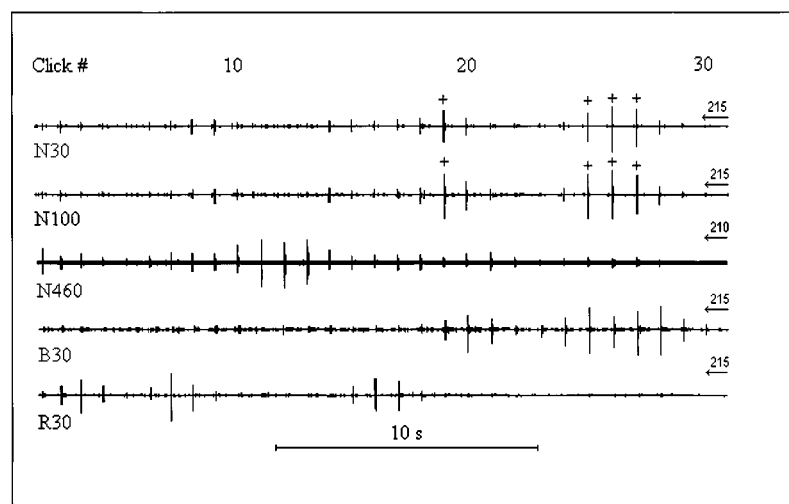
Source positioning of 1998 data was calculated analytically with a 3-D algorithm adapted to Matlab 4.2 after Watkins and Schevill (1971). A modified version of this algorithm was used for 2-D positioning of the 1997 data. In a few situations a vertical array configuration was used, utilizing surface-reflected signals as if recorded by virtual hydrophones (Møhl *et al.*, 1990). Error propagation analysis (Taylor, 1997) was implemented in Matlab to estimate the rms error in the calculated source positions due to uncertainties in sound velocity, receiver positions, and time-of-arrival differences (TOAD) measurements (Wahlberg, 1999a, b).

Absorption at the centroid frequency of the clicks at 10

FIG. 4. Sequence 990/98 showing geometry (a) and time series (b). (a) The arrow shows the position and general heading of the whale. N, R, and B are the three platforms, with N in origin. (b) Synchronized time series (oscillogram format), recorded at the five hydrophones. The series are normalized *re* max amplitude of each channel. Arrows at the right signify the specified ASLs in dB *re* 1 μ Pa per RMS, valid only for the positioned whale. Clicks, overloading the recording, are marked with a +. Low-level clicks from other whales set the noise background and dominate the N-traces between clicks 9 and 37.



(a)



(b)

FIG. 5. Sequence 898/98 showing geometry (a) and time series (b). Symbols as in Fig. 4.

kHz (see Madsen and Møhl, 2000) is a minor factor, reducing the recorded levels by about 1 dB/km (Urick, 1983). This correction has been applied to the apparent source level (ASL) numbers in Table II.

II. RESULTS

The criteria applied for the selection of the data presented in this paper were that clicks belonging to the same sequence should be identifiable at all hydrophones of all three platforms. For 1998, an additional condition was for the sequences to occur within 6 min of the period in which array geometry was established by the firing of the blasting caps. In this period 20 sequences were identified, 4 of which were simultaneously detectable on all platforms. From 1997, 15 sequences were examined, 4 of which yielded position data. The start and end of a sequence are determined by the operator, not necessarily by the whale. The shortest sequence analyzed consisted of 5 consecutive clicks, the longest of 64. Within a sequence, the time-of-arrival differences (TOADs) did not vary by more than a couple of milliseconds from one click to the next.

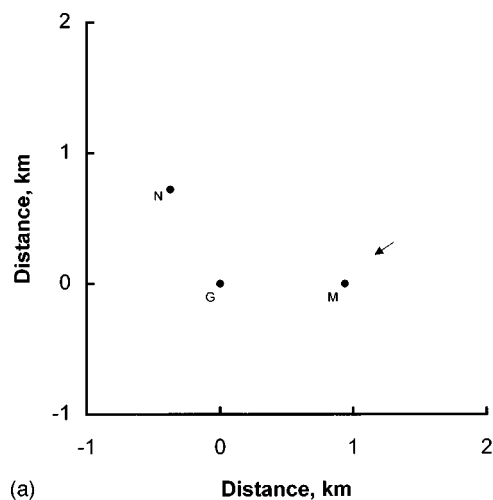
Figure 2 shows the GPS positions of blasting-cap-generated transients (shots), used in 1998 to establish the

geometry of the array. Shots 1 to 3 were set off from the recording platforms. Shots 4 and 5 were fired from an independent, GPS-positioned platform. Also given are the acoustically derived locations generated from observed travel times to the recording platforms (the crosses).

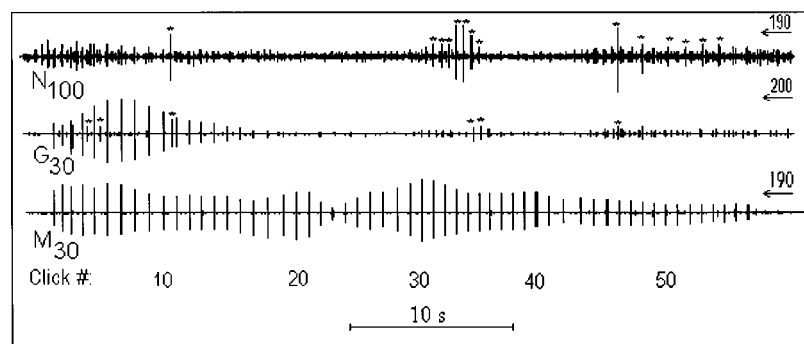
In Fig. 3, the track of the whale generating sequence 990/98 is plotted (geometry and click pattern of this sequence are presented in Fig. 4). The track is interrupted during two periods, where it was not possible to detect the same click at all three platforms.

Figures 4–6 show the recording geometry, plotted in 2-D format with the associated time series of three sequences. The time scale is chosen so as to illustrate a conspicuous feature: the smoothly varying, yet profound change in amplitude over the course of the sequences. With the scales used it is not possible to identify clicks as belonging to the same sequence; contributions from other whales contaminate the picture somewhat, as described in the legends.

The influence of recording geometry shows up in the rms error of positioning, given in Table II. In Fig. 4, uncertainty of the position only moderately affects the SL determination. Figure 5 illustrates a situation with a whale in line with two of the platforms (end-fire position). Here the linear error propagation model is not applicable for the positioning



(a)



(b)

FIG. 6. Sequence 1659/97 showing geometry (a) and time series (b). Symbols are as in Fig. 4. (a) Platform G is at the origin. Only three hydrophones used. Platform N is positioned by a transposed radar fix, while G and M are positioned by GPS. (b) Oscillograms. At the far hydrophone (N100) a second whale is dominating (marked *).

error in the direction towards the array. From the 2-D array in 1997 there is data from three such sequences presented in Table II. From the 3-D array in 1998 there is data from two whales in end-fire positions (Table II). In the 3-D cases the vertical array configuration from platform N was used to check the position given by the 3-D algorithm. The estimated range from the whale to the array obtained with the linear array was within 200 m from the 3-D solution for both sequences.

The amplitude span of the clicks at each hydrophone exceeds 20 dB. However, the patterns of the amplitude changes are not correlated between the three platforms. In time series from the three hydrophones suspended from the main platform, changes in click amplitudes from the one at a depth of 460 m are only weakly correlated with those from the upper hydrophones. This is most evident for sequence 898/98 (Fig. 5), for which the source is fairly close to platform N, resulting in increased angular separation for the string of N hydrophones.

From Figs. 4–6, it is evident that the derived SLs of each click as seen at the different hydrophones cover a wide range. As we interpret such differences to be caused by directionality, we propose to refer to them as source level anomalies, and we call the derived source levels ASLs (apparent source levels). This is done to signify the interpretive aspect.

Table II lists key data on maximum level clicks from sequences selected for source positioning. From each sequence the click of maximum ASL was selected and the

properties of the P1 component were derived for all elements of the array (the P1 component is defined in Fig. 1). The amplitude spectra of the P1 component from the same click are highly variable between platforms, sometimes multi-peaked, sometimes flat. As an attempt to quantify the spectral properties in a way that is not sensitive to the shape of the spectra or to arbitrary definitions, we have computed the rms bandwidth. This measure defines the range resolution properties of a pulse in a sonar system that use all information available (Menne and Hackbarth, 1986). With a rather uniform low-frequency cutoff at 2 kHz, the rms bandwidth describes the extent of spectral energy. A correlation can be established between ASL and bandwidth (Fig. 7). The trend is statistically significant at $\alpha=0.01$ level, but explains only some 15% of the variation [linear regression ANOVA test (Zar, 1996)]. Note that the clicks analyzed come from different sequences, different geometries, different equipment, an unknown number of individuals, and from recordings obtained in two different years.

Waveforms of the blasting cap signals could not be reliably recovered due to overload of the recorders.

III. DISCUSSION

A. Array properties

Figure 2 demonstrates a fair correspondence between acoustically derived positions and GPS-determined positions. It should be understood, however, that this represents the easy case of a source close to the plane of the hydro-

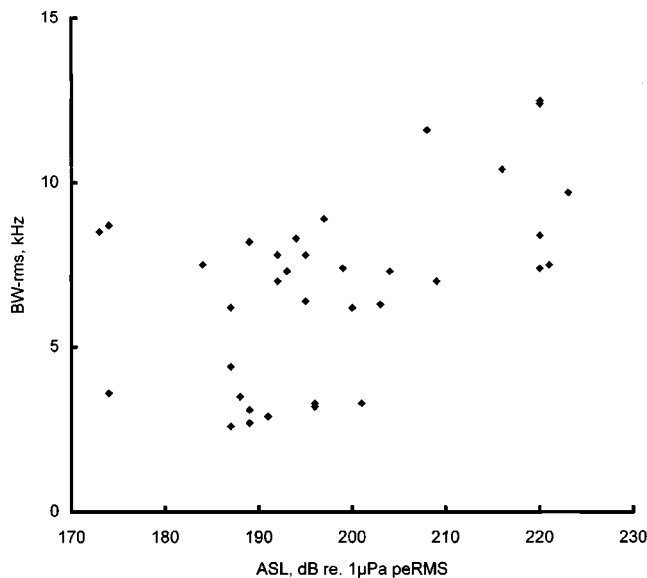


FIG. 7. Plot of RMS bandwidth versus ASL for clicks listed in Table II.

phones, and at the very borders of the array. For distant and deep sources, and for sources in end-fire positions, a number of factors combine to increase uncertainty about the position of the source. This is illustrated by the rms error values in Table II. The whale generating the data in Fig. 5 was in the end-fire direction of the array where the rms error of position becomes particularly high. In this case, the vertical array configuration of the N hydrophones was used for distance assessment. For sequence 1659/97 (plotted in Fig. 6), the large rms error in source positioning is caused by positioning uncertainty of the N platform.

The data in Fig. 2 does show that the combined system of a GPS fixed array, telemetry of signals, sound velocity measurements, and time stability of recording and analyzing processes is acceptable for the task of positioning. The main source of uncertainty lies in the geometry of the recording situation, rather than in the equipment.

The omnidirectionality of the transient blasting cap sources expected from theoretical reasoning was indirectly demonstrated by the invariable, intense reverberation following the first echo from the bottom (Madsen and Møhl, 2000). The time constant of this reverberation was on the order of 600 ms.

The track of a whale in Fig. 3 illustrates how positioning on a macro-scale is quite consistent, with the whale progressing along a rather stable course towards the array. On a micro-scale, the track is erratic and with many reversals. This pattern is characteristic for a geometry with the source well outside the array. The micro-perturbations are not believed to reflect movements of the whale, but are considered to be consequences of noise *sensu latu* in the system.

B. Source anomaly and directionality

The variation in SL seen in Figs. 4–6 is found in all series examined. The variation in click amplitude is gradual. This is most simply explained by directional effects, combined with scanning movements of the source, rather than by some kind of source modulation. The lack of correlation of

SL changes between platforms—or at times a negative correlation—is consistent with this view. The sequences last less than 1 min, during which period the geometry of the recording situation is essentially unchanged. This counter-indicates transmission path effects as being the cause of the change in patterns observed.

In smaller Odontocetes it is established that scanning is obtained by moving the head with its fixed acoustical axis relative to the body (Norris *et al.*, 1961). It is not obvious that this solution will be feasible in sperm whales, where about 10 tons of tissue with its surrounding water would have to be moved. Another possibility is that the scanning mechanism is within the sound generating organs. Our data only suggests that scanning takes place, not by which mechanism.

The course of amplitude changes (see, e.g., the alternation of ensonification between platforms in Figs. 4 and 5, and the onset of sequence 1659/97 in Fig. 6) further suggests that click amplitude for any given series is largely constant. This conjecture, however, is not testable, and is not important for the discussion of the data.

It is interesting to compare the reverberation pattern of the omni-directional blasting cap transients (Madsen and Møhl, 2000) with that of the sperm whale clicks. While the ASLs of the more intense clicks were approaching the magnitude of the SLs of the transient (231 dB *re* 1 μPa peRMS, measured at 40 m and referred to 1 m, data from Thiele and Oedegaard, 1983), the reverberation patterns for the clicks were either absent or quite different from the smoothly decaying pattern of the transients. Notably, in cases where reverberation caused by clicks can be seen, the echo pattern changes from click to click. This difference between transients and clicks can again be explained by ascribing high directionality to the clicks, combined with scanning so that not all clicks are directed towards the bottom and, if they are, only a limited patch of the bottom is ensonified by each click. A similar variability is seen with reflections from the surface: at times they are prominent, at other times not detectable at all.

When ASLs of individual clicks are compared between platforms, as well as between real and virtual hydrophones, we find differences as large as 35 dB (the entire dynamic range of the instrumentation recorder). Without knowledge of the acoustical axis of the animal it is not possible to establish SL or directional indices (DIs). However, some guidance can be obtained by means of the theory of a vibrating plane piston in an infinite baffle. Although it may be a little hard to imagine that the anatomy of the sperm whale's nose fits this description, it helps to recall that this model has been useful in describing directionality in a number of other biological cases, including small Odontocetes (Au, 1993). The piston model predicts a behavior of the transmitter somewhat akin to that of a low-pass filter with the cutoff frequency being inversely proportional to the off-axis angle. Figure 7 is a scatter plot of bandwidth versus ASL for all clicks in Table II. The trend is qualitatively in agreement with piston theory, but hardly a good starting point for quantitative arguments.

It is instructive to consider the consequences if indeed sperm whale clicks were omnidirectional, as previously re-

ported (Watkins, 1980). The power emitted by an omnidirectional point source is

$$P_o = 4\pi r^2 I,$$

where r is distance and I is the acoustic intensity, given by $I = p^2/\rho c$ (ρc is density and sound velocity of the medium, respectively). Using the measured maximum value of 223 dB *re* 1 μ Pa pRMS from Table II for p , the emitted acoustic power will be 22 dB *re* 1 kW or about 167 kW. This would indeed be surprisingly high. A directivity index in the order of 30 dB, similar to that found in dolphins (Au, 1993), would reduce this number to a more reasonable 167 W. This would still be a very powerful sound, about three times as powerful as the most intense signals recorded from dolphins (Au, 1993, table 7.2).

In Figs. 4(a)–6(a) the general heading of the sources is given (course from source position at sequence onset to position at sequence end). The value of this information is problematic for several reasons, one of which is that it is a 2D statement about a 3D world, another that it does not account for scanning or other movements. Still, a tendency is seen in Table II that in sequences with high ASLs, the whales are approaching the array, while in lower level sequences they are moving away from, or parallel to it. The concept of directionality is consistent with this tendency, which is of a different nature than that of SL anomalies seen within a sequence from an individual whale. The observation also underlines the importance of the completely uncontrollable condition of having the whales pointing towards the array during measurements of maximum levels. Our lack of knowledge of direction of the acoustic axis of the whales precludes any statement about the maximum capability of the sound generator. We can only report on the maximum levels that our hydrophones happened to register.

The data in Table II do not indicate that deep hydrophones are essential for the recording of maximum ASL. This observation may be biased because the N460 chain was deliberately operated at high gain, leading to a high rate of occurrence of saturation. The prime purpose of this hydrophone was to provide time information.

C. ASL

The most difficult condition to meet for the derivation of ASL is the requirement to localize the source. This is the basis for the estimate of the transmission loss (TL), numerically the largest element in ASL calculations. The problem of localization is dealt with in Wahlberg (1999a, b). It should be recalled that the data in Fig. 2 shows positioning accuracies of the system that will produce only fractional dB errors in transmission loss estimates. Larger errors are to be expected for sources far from the array, and in end-fire positions, as evidenced by the occasionally large standard deviations of ASL, given in Table II. In sequences such as 898/98 the rms error is so large so as to make determinations of ASL rather meaningless. However, the vertical array of platform N was advantageously used here to get a better confidence interval in determining source positions.

With the source localized, TL can be calculated from the law of spherical spreading, which describes the propagation

of the click as the distribution of sound pressure on an ever-expanding sphere. For straight, vertical SVPs this relation is a good description, but with increasing velocity in the top layers the sphere becomes distorted, resulting in lowered ASLs for distant, shallow sources. This might introduce an offset or bias of SL anomaly for certain recording geometries. Since geometry during sequences of about 1-min duration is largely constant, this effect cannot explain the fast, relative changes in ASL between platforms (Figs. 4–6).

Determining the sound pressure impinging on the hydrophones is, in principle, straightforward with knowledge of the transfer functions for the various recording chains available. The use of fixed gain results in the occasional, strong signals overloading the electronics, which might lead to underestimated ASLs. While overloading leaves its footprint on the analog tapes and thus can be taken into account, the situation is more complicated with the DAT recordings. The limited bandwidth of the various recording chains will also reduce the derived ASLs. Thus, most of the known sources of errors combine to bias the derived ASLs in a negative direction, with positioning errors being neutral.

Because of the large anomalies observed and from the direction of the various errors discussed, it is clear that any kind of mean, standard deviation, or similar measurement is not a meaningful description of SL, as long as the orientation of the acoustic axis remains unknown and constantly varying. Instead, ASLs are given for the most intense click from each sequence as such clicks are likely to have been recorded closer to the acoustic axis. The levels found for the eight sequences of Table II are large, some of them extremely large, some 40 or 50 dB above generally cited values for sperm whales (Watkins, 1980). In fact, all levels above 219 dB *re* 1 μ Pa pRMS² are larger than any level previously reported from any Odontocete species (Au, 1993, Table 7.2).

The fact that sound levels reported here are within the range given by Zagaesky (1987) for debilitating effects in fish solves one of the problems with the debilitation hypothesis of Norris and Møhl (1983). It is emphasized, however, that the general properties of the sequences recorded, particularly their rather constant and slow repetition rates, are suggestive of sonar as the function of the clicks (Goold and Jones, 1995), rather than the capture of prey. Other proposed functions of sperm whale clicks such as communication (Watkins, 1980) cannot readily be deduced from our recordings.

D. Comparison with previous data

Why have such extreme source levels and high directionality in sperm whale clicks remained undetected for so long? There is no single answer to this question. A part of the explanation may be that our recordings are from the northernmost population, a population exclusively made up of adult, foraging males (Berzin, 1971), whereas all other recordings are from lower latitudes, where females and calves are also found. Sexual dimorphism leads to nonallometric growth of the nasal (i.e., sound producing) organs in male sperm whales (Nishiwaki *et al.*, 1963). Thus, clicks

from old males may simply be more intense than those from females and calves, as suggested by Weilgart and Whitehead (1988).

Another part of the explanation is that a number of analyses on sperm whale clicks have not been designed to include SL, measurements (e.g., Gordon, 1991; Weilgart and Whitehead, 1988; Goold and Jones, 1995). However, as we show, on-axis signals are so intense that they can hardly go unnoticed. Weilgart and Whitehead (1988) do in fact report about "loud, distinctive clicks," but the recording procedure used in their studies involved spotting the whales at the surface, approaching them and identifying them, and making recordings as they dive. This procedure was likely to increase the probability of getting signals from the rear of the animal, opposite the putative acoustic axis.

Further, we have specifically looked for, and have set up our instruments to record, high ASLs. Despite this, only some of our sequences contain a few clicks with very large ASLs, while in several of the sequences the levels were more comparable to previously published maximum levels (Watkins, 1980; Dunn, 1969; Levenson, 1974).

The other conspicuous difference between our data and those found in the literature on sperm whale clicks is the pronounced directionality we infer from our observations. The simplest explanation of this difference is that a cumbersome array of considerable size is required to detect the anomalies. To the best of our knowledge the array we used here is unique. The sonobuoy technique presently used by Orion aircraft for submarine surveillance would be ideal for such measurements, but dedicated missions for civilian use of data by this system appear unlikely at present. The fact that the early use of this technique by Dunn (1969) and Levenson (1974) did not result in findings as reported here can be explained by short exposure times and by the limited number of hydrophones deployed (one and three, respectively).

Finally, our findings may not be that unique as they are not very different from early work by Whitney (1968). His report, however, has largely been overlooked. He describes properties of sperm whale clicks recorded with a large-aperture, two-hydrophone array. Directionality is inferred from alternating illumination of the hydrophones, as well as from a relationship between spectral composition and SL akin to that shown in Fig. 7 of the present paper. Maximum source levels are stated to be in the range of 175 to 200 dB re $1 \mu\text{Pa}$. From this it is tempting to conclude that the use of small as opposed to large-aperture arrays can explain some of the differences between currently accepted properties of sperm whale clicks (e.g., Watkins, 1980) and those described by Whitney (1968) and us (this paper).

IV. CONCLUSION

Results from recordings of sperm whales at high latitudes with a large-aperture array are interpreted to show high directionality, with maximum recorded SLs exceeding 220 dB re $1 \mu\text{Pa}$ per RMS. Such levels are 40 to 50 dB above previously published levels. The findings support the Norris and Harvey (1972) theory of sound generation in the sperm whale by demonstrating high outputs from the putative large-

est known biological generator of sound. Acoustically, the sperm whale may thus no longer be thought of as an aberrant, degenerated odontocete species without biosonar [as may be implicated from previous data, apart from those of Whitney (1968)], but rather as a specialized one with noteworthy properties. That it may also use its sound generator for other purposes such as communication (Watkins, 1980) is only to be expected, since biosonar generally has such a collateral function. From this, more specialized communication, such as coda exchanges, may have evolved.

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¹The measurements were carried out by K. J. Diercks of the Defense Research Laboratory, University of Texas. The value obtained, about 2.7 m/ms, has not been found by other researchers and is now considered to be off by a factor of 2 (Goold *et al.*, 1996). In a correspondence between Diercks and Møhl (in 1976), Diercks proposed that the value might apply for a transversal or shear mode of propagation. Such modes are conceivable since spermaceti crystallizes in a range of temperatures just below normal body temperature.

²Note that 9 dB should be added to the levels given here to make them comparable with previous figures for, e.g., *Tursiops* (Au *et al.*, 1974), as explained above.

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