

## HIGH INTENSITY NARWHAL CLICKS

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### INTRODUCTION

The hypothesis that some odontocetes use their sonar not only to find prey, but also to debilitate it (Norris and Møhl, 1983) requires that odontocetes produce sound pressures in excess of 230 dB re. 1  $\mu$ Pa (Zaegaesky, 1987; Hubbs and Rechnitzer, 1972). While maximum source levels<sup>1</sup> (SL) of clicks recorded from trained Tursiops (Au et al., 1974) and Delphinapterus (Au et al., 1987) are only a few dB short of this value, there is a gap of 50 to 120 dB between the debilitation threshold and the SL's reported for odontocete clicks in nature (Levenson, 1974; Watkins and Schevill, 1974; Watkins, 1980a,b).

Is this dB gap real? Or, is it simply an indicator of the difficulties inherent in SL measurements of free-swimming animals? On face value, the latter explanation seems unlikely; it implies millions of extremely powerful sound pulses being emitted each day and in all oceans, but without having been noticed.

Requirements for measuring SL's of foraging odontocetes include: reliable, non-interfering access to the animals, a favourable acoustic environment, suitable recording equipment, and methods to derive source positions relative to the hydrophone. As an attempt to meet these requirements we brought

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<sup>1</sup>SL is defined as the intensity of the sound, referred to 1 m from the source and measured in the direct acoustical axis of the emitted beam. The acoustical axis specification is important due to the high directionality of odontocete clicks (Au et al., 1986; Au et al., 1987).

linear, vertical hydrophone arrays and instrumentation recorders to Inglefield Bay (Thule district, NW-Greenland (77°N, 67°W), where narwhals (Monodon monoceros) enter during the month of August to feed on halibut and polar cod. Our findings show that foraging narwhals produce clicks as powerful as those emitted by trained, captive odontocetes. For the narwhal, at least, the dB gap is not real.

## MATERIALS AND METHODS

### Site

Inglefield Bay is attractive for acoustic studies of narwhals due to its depth (in excess of 600 m), and low background noise (Thiele, 1983). The latter is in part due to restrictions on motor boats, which are banned in certain areas by local regulations as a measure not to frighten the narwhals that are important to the prevailing subsistence hunting economy.

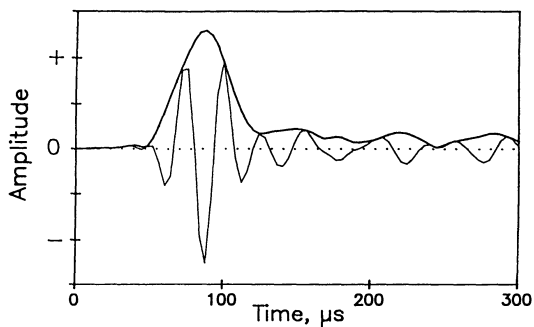


Fig. 1. Waveform and envelope of a narwhal click.

Narwhals are wary of any unnatural sounds. We had to be on station with the arrays deployed before the pods arrived. Only once were they observed at close range. Between 13 and 19 August 1987, we had a total of 3 hours of recording time and about 20 hours of monitoring. Often we recorded clicks when narwhals were not seen. No other cetaceans were observed in the area within this period.

### Instrumentation

Two identical arrays, each consisting of 3 hydrophones, were lowered to depths of ca. 5, 35, and 65 m from two, 5 m dinghies. The two deeper hydrophones were model B & K 8101,

while the shallow ones were uncalibrated, surplus sonobuoy types. The sonobuoy hydrophones were operated above their normal frequency range at resonances at 24, 41 and 56 kHz; the data were used for time-of-arrival measurements only. Two instrumentation taperecorders were used, one with an upper 3-dB limit at 60 kHz (B&K 7005, 4-channel), and the other with a bandwidth extended to 100 kHz (B&K 7006, 4-channel). A B&K 4223 hydrophone calibrator served to verify calibration of the entire recording chain at the recording sites with an accuracy better than 1 dB. The frequency response of the chains were governed largely by the recorders. Accuracy of time difference measurements was limited by recorder flutter, specified to be below 0.5 %. The depths of the hydrophones were calculated using pingers at the surface. The sound velocity profile (SVP) was not measured, but an average velocity of 1.455 m/ms was assumed, based on data from nearby Baffin Bay (Mellen et al., 1975).

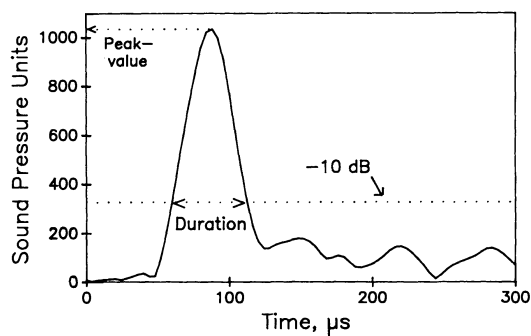


Fig. 2. Envelope of a narwhal click. Conventions for reading duration and peak value are shown.

### Analysis

Based on criteria of non-saturation of electronics and sufficient number of time differences for positioning, we analysed 62 clicks from 8 distinct positions and probably representing 8 different animals. The 4-channel recordings were anti-aliasing filtered, multiplexed and digitized at an effective rate of 250 kHz, using 12-bit resolution. Time domain measurements (time of occurrence, amplitude and duration) are based on the click envelope, generated from the Hilbert transformed signal (Thrane, 1984, cf. Fig. 1). Amplitudes are given in dB referenced to the rms value of a continuous sine wave signal having the same amplitude as the transient (Stapells et al., 1982). Durations are given at the -10 dB level on the envelope function (cf. Fig. 2). In the frequency domain, clicks are characterised by the lower and upper -10 dB cut-off of the spectrum (Fig. 3).

Calculations of positions were done assuming the hydrophones were on a straight, vertical line. Surface reflected signals were treated as if recorded by virtual hydrophones above the surface. Thus, each click is represented by a set of up to 6 time series (the click set). Two algorithms were used. One calculated and plotted the hyperbolas for each set of "time-of-arrival-differences" for all possible pairs of hydrophones (Fig. 5). The other algorithm used a least-square method to estimate positions. Source levels are derived from the latter method. When the number of hydrophones with usable signals changed within a click series, positions were calculated using the lowest common set of usable hydrophones (usually 5).

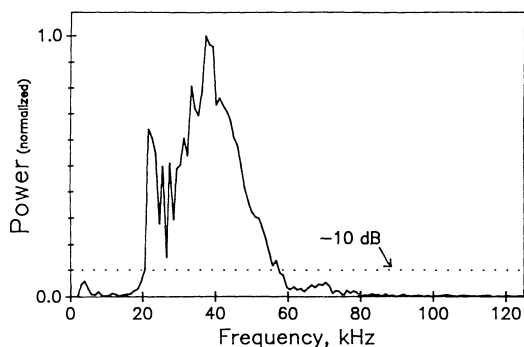


Fig. 3. Power spectrum (128 points) of a narwhal click. The oscillations are caused by the low-amplitude, trailing oscillations (see Fig. 1).

## RESULTS

The waveform of narwhal clicks is a simple, 1.5-cycle oscillation that lasts for about 50  $\mu$ s. The waveform resembles that reported for Tursiops by Au and co-workers (e.g. Au et al., 1974), using "state-of-the-art" equipment. The spectrum, however, is distinguished by having a sharp low frequency (LF) cut-off at 20 kHz, and a more variable high frequency (HF) cut-off in the 50 kHz region. While the latter appears to be influenced by directionality, the former displays a remarkable invariance throughout our recordings. Quantitatively, the spectrum resembles that of clicks from a captive beluga in San Diego Bay (Au et al, 1985). A low-frequency component at 1 to 5 kHz is often observed in low-level recordings, but never above the -10 dB level of the ultrasonic component.

The maximum SL observed for each source position is plotted in Figure 4. Within each set of click-representations, the SL varies considerably, the maximum observed difference was 28 dB. The highest SL found was 218 dB re 1  $\mu$ Pa. It occurred within a series of 17 clicks with a repetition rate of about 4 pps, and with a mean level of  $214 \pm 3$  dB re 1  $\mu$ Pa. Within some click series, maximum sonification was observed to change from one hydrophone to another, indicating a moving, directional source.

On some occasions, we recorded clicks with a high repetition rate. In a typical recording where there was no interference from other whales we recorded several clicks from a whale swimming close to the surface around 300 m from the hydrophone array (Fig. 4). The repetition rate varied around 2 Hz and the SL was 180-190 dB re 1  $\mu$ Pa. Suddenly, the whale emitted a series of about 30 clicks at a rate of 200 Hz, (resembling the buzz phase of the emissions from a bat pursuing an insect). The duration and spectrum of such a click was like that of the clicks previously described, but the amplitude was much lower (-20 dB relative to the preceding clicks). The high repetition rate and reduced amplitude was typical for all recorded buzz sequences.

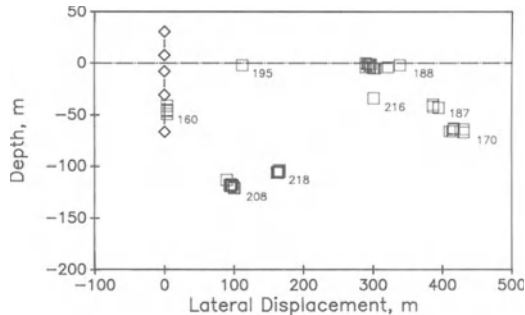


Fig. 4. Composite plot of positions of 66 click sources, probably representing 8 animals. Open diamonds: hydrophones. Open squares: source positions. Maximum measures SL in dB re 1  $\mu$ Pa is given for each position.

## DISCUSSION

The accuracy of our determinations of the 2-dimensional positioning of click sources is unknown. Many poorly known factors are involved in these determinations like the sound velocity profile, deviations from strict verticality (skewness) of the array, and the geometry of the source in relation to the skewed array. However, the use of surface-reflected clicks

effectively increased the number of sensors above the minimum of 3 required for calculation of the source position. Besides adding information about the clicks, the redundant sensors carry information about the magnitude and sign of the skewness of the array, see Fig. 5. From this information we estimate the ranging error to be less than 30%, except for sources near the axis of the array. Positions reported here are not corrected for skewness of array, as the resulting error from this source in the SL estimates is 3 dB or less.

The SL measurements are also subject to errors deriving from the non-uniform directivity of the hydrophones in the XY-plane. This error, which can be as high as 60 dB, can only reduce the value of the estimated SL.

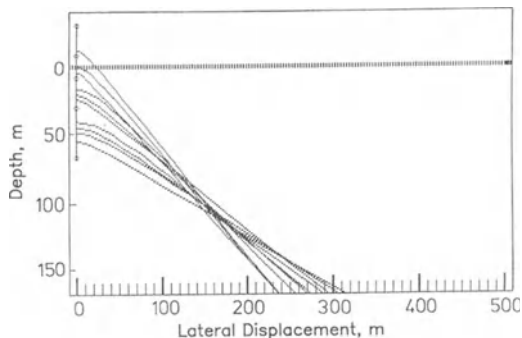


Fig. 5. Family of hyperbolas, generated from differences in time-of-arrival of a narwhal click to the hydrophones of an array. The two hydrophones above the surface symbolise virtual hydrophones, introduced to process surface reflected clicks. The de-focussing effect is caused mainly by deviation from ideal linearity of the array.

Using the envelope for time domain measures was adopted in some of the analyses because it incorporates the entire waveform, rather than just a few samples of the analog waveform, as in conventional pp-measurements. While the advantage of using the envelope function (Fig. 2) is obvious with regard to measurements of durations (and often also in time difference measurements where phase changes may cause ambiguity), it is less obvious with regard to amplitude measures. The method returns peak values, not peak-to-peak values, as traditionally used. This difference, however, is inconsequential as long as the nature of the reference is stated. However, for clicks that

are asymmetric around zero, values obtained by the envelope method are about 1 or 2 dB larger than those obtained by traditional pp-measures. In our opinion, the method is useful by eliminating a number of minor error sources, while still retaining a general compatibility with peak measuring methods. Further, the envelope method presents the salient temporal and amplitude data in a simpler manner relative to that of the 'raw' waveform.

The vertical hydrophone arrays proved possible to operate from small boats, but methods to estimate skewness should be used when greater accuracies are required. Surface reflections were found valuable to estimate the size and sign of the errors in position determinations.

The spectra and waveforms of the narwhal clicks in our recordings differ from previously reported values (Watkins et al., 1971; Ford and Fisher, 1978) by having all significant energy confined to the ultrasonic range and by having durations of about 50  $\mu$ s. The differences seem well-explained by differences in instrumentation, which in the previous works was limited to audio frequencies. Energy may well be present in the narwhal clicks above our limit of 100 kHz.

With the conventions adopted here, the time-bandwidth-product of the narwhal pulse is 1.75 (50  $\mu$ s \* 35 kHz). If the -3 dB values are used, the product reduces to about 1. The low value for the time-bandwidth-product indicates a signal achieving a maximum concentration in the time/frequency space. Theoretically, such signals yield the best possible signal-to-noise ratio for echoes to be detected by a sonar limited by broad band noise (Wiersma, 1988). Also, increased resolution in time difference measurements using cross-correlation is not possible with this kind of signal.

From the observed depths, we assume that some of the animals were feeding, rather than just travelling. Our admittedly limited data set contains no indications of a depth-related effect on the waveform of the clicks. Still, the observation of very intense SL's at depths of about 100 m may have some relevance with regard to speculations about the sound generation mechanism. Here, the ambient pressure is increased by a factor of 10. If a cavitation mechanism is hypothesized, it should include means of dealing with large variations in hydrostatic pressure.

We want to emphasize that a SL of 218 dB re 1  $\mu$ Pa represents an acoustic intensity of about  $\frac{1}{2}$  W/cm<sup>2</sup>, corresponding to a level in air of 156 dB SPL. To our knowledge, this is the most intense sound recorded so far from an animal in nature. And yet, our conditions do not insure that we have sampled the maximum capacity of the narwhal. However, the maximum SL's observed are similar to the most intense ones measured experimentally on trained, captive dolphins. While our results thus meet the objection against the hypothesis of acoustical debilitation by odontocetes, namely that high intensity pulses have not been observed in nature, they certainly are not evidence that the clicks served such purposes, neither do other parameters in the analysed sequences suggest such a function. Rather, our results imply that no major evolutionary step is required to bridge the

gap between the source levels observed during feeding and those necessary for prey debilitation.

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