

INVESTIGATIONS ON CETACEAN SONAR V. THE TRUE NATURE OF THE SONAR SOUND OF *CEPHALORHYNCHUS COMMERSONII*

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Summary

High-grade echolocation signals from captive *Cephalorhynchus commersonii* (Commerson's dolphin) are described. This type of sonar is yet another example of a dolphin signal that, like *Phocoena phocoena*, contains a narrowbanded high-frequency component. Sustained, long sequences of clicks indicate a remarkably consistent wave shape and dominant frequency of 125 kHz with pulse-repetition rate up to 500-600 Hz, one of the highest figures reported in literature.

Although a similarity with *Phocoena* signals was to be anticipated on the basis of anatomy, the wave shape actually shows more affinity to the high-frequency component of Beluga sonar. Moreover, no low-frequency could be detected over an amplitude range of 41.5 dB.

Introduction

From several standpoints it would appear to be advantageous to use a frequency-domain representation of echolocation signals.

Acoustical analysis of sonar systems shows that the frequency concept as a classic method permits a concise description of the spectrum involved. Furthermore, there is evidence that dolphins make a frequency analysis in their hearing (REYSENBACH DE HAAN, 1957) as do human beings in the case of hearing involving speech.

One should, however, bear in mind that analysing sonar signals in terms of a frequency spectrum is not always necessarily an analysis technique that reflects the features that make a sonar signal biologically adequate. The fact that frequencies up to 265 kHz have been recorded in the clicks of, for example, *Steno bredanensis* (NORRIS c.s., 1967) does not mean that the dolphin makes use of his entire frequency spectrum.

In terms of a frequency-domain interpretation we observe that in the spectrum of most odontocete sonar the signal energy is concentrated in one or two relatively narrow frequency bands, sometimes designated as the dominant frequencies.

This paper deals with a detailed description of the echolocating signals of the delphinid *Cephalorhynchus commersonii* (GRAY, 1846), belonging to a genus comprising also three other species (*C. heavisidii*, *C. eutropia* and *C. hectori*). Descriptions of *Cephalorhynchus* species, in particular those of the acoustic behaviour, are still few and far between. It is therefore heartening to note that subsequent to the publications of WATKINS et al. (1977) and WATKINS and SCHEVILL (1980), more adequate and in depth studies are being made available, although they unfortunately focus on the behaviour of only one species, *C. commersonii* in captivity. We note the recent appearance of a chapter on sounds of *C. commersonii* by SHOCHI et al. (1982), which followed on the heels of a paper describing sounds of the same population living since 1980 at the Duisburg Zoo (KAMMINGA and WIERSMA, 1981).

To further a broad study of the process and methodology of sonar signal analysis, it is necessary to obtain more detailed insight into the peculiarities of the acoustics of *C. commersonii*. To that end, a concise description is given of the frequency spectrum of Commerson's dolphin in the range from 1000 Hz - 200 kHz. The energy-density spectrum is not studied on the usual linear scale, but on a logarithmic scale to facilitate information gathering about the dynamics of various frequency components.

The frequency scale is described in terms of the usual linear constant bandwidth as well as in a so-called constant Q-version involving a constant relative bandwidth resolution of 23.15% (1/3 octave).

As in the analysis of speech signals one is tempted to take into account the frequency analysis by the human ear, which nearly conforms to a 1/3 octave bandpass filtering with 24 bands that cover the audible spectrum. In the same way *Tusiops* turns out to have an estimated number of 40 bandpass filters for the audible spectral range (JOHNSON, 1968), although direct measurements are not yet available. In order to deal with the rather narrow bandwidth character of dolphin sonar signals, the method of constant Q-analysis, should rather comprise constant relative bandwidths other than 1/3 octave. The decision how wide, however, demands a better knowledge of hearing in Cetacea.

Quite another viewpoint is taken when the echolocating system is conceived of as an information transmission-system that relies for effective use on dominant energies in the frequency range. The spectrum is then not a description as a whole, but a search for certain frequencies, suited to the process of detection and identification.

Experimental method

The recording of the sonar sounds was carried out by means of a hydrophone assembly, consisting of a Bruel & Kjaer type 8101 and a type 8103.

As the dolphins were confronted with these unfamiliar objects for the first time, abundant sonar production was recorded with very high repetition rates. The signal-to-noise ratio was excellent, due to the fact that in this main pool at the Duisburg Zoo water circulation was temporarily shut off, so no pump noise was heard at all. The normal noise level due to water movement, splashing, etc. formed a background of more than 40 dB below the main energy in the sonar pulses. A frequency range from 200 Hz up to 150 kHz was attained by the RACAL recorder running at a speed of 30 ips. The signal-to-noise ratio of the recording system was measured over the 200 kHz bandwidth and resulted in a figure of merit of 45 dB.

Data processing

Out of a myriad of sonar signals several pulse trains were inspected at reduced playing speed. A typical pulse train was selected at random and isolated for further analysis (Fig. 1). Due to the

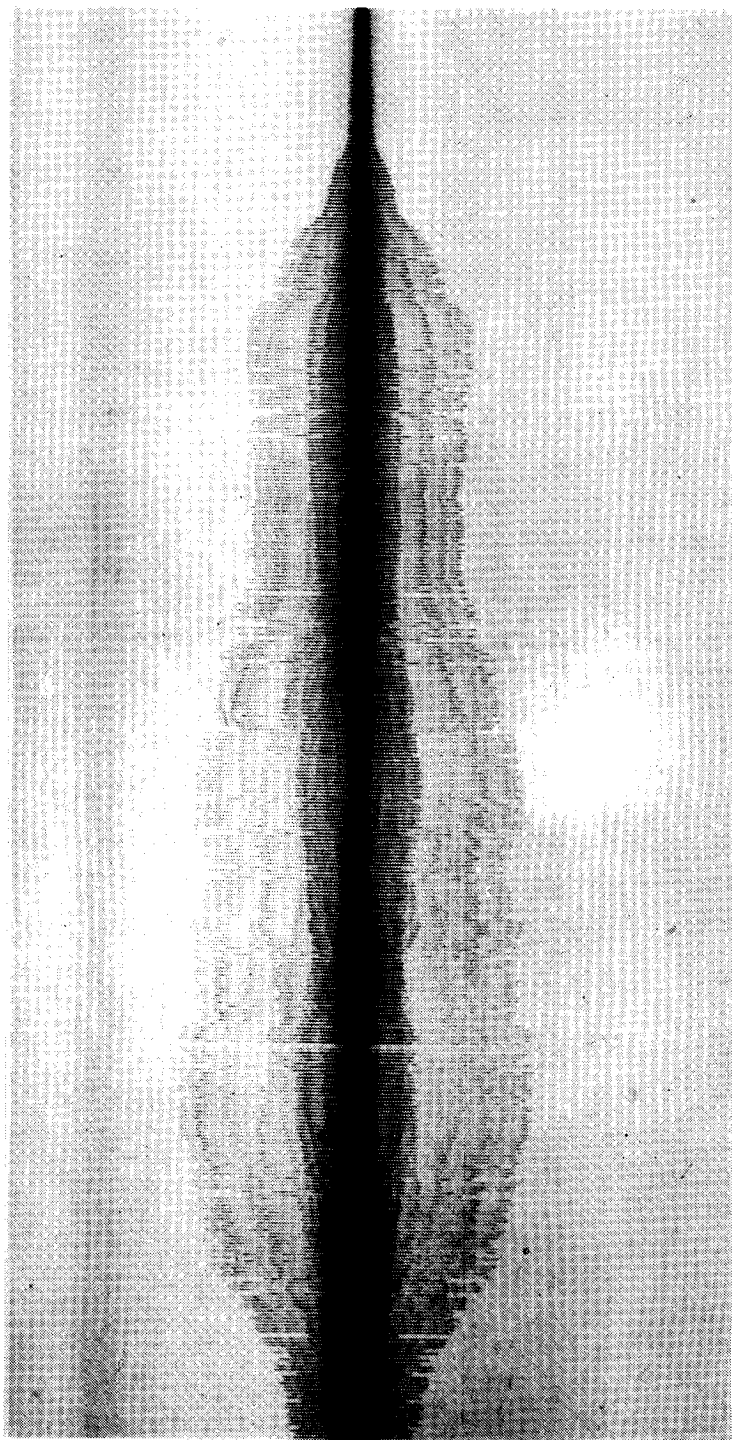


Fig. 1. Oscillogram of a typical echolocation pulse train for *Cephalorhynchus commersonii*.

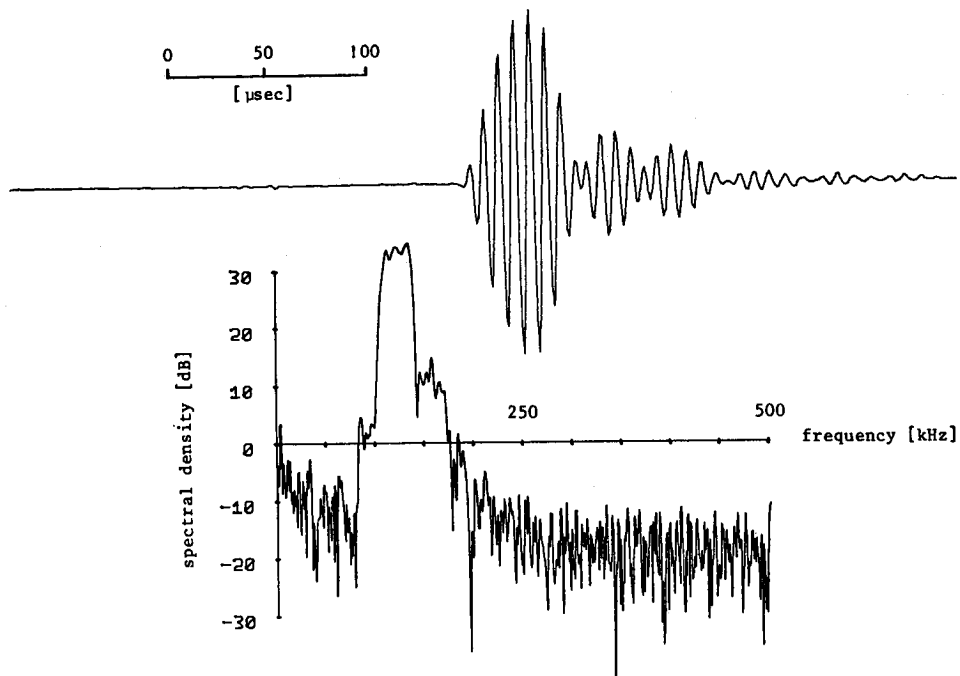


Fig. 2a. Echolocation pulse of *Cephalorhynchus commersonii* and associated frequency spectrum, showing two reverberations and the background noise.

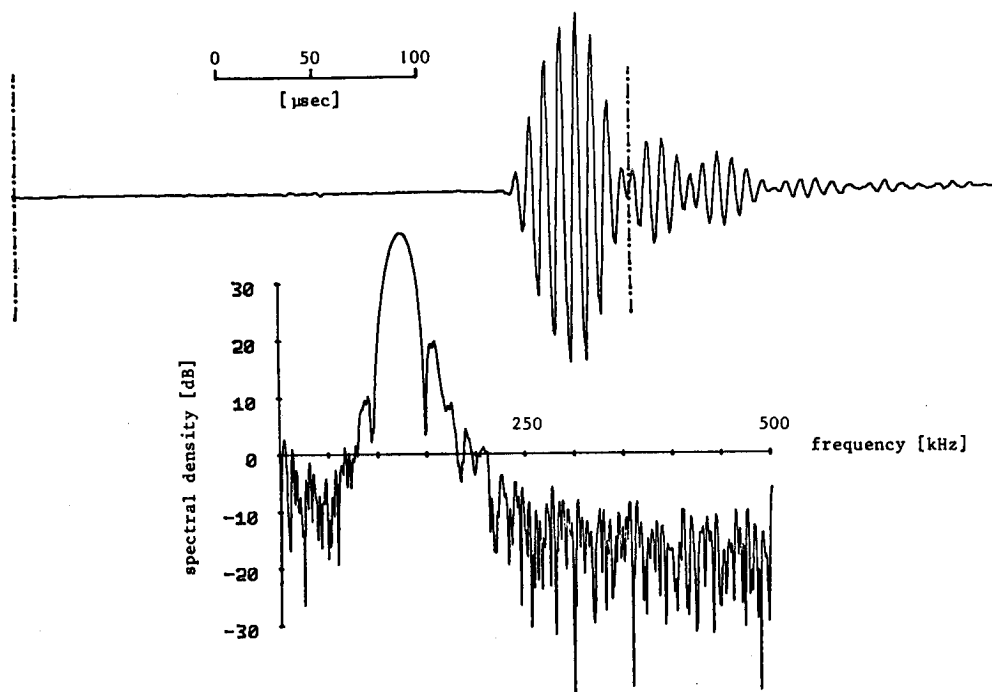


Fig. 2b. The frequency spectrum of the echolocation pulse without reverberations. Background noise preceding the pulse is included.

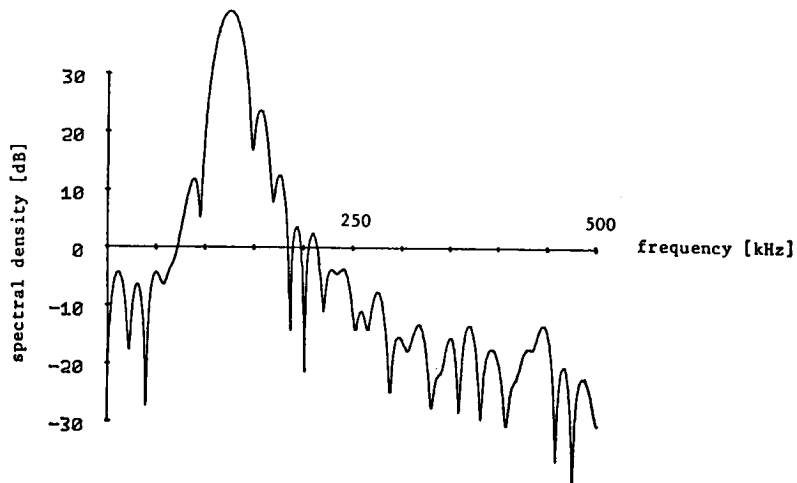


Fig. 2c. Frequency spectrum of echolocation pulse without reverberations and surrounding noise.

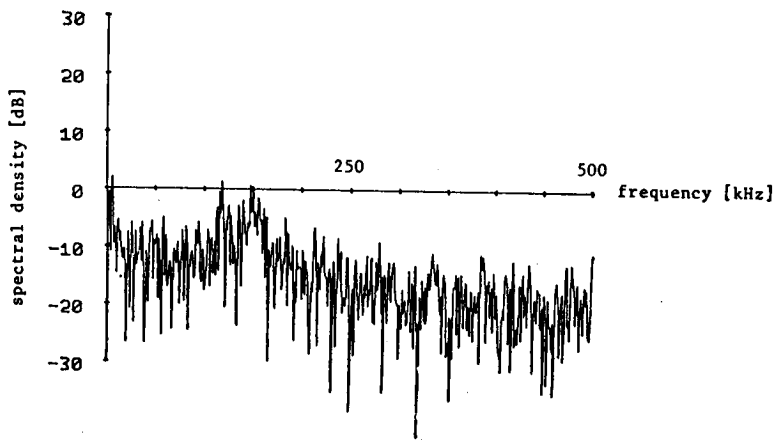


Fig. 2d. Spectral representation of the background noise.

recording method - amplitude modulation - slight variations in amplitude were noted but are in fact negligible. Fig. 2a,b,c,d presents a single pulse in its various aspects together with the background noise and the accompanying frequency spectra. Various clicks - all of them with a relevant dominant frequency of 125 kHz - were analysed in the spectral domain, all together covering a pulse train of 0.81 sec time duration.

The spectral intensity was studied on a logarithmic frequency scale and the spectrum by a constant-Q analysis; the frequency scale was then segmented into 1/3 octaves by means of a bandpass filter bank (General Radio type 1925), as we have no Fast Fourier Transform available for a constant relative bandwidth.

Following the 1/3 octave filtering, the narrow bandwidth signals were sampled at a rate of 4 times the centre frequency of the filters to obtain a detailed image of the frequency components.

For every filter in the range 100-160 kHz the complete click train of figure 1 was then averaged to obtain an estimate of the intensity.

The Shannon sampling theorem prescribes a sampling rate of two times the bandwidth in the case of a narrow band signal. However, as we are dealing with a bandwidth that comprises 23.15% of the centre frequency with 1/3 octave bandpass filters, it is not redundant to carry out the sampling at a rate of $4 f_c$, but in fact necessary for amplitude reconstruction as well as the calculation of the intensity of the wave form.

Discussion and conclusions

For reference, a complete spectrum of a click together with background noise and reverberations is presented in Fig. 3 while the different spectral data points of the filtered click train in the range 1000 Hz - 160 kHz are presented in Fig. 4 I/II. For a better presentation of

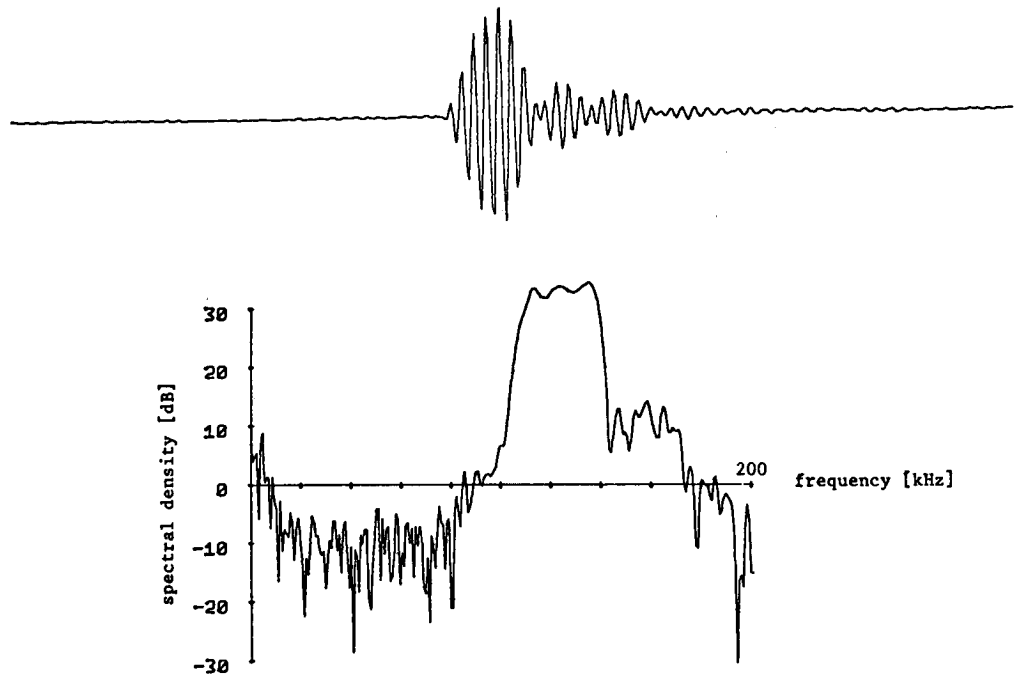


Fig. 3. Spectral density of echolocation signal and surrounding noise of *Cephalorhynchus commersonii*.

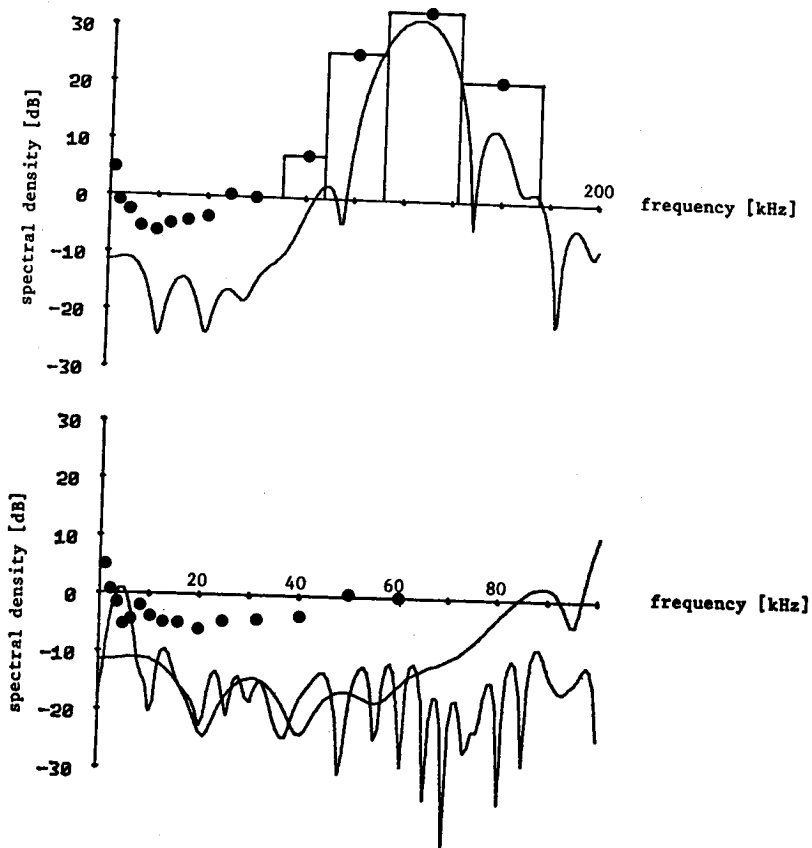


Fig. 4. Spectral density of averaged click train of *Cephalorhynchus commersonii*.

I. 1/3 octave spectrum (the dots) and FFT spectrum (the solid line)

II. 1/3 octave spectrum over the range 1-60 kHz (the dots) compared to the spectrum of background noise and sonar signal.

the frequency content the frequency scale is enlarged up to 200 kHz full scale. Using a Fourier analysis only on the main lobe of the echolocating signal, we obtain the frequency spectrum as shown in Fig. 5. This image reveals at first glance that the spectrum consists of a dominant frequency of 125 kHz, with a sub-dominant component centred at 160 kHz with a level of 20 dB below the main lobe. This is certainly not a result of looking at the time function by means of a rectangular window, but may be present for other reasons. The meaning of this component is still obscure and needs to be clarified.

Due to the fact that an anatomical comparison of the head of *C. commersonii* and *Phocoena phocoena* led ANDERSEN (1980) to expect a sonar behaviour with two components, the frequency spectrum should be inspected for the existence of components around 20 kHz, or maybe 10-30 kHz (KAMMINGA and WIERSMA, 1981).

Bearing in mind this hypothesis, we searched in the spectrum for components containing enough energy to function as a sonar signal.

To this end, we have to expand the frequency axis up to 100 kHz full scale, as shown in Fig. 4II

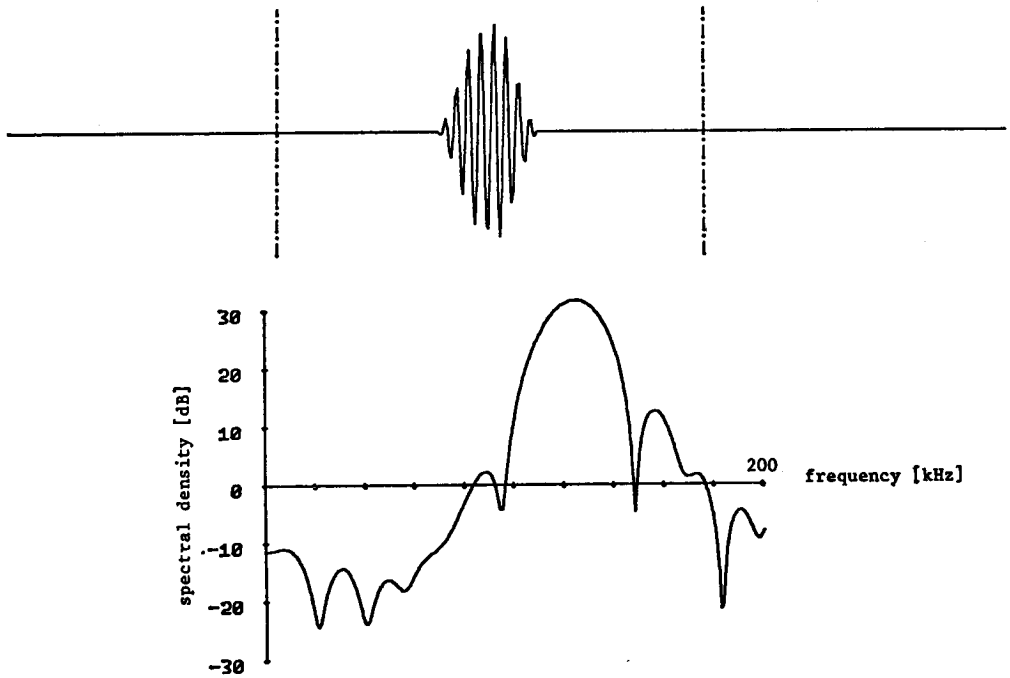


Fig. 5. Spectral density of the sonar signal without reverberations.

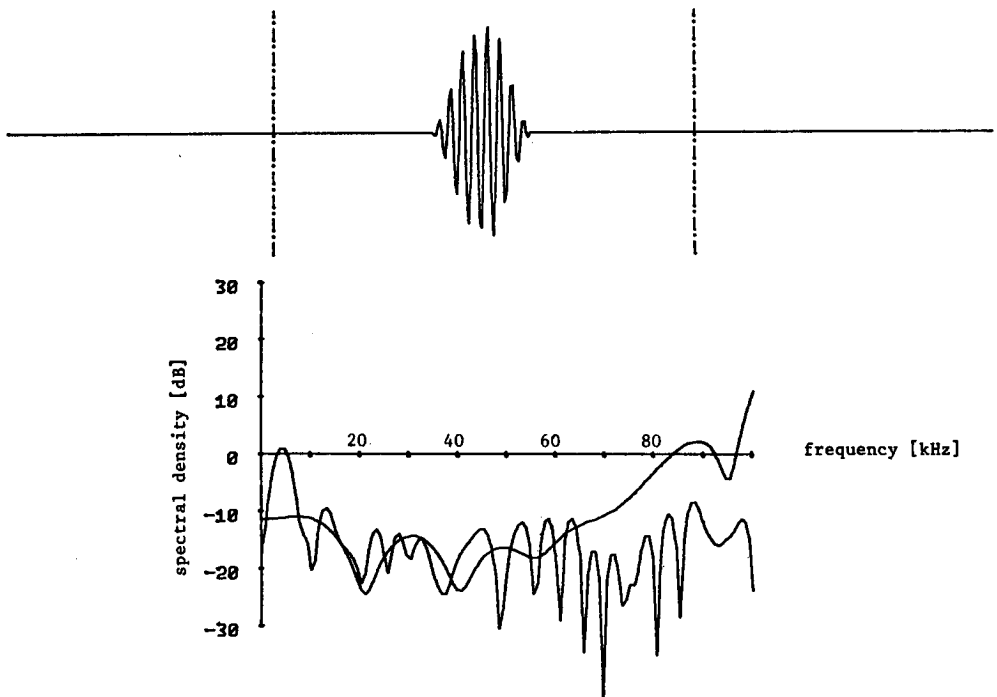


Fig. 6. Spectral density of the main lobe of the sonar signal together with the background noise in the range 1-100 kHz.

where together with the smooth line for the frequency content of the main lobe, the rather irregular spectrum of the overall background noise is presented. It can clearly be observed in this picture that up to a frequency of about 60 kHz the sonar signal is below the noise, all together at a level of some 40 dB below the maximum intensity of the dominant frequency. This level is at about the same magnitude as the signal-to-noise ratio of the sonar signal itself. This ratio was measured in a rather classical manner, i.e. the maximum instantaneous power of the main lobe of the sonar pulse was measured with regard to the noise power over a fairly large time span preceding the pulse.

This method resulted in a reproducible figure of merit of 41.5 dB, in the case of an unfiltered pulse train.

Looking back again at Fig. 3 we now conclude that the increase in spectral intensity towards lower frequencies is confusing so far as the sonar signal is concerned. This effect can be fully credited to the noise, as the frequency content of the sonar spectrum decreases toward the lower end of the frequency range, which is demonstrated by the smooth curve in Fig. 6. A statement about possible sonar frequencies in the lower regions based upon measurements on the complete pulsetrain, which includes the sonar signal, reverberations and background noise, is thus not permitted. Every component that apparently shows up in this region has to be classified as an artefact, due to the method of analysis.

As no component less than 41.5 dB below the dominant frequency of 125 kHz turned up, we are of the opinion that a biologically adequate low-frequency component in the sonar production of *C. commersonii* does not exist.

The fact that strikes the eye at once when comparing the time function of *Phocoena* sonar to that of *C. commersonii* is that the latter does not demonstrate the prominent low-frequency component of the former, which was established earlier by KAMMINGA and WIERSMA (1981, Fig. 6a).

There is another feature of note that distinguishes the wave shape (WIERSMA, 1982). *Phocoena's* sonar signal shares a basic wave shape with *Tursiops*, *Inia* and *Sotalia*. Following WIERSMA, if the total number of cycles is considered as one of the characteristic signal parameters we note for *C. commersonii* a value of $N_C = 8.2$ compared to $N_C = 4.23$ for the high-frequency component of *Phocoena*.

This figure of N_C tends to be more in agreement with $N_C = 7.42$ as measured for the high-frequency component of 60 kHz in the sonar recorded from *Delphinapterus leucas*.

Despite the higher relative bandwidth of 30%, the wave shape of the Commerson's signal indicates a strong similarity with the sonar from Beluga (Fig. 7), and could be included in the same category.

The visual comparison of the remarkably constant wave form of Commerson's sonar to the high-frequency component of Beluga, as presented in Fig. 7, is left to the reader.

In the behavioural situations in which the animal was confronted with strange objects or fish, and was thus on the alert, a remarkable high and persistent pulse repetition rate was present, sometimes with slight modulations around a figure of some 500-600 Hz. There is, of course, strong evidence that the animal is able to increase its pulse rate when approaching or pursuing a target as a result of diminishing distance.

However, there might be another reason to explain the occurrence of this observed high repetition rate. Recent observations in the field of time difference perception with regard to human binaural hearing attribute the increase in the threshold for localisation to other phenomena. A psychophysical experiment (HAFTER and DYE, 1983) denotes some interesting results for stimuli other than sinoids. When a click train with a varying click rate was used as a stimulus, the auditory threshold versus the log (number of clicks) produced a linearly decreasing relation.

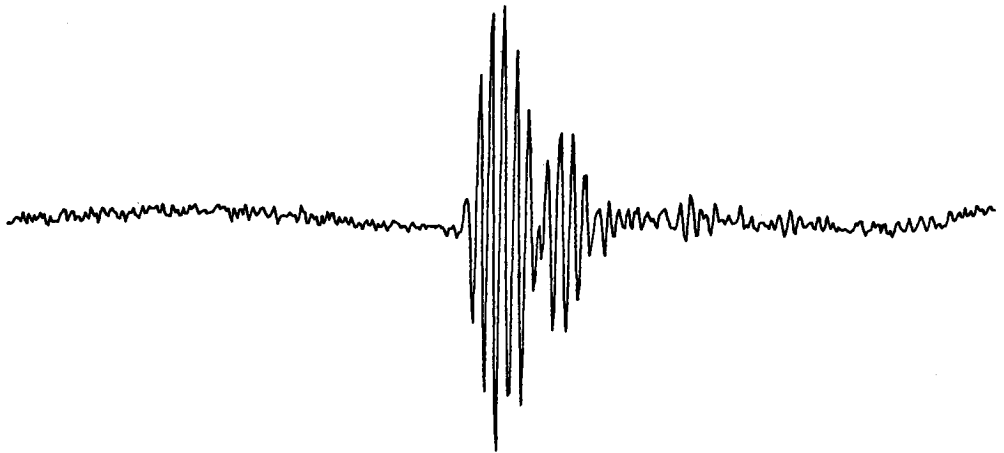


Fig. 7. High-frequency component of an echolocation wave form of *Delphinapterus leucas*.

A high click rate could thus be used by an animal for reasons other than decreasing target distance.

If we extrapolate this result to hearing in dolphins such as *Phocoena* and *Cephalorhynchus*, a high click rate could be used to augment the acuity of binaural hearing, i.e. localisation will be more accurate.

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