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Investigations on Cetacean Sonar IX

Remarks on dominant sonar frequencies from *Tursiops truncatus*

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Abstract

A large collection of underwater sounds (sonar clicks) from six specimens of *Tursiops truncatus* have been investigated with regard to their behaviour in dominant frequency. The recordings include not only the Atlantic and Pacific Tursiops in captivity, but also include the sonar sound of free-ranging wild *T. truncatus* from the Atlantic.

Applying a parametric description of the sonar waveform, following the GABOR-model, a cluster representation of the two highest-ranking features of the sonar signal is given to illustrate the acoustic behaviour. Dominant frequencies for the whole signal collection range from a lower 40 kHz to up to 80 kHz. Up to a certain level, separate clusters are distinguishable. The ellipsoid cluster for all the data in the scatter plot indicates for the dominant frequency a tendency towards a linear relationship based on the concept of constant relative bandwidth. This phenomenon is closely related to the observed functioning of the peripheral auditory systems of delphinids and humans.

Key words: bio sonar, echolocation, underwater sound, Tursiops truncatus.

Introduction

Although the use of voluntarily produced clicks such as echolocation signals in many odontocetes has been described at length (Norris, 1969; Evans, 1973; Busnel & Fish, 1980) there is still no complete agreement on the underlying wave shape model that generalizes a description of the active acoustic behaviour.

A noticeable difference in the characteristics of echolocation signals is also emphasized in most papers describing acoustic behaviour and is due to species variety, nature of the echolocation task, acoustic environment and captive versus wild behaviour (Au *et al.*, 1985; Thomas *et al.*, 1988).

It is the aim of this paper to present a detailed look into the wave shape parameters of sonar clicks of *T. truncatus* on the basis of a well-proven, simple model. The echolocation clicks obtained from 6 specimens of *T. truncatus* are compiled and depicted using a clustering method in a scatter plot. Only those sonar recordings that are believed to be used for echolocation, with the best achievable signal-to-noise ratio in well-controlled, reproducible situations are of interest here.

Click trains were obtained not only from captive animals in a restricted environment such as a dolphinarium, but also from animals in semi-captivity, i.e. open waters in a bay adjacent to oceanic waters and from a free-ranging, wild, Atlantic Tursiops. Finally, a plot of dominant sonar frequency versus bandwidth will be presented. This choice of possible parameters for describing a sonar click is not arbitrarily made, as will be discussed below. The mechanism involved in the discrimination of signals in noise, which is a most normal behavioural situation for an echolocating dolphin, is based on the concept of critical bandwidth (Scharf, 1970; Johnson and McManus, 1988). Auditory masking experiments have indicated that human and cetacean hearing systems function in a manner analogous to a series of band-pass filters with bandwidths that increase approximately in proportion to the centre frequency. Each filter passes only those signals within its own frequency range and eliminates noise outside the pass band and will thus give a better signal-to-noise ratio.

The critical bandwidth concept also indicates that for an efficient sonar signal the animal has no need to emit a broad band frequency range, when critical bandwidth matches the signal width.

The two signal parameters, dominant frequency and accompanying bandwidth, are thus the features that will be our primary interest.

Underwater sounds for echolocation have been recorded at length over a period going back for more than 25 years. It is interesting to look back over this period in a rather contemplative way to get an idea of how echolocation clicks are described. From a perusal of the literature, partly historical, a sample of the descriptions is given below, covering a time span up to 1988.

A DOLPHIN ECHOLOCATION CLICK IS:

..... more or less a white noise (1)
1966 Dudok van Heel (Whales, dolphins and porpoises, p. 601)

..... a short duration transient (10–200 μsec) (2)
1973 Diercks, Trochta, Evans (J. A. S. A. 54, p. 200)

..... a simple exponential pressure pulse with broad band energies, sometimes a very short transient (3)
1974 Watkins (J. A. S. A. 55, p. 850)

..... a linear period-modulated signal (4)
1975 Altes (J. A. S. A. 57, p. 1222)

..... a short, broadband, rapid rise-time pulse (5)
1980 Watkins (Animal Sonar Systems, p. 293)

..... varying greatly in length, frequency content, intensity and directionality (6)
1986 Johnson (Dolphin Cognition & Behavior p. 129)

..... a short transient broadband signal, in the time domain an exponentially damped sine wave of 6–8 cycles (7)
1988 Au (J. A. S. A. 83, p. 662)

We will start a few years after Norris *et al.* (1961) confirmed without doubt the echolocation capability of Tursiops.

It is the first definition that probably shows how we have deepened our insights in the course of time. However, from the viewpoint of communication theory, it is possible that a burst of white noise (with a fairly large bandwidth) is used as an echolocation signal. The presence of low and high frequencies in the pulse burst are then suggested to have functional significance in obtaining long-distance range information as well as nearby information in one signal.

Surprisingly, a modified version of this hypothesis turned out to be present in the two component sonar of *Ph. phocoena*, as was pointed out by Kamminga *et al.* (1981). The second description, as well as (3), (5) and (7) have in common the concept of the short transient in the time domain. It is not surprising that a closer look at the sonar click leaves the observer with an impression of a phenomenon with an abrupt onset, a fast rise time. But then we have to bear in mind that we are dealing with a biological sound pulse generator, and not confuse it with an electronic pulse generator. It is perhaps this idea that leads to the frequent misconception that an echolocation click is a broadband signal. A true transient signal as we understand it in physics, has indeed a broad frequency width, ranging from low to high frequencies. Observing spectra from delphinid clicks rather gives us the impression that the frequency content of the spectrum goes up to high frequencies, but there is always a preference for a dominant spectral component. We then arrive at the question: what is broadband? and vice versa, what is narrow band? Both expressions are commonly used in communication theory. Speaking specifically about bandwidth, we have to indicate where the bandwidth is situated along the frequency scale, i.e. we introduce, in fact, the concept of relative bandwidth (see Figs 3 and 4). These figures express the ratio of bandwidth and centre frequency.

Description (4) does not seem to fit very well in the list. Following Altes *et al.*, this behaviour of the sonar click as a function of time is characterized by a linear increase in the zero crossing interval and is based on observations of the *Ph. phocoena* clicks and the clicks of Tursiops spp from Dziedzic recorded in 1970.

This form of modulation should indicate a non-linear phase behaviour during the click, which is never confirmed by the authors, neither for *T. truncatus*, nor for the 6–8 cycled waveform of *Cephalorhynchus commersonii*. In the following part of the paper a description of several Tursiops clicks, recorded over the past 10 years will be given. A comparison with the descriptions of clicks cited above is left to the interested reader.

Materials and Methods

The typical examples of sonar clicks from *T. truncatus* presented in Figure 1 are random samples from a collection of a total of 343 clicks, which are in their turn a random selection from a large number of click trains. Unless sonar recordings are made during a carefully controlled (echolocation) experiment using a suitable, fixed-measuring setup, a preselection procedure has to be carried out to sort out those types of pulse trains that are not too disrupted by noise and spurious reflections.

This procedure will be possible if there is enough precise knowledge available of the position and direction of the dolphin with respect to the hydrophone. In the case of the recordings of a wild dolphin, we have to face these two major problems: distance to the hydrophone and the directionality of the emitted sonar beam. As our recordings at sea were carried out by a diver, who was holding the hydrophone, we had precise knowledge of the direction in which the dolphin was pointing in relation to the hydrophone. Among all the sonar clicks presented and discussed in this paper, the clicks of the wild dolphin are among the finest we have ever recorded.

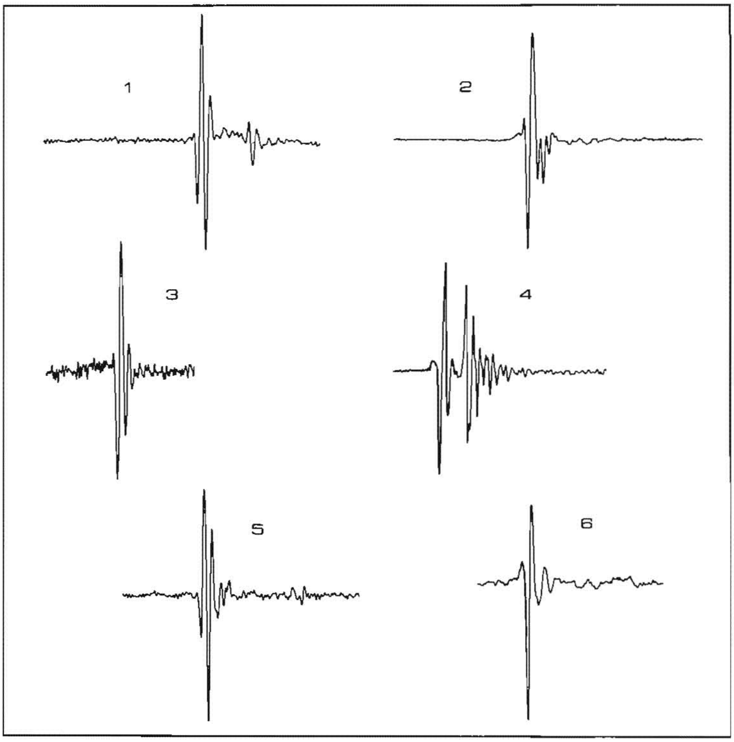

Figure 1. Typical wave forms sonar clicks from *Tursiops truncatus*
1). Sonar pulse from a wild, free ranging dolphin (JEANNE LOUISE) off the coast of Brittany, France. Dominant frequency 80 kHz.
2). Sonar pulse from HEPTUNA, recorded at the N.O.S.C. (Hawaii). Dominant frequency 67 kHz.
3). Sonar pulse from HENRY, born in captivity at the N.O.S.C. Recorded in open water. Dominant frequency 80 kHz.
4). Sonar pulse from SKINNY, echolocating for sinking plexiglass rings. Dominant frequency 49 kHz.
5). Sonar pulse from DORIS during a threshold experiment. Dominant frequency 55 kHz.
6). Sonar pulse from ILIAS, echolocating for fish. Dominant frequency 44 kHz.
All clicks are represented on a normalized time scale for case comparison in wave-shape behaviour in the time domain.

A final remark about the examples given in Figure 1: As we have noted over the years studying sonar click trains, there is always a more or less distinguishable interference, due to reverberations, with the actual sonar signal, which results sometimes in a considerable wave shape alteration during the complete pulse train or even in a single pulse. Referring to click (2) in Figure 1, this effect is clearly visible in the second oscillation. For this reason it is clear that the method of averaging all the pulses in a pulse train is not the most plausible method. (Kamminga, 1985).

Standard recording equipment was used during our recording sessions. It consisted of Bruel & Kjaer hydrophones 8101, 8103, 8104, amplifiers 2608, 2610, 2635 and a Racal $\frac{1}{2}$ inch instrumentation recorder, covering a frequency range up to at least 150 kHz. Only click 5 was recorded in a different way, by means of a LC10 hydrophone, mounted in a suction cup on the tip of the rostrum of the dolphin.

Processing of the analogue tapes was done by a 12 bit A to D conversion at a sampling frequency of 500–800 kHz. The spectral analysis was carried out by a normal FFT-procedure on a number of data points covering the echolocation click without including noticeable reverberations.

A few notes on this method of spectral analysis will be given in the following paragraph.

A closer look at the echolocation click in Figure 2 reveals that the envelope of the click shows a definite dip after the first part of the click. This point is

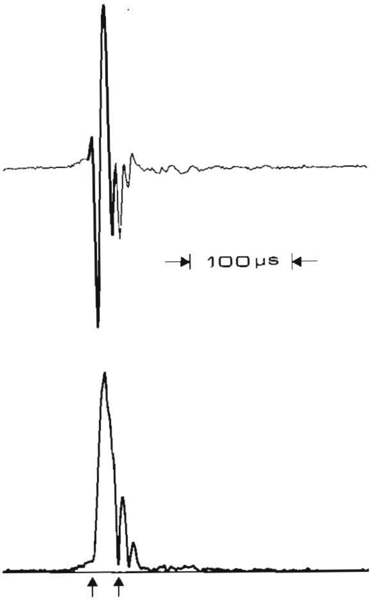

Figure 2. Sonar click No. 2 from Figure 1. Main part of the click is indicated by the click line in the upper half. Lower part presents the envelope of the click. Arrows indicating the beginning and the first dip establish the main part of the click.

indicating where reverberations, possibly due to reflections inside the dolphin's head, against the skull or air sacs, interfere with the actual first-emitted sonar signal. If we conceive this second part to be of minor significance because the energy contained there represents only a little, up to 15%, and consequently does not have a substantial function in the echolocation process, we should truncate the time function at this point. Whether the tail of the recorded click may or may not be part of the echolocation click, then, the question as to or not to include this part in the analysis window, had already been posed by Diercks *et al.* (1973). It seems that this phenomenon has not been as much in the public eye as it deserves. In the opinion of the authors the answer is given by observing the envelope of the wave form. Further calculations and model forming in this paper will be based on the first, undistorted part of the recorded signal. This main part is indicated by the thick line in the graph, corresponds with the beginning of the envelope and ends at the first dip. If we were able to display a flip book of the complete pulse train, we would be left with an image of a fairly stable main part of the click, followed by a rather arbitrarily fluctuating segment, caused by reverberations.

If we now follow the definitions for time duration and frequency bandwidth given in Wiersma (1982), putting $\Delta t = 2\pi\,\sigma_t$ and $\Delta f = 2\sigma_f$ with σ_t and σ_f being used analogously as in statistics, then the wave form within the first part of the envelope exhibits a time-duration-bandwidth product which approaches the value 1 within 20%. The fact that the product Δt times Δf approaches this theoretical lower band, justifies the application of the parametric description of the click wave form in terms of the well-known Gabor representation (Gabor, 1947).

In an analytical form we can write down this expression as follows:

$$f(t) = e^{-\frac{\pi^2}{\Delta t^2}(t - t_0)^2} \cos\left(2\pi f_0 (t - t_0) + \varphi\right)$$

t_0 = mid epoch of the time function
f_0 = dominant frequency
φ = phase of f_0 within the envelope

Our main objective being the behaviour of dominant frequency f_0 for a large collection of Tursiops data, we will apply a simple clustering method to obtain a scatter plot for f_0 versus Δf.

Experimental results

Our collection of data presented in figures 3 and 4 contains of a total of 343 clicks, built up of 13 individual clusters, which partly overlap each other. Each individual cluster represents a sample from a click train.

The ellipsoid boundaries are determined by calculating the standard deviation along and perpendicular to the regression line through the data points.

Looking at the available individual clusters as they are presented in Figure 3, we will review the origins of the data.

The two clusters, indicated as JL, originated from the recordings of lonely JEANNE LOUISE, a 3.5 m large, female Tursiops. She is the social dolphin along the coast of Brittany, France and has been a well-known phenomenon for a period of more than 10 years. Recordings were made with an 8101 B&K hydrophone on 15 August 1985 and on 2 July 1986. This animal is the one with the most impressive $\Delta t.\Delta f$ figure of merit of 1.03 and an average dominant frequency of about 80 kHz. Two clusters HPT come from HEPTUNA, a highly experienced, 18 year old echolocator at N.O.S.C., Kailua, Hawaii. Data were gathered from runs during a target present/target absent echolocation experiment, which was recorded by Whitlow Au, Patrick Moore and Cees Kamminga on 9 September 1985. Recording hydrophone: B&K 8103.

The three clusters HRY were also obtained from a N.O.S.C. dolphin, named HENRY, who was born in captivity. The animal was echolocating in a target present/target absent situation. Both HEPTUNA and HENRY were echolocating in an open water

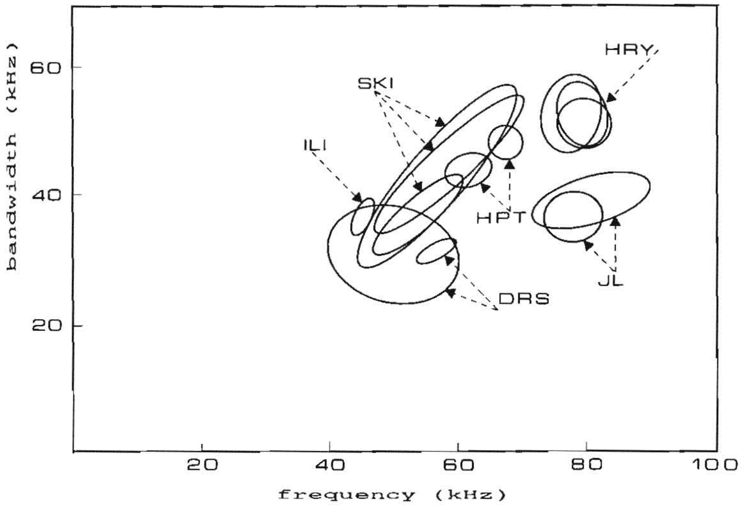

Figure 3. Individual cluster boundaries of sonar clicks from a collection of pulse trains for the different specimens of *T. truncatus*. Ellipsoid boundaries were obtained from rms values using a regression method. For abbreviations, see text.

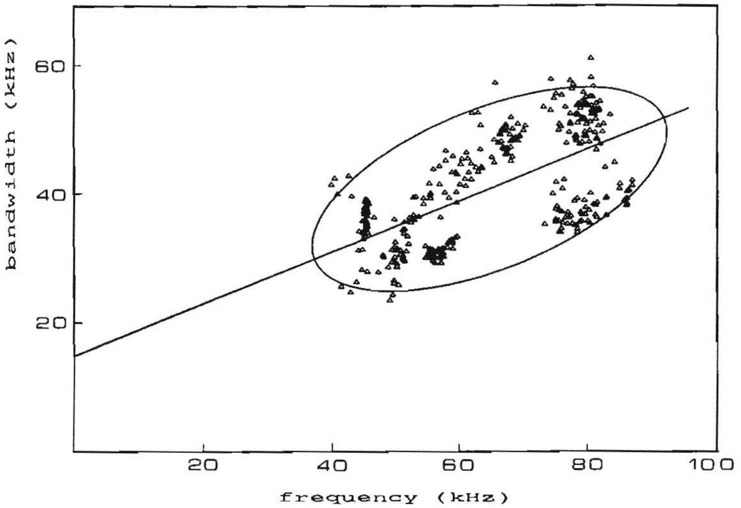

Figure 4. An overview of the representation of the dimensions dominant frequency and bandwidth of 343 sonar signals from 6 *Tursiops truncatus*. The regression line indicates the linear relation between the wave forms with different dominant frequencies, ranging for about one octave.

environment with a fairly high background noise level of 55dB SPL, mainly due to snapping shrimp. Recordings took place on 9 September 1985. Recording hydrophone: B&K 8103.

Three elongated clusters SKI were collected from an offshore Atlantic Tursiops which had been in captivity for several years and is experienced in echolocation. Data were taken from the animal when, blindfolded, it was searching to retrieve slowly sinking, plexiglass rings. Recordings were taken on 13 January 81 with a B&K 8104 hydrophone. The spectrum spans a frequency range of 45–65 kHz.

Cluster ILI was recorded from a 15 years old male Tursiops from the Gulf of Mexico in captivity since 1982. The recording hydrophone was a B&K 8104

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