

## Investigations on cetacean sonar VII

### Underwater sounds of *Neophocaena phocaenoides* of the Japanese coastal population

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#### Summary

This paper describes the sonar sounds from four captive *Neophocaena*, two males and two females, which were tape recorded and processed with regard to their behaviour in the time and in the frequency domain. The echolocation-type pulses produced by the animals fall into two categories, with dominant frequencies of 128 kHz. The time duration of the typical waveforms ranges from 40 to 80  $\mu$ sec with a number of cycles of 5 to 10. A qualitative inspection of the overall wave shapes shows a remarkable similarity to signal types from *Ph. phocoena* and *C. commersonii*. *Neophocaena* sonar turns out to be another example of an optimal signal in a time-frequency duration with a figure only 15% above the theoretical lower bound of 1. Clear differences in reverberational aspects of different sonar pulses were noted, possibly indicating individual features. No frequency modulation was detected, as the low-valued uncertainty product indicates. There was no indication of any whistle activity pattern during the recording period.

**KEY WORDS:** sonar, echolocation, *Phocoenidae*, underwater sound.

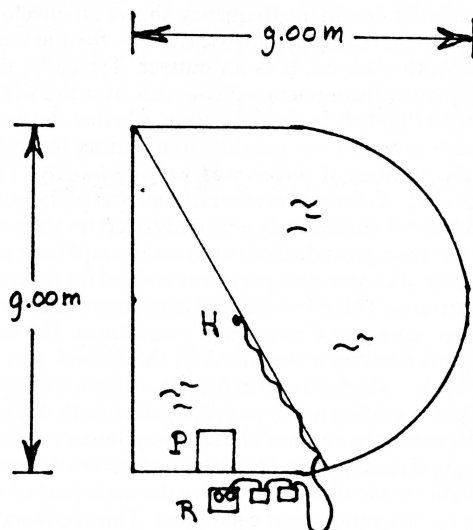
#### Introduction

As far as the present knowledge of descriptions of underwater sounds from *Neophocaena phocaenoides* is concerned it seems that the first reports were given by Mizue *et al.* (1968) about vocalizations of some captive species held in dolphinarium in Japan. The

species studied inhabits the coastal waters of Japan. In that report it was shown that this dolphin uses click trains as underwater sounds. Unfortunately, however, the information presented relied on recordings with a system limited in response above 20 kHz. Since that time it has been established that odontocete sonar sound could range up to some 150 kHz. This is especially the case with sonar sounds from the *Phocoenidae* family, as was shown by Møhl and Andersen (1973) and Kamminga *et al.* (1981). To this end we used for our recordings a bandwidth of 150 kHz with an accompanying signal-to-noise ratio of 42 dB. This a priori information from our earlier studies turned out to be a justified prediction, as is shown by our results. Data were recorded during free swimming in a tank, while the attention of the animals was attracted by a miniature hydrophone. This article deals with the first extensive description of the sonar sounds from a group of four *N. phocaenoides* in captivity at the Toba Aquarium in Japan. As far as could be traced in the open literature, up till now no indication has been given of the detailed nature of the underwater sounds produced by *N. phocaenoides*.

#### Subjects and behaviour

The Finless Porpoise is a small porpoise; its length averages 1.4 to 1.5 m, with a maximum of 1.92 m (Kataoka *et al.*, 1969). The Finless Porpoise is found in shallow, muddy estuaries in the north Indian Ocean (from Iran to Indonesia), in the China Sea and



**Figure 1.** *Neophocaena* pool in Toba Aquarium (9 × 9 × 5 m)  
H = hydrophone attached to a rope, approx. 1 m above water level, R = recorder, P = feeding platform.

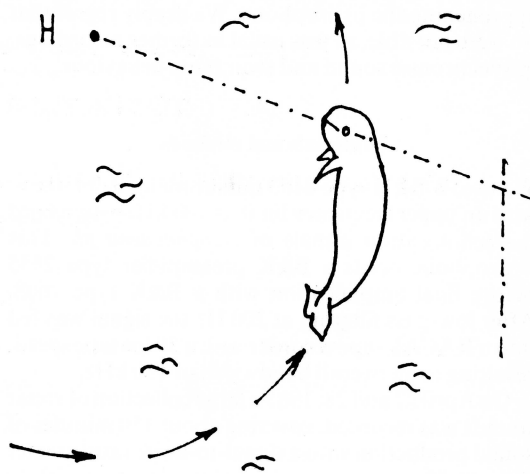
along the coast of Korea and Japan. This species is also known as a fresh water inhabitant. The Toba porpoises have been collected in Ise Bay, north of Toba.

The Finless Porpoise is surprisingly quick and lively animal, swimming just beneath the surface with sudden, darting or circular movements (Watson, 1985). The figures shown in Izawa and Kataoka (1965), a paper dealing with, amongst others, 'Ecological observations of the Finless Black Porpoise', show the great flexibility of the body of this species.

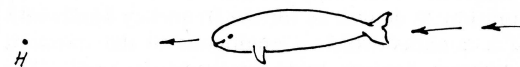
The Finless Porpoises studied in Toba Aquarium were housed in a more or less circular pool with a diameter of 9 metres and a depth of 5 metres (Fig. 1).

All animals, the two small young ones as well as the two big ones, appeared to be swift swimmers. The underwater visibility in the pool was limited. Due to this factor as well as the liveliness of the animals it was not possible for us to identify the porpoises individually during recording sessions.

With the 8103 hydrophone underwater a very specific swimming behaviour, at times that scanning was supposed to be performed, could be observed. Apart from the 'straight-in approaches', *Neophocaena* often swim around the hydrophone in a circle, most of the time completed about halfway. The distance to the hydrophone averages 1.5 to 2 metres. During this manoeuvre the porpoise is in level with the hydrophone and is swimming on its side with its belly directed towards the hydrophone. Its head is bent 'downwards'; the estimated angle between head-axis and body-axis is 120° (Fig. 2).



**Figure 2.** *Neophocaena* swimming around the hydrophone, as seen from above, while 'sonar scanning'. Angle between head-axis and body-axis is approx. 120°. Distance head to hydrophone is approx. 1.50 m. H = 8103 hydrophone.



**Figure 3.** *Neophocaena*, straight-in approach. H = 8103 hydrophone.

On one occasion it was observed that the head was bent further downwards; it appeared as if the animal was looking or scanning back at the hydrophone, when it was already past the hydrophone. The animal was also swimming on its side. This very peculiar swimming-behaviour-while-scanning has been observed by the first author in another dolphin, namely the Irrawadi dolphin from the river population, during studies at the Oceanarium in Jakarta, Indonesia (Kamminga *et al.*, 1983). In addition to the swimming and scanning on its side, scanning during straight-in approaches was also seen (Fig. 3). In what way the swimming behaviour is the result of the restricted diameter and shape of the pool is not known. Echolocation recording in the other Toba pool, which is rectangular, and observation in open sea (or Ise Bay) might add more information.

The still photography carried out on the high-speed Fujichrome 1600 slide-film did not reveal details of the swimming behaviour described, but left us with a general impression. Monitoring with an underwater video-camera during recording sessions will be necessary in order to obtain more details of the swimming behaviour of *Neophocaena* while

approaching the hydrophone. We deeply regret that we were not able, as was usual in former recordings, to synchronise sound and swimming behaviour.

### Materials and methods

We used a B&K type 8103 miniature hydrophone—with an upper frequency limit of 200 kHz—to record the echolocation signals of *Neophocaena ph.* This hydrophone needs a B&K preamplifier type 2635 before final amplification with a B&K type 2608. After low-pass filtering at 200 Hz the signal was fed into a RACAL tape recorder with a 30 ips tape speed, resulting in an overall bandwidth of 150 kHz.

On April 27 and 28, 1985 a large collection of sonar sounds was recorded, covering about 150 minutes of sound production with a signal-to-noise ratio greater than 40 dB.

To compete with the limited speed of the A/D conversion needed for the computer processing, the recorded signals were played back at reduced speed (1/16) to obtain sample frequencies of 800–1000 kHz. For the spectral analysis a 1024-point FFT procedure was used on an interactively selected number of data points of the sonar pulse, resulting in a 1 kHz resolution. The data points are selected by the minimum obtainable uncertainty product  $\Delta t \cdot \Delta f$ . For the time duration  $\Delta t$  as well as for the frequency bandwidth  $\Delta f$  a quantity which is analogous to the standard deviation known from statistics is used. The interested reader is referred to a more detailed explanation in Wiersma, 1982. A possible modelling of the echolocation signal is further completed by adding another two parameters, the centre of gravity in the time domain and the centre of gravity in the frequency domain. The latter is closely related to the so-called dominant frequency, the peak value of the frequency spectrum. Another qualitative parameter can be added as a characteristic feature of the sonar signal, the number of oscillations of the dominant frequency.

### Signal Description

#### 1. General aspects

Typical click waveforms for the species *Neophocaena* are presented in Fig. 4. A closer inspection of the pulses reveals that *Neophocaena* pulses are very similar in both duration and frequency spectrum to those of *Ph. phocaena* as well as to *C. commersonii* (Møhl and Andersen, 1973, Kamminga and Wiersma, 1981). Such agreement greatly facilitated the spectral analysis, as we could draw from previous experience.

Characteristic features such as time duration range from 40 to 80  $\mu$ s and the frequency bandwidth is spread from 15 kHz for the longer duration pulses up to about 35 kHz for the shortest pulses. The

modulated dominant frequency shows an envelope with a remarkably symmetrical shape for the main part, with click no. 0 as an outlier. Typically, this bell-shaped form remained constant over the whole number of pulses in the pulse train, whether the pulse repetition period was ranging from 25 msec to 8 msec or the number of pulses was varying largely. This does not hold for the reverberational part of the pulse that follows immediately or slightly overlaps the main part. Here a great deal of variation in amplitude and number of consecutive parts was noticed for different pulse trains. This effect was also encountered earlier in our recordings of Commerson's waveform. The time difference between the first and the second part of the click—which equals in fact  $\Delta t$  = time duration—indicates a difference in its propagation path due to a reflection in the dolphin's head. It is quite easy—if one has good recordings with adequate time resolution—to indicate the time point where the main part of the first reverberation meet each other. This is enhanced by the phase distortion that occurs.

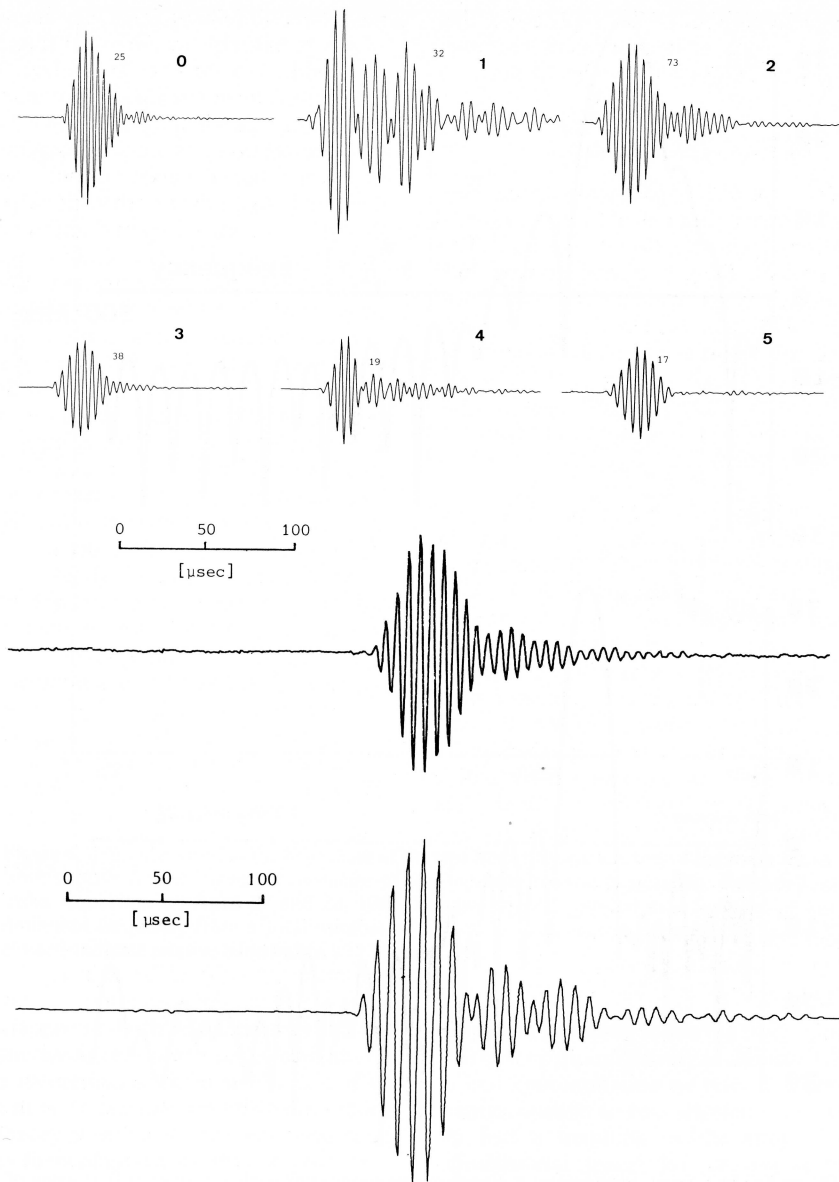
As a remarkable fact it should be noted that no low-frequency components are present in our data.

Returning to the figure observed qualitatively at first a partition into two graphs:

- I pulses 0, 2, 3 and 5 with a number of cycles in the order of 9–10, followed by very small amplitude reverberations. Click no. 5 is an example of a practical reverberation-free basic wave shape.
- II pulses 1 and 4, containing 5–6 cycles in their main waveform, followed by several reverberations, largely modulated in amplitude.

All these pulses are a random selection from likewise randomly chosen pulse trains out of a total of 150 minutes of sonar recordings. As can be seen, the signal-to-noise ratio is very high, which enables the onset of the pulse to be estimated accurately. As a matter of fact, the question of similarity to formerly recorded signals of *Ph. phocaena* and *C. commersonii* forces itself upon one. The reader is referred to figures 4b and 4c where two examples of the concurrent clicks are pictured. This has to be investigated more quantitatively by looking upon the parameters involved in terms of a structural description, as will be done below.

However, relying on earlier-described sonar signals from delphinids, we are tempted to separate the signals into pulses with a low number of cycles (2–3) and a higher number (5–10) of oscillations. *Phocaenidae* signals are placed initially in the second group. But, the characteristic feature they all share is a basic wave shape, simultaneously short in time and narrow in frequency. A large variety in the numbers of clicks in a pulse train was observed, ranging from 15 to over 300 with a pulse repetition rate of 40–120 Hz. Figure 5a shows a typical example of a sonar click together with its frequency spectrum. We note that the spectral energy is highly concentrated around the



**Figure 4a.** Typical wave forms of different sonar pulses of a captive *Neophocaena phocaenoides* of the Japanese coastal population, recorded on April 27 and 28, 1985 at the Toba Aquarium, Toba, Japan. None of the six clicks contains a low-frequency component.

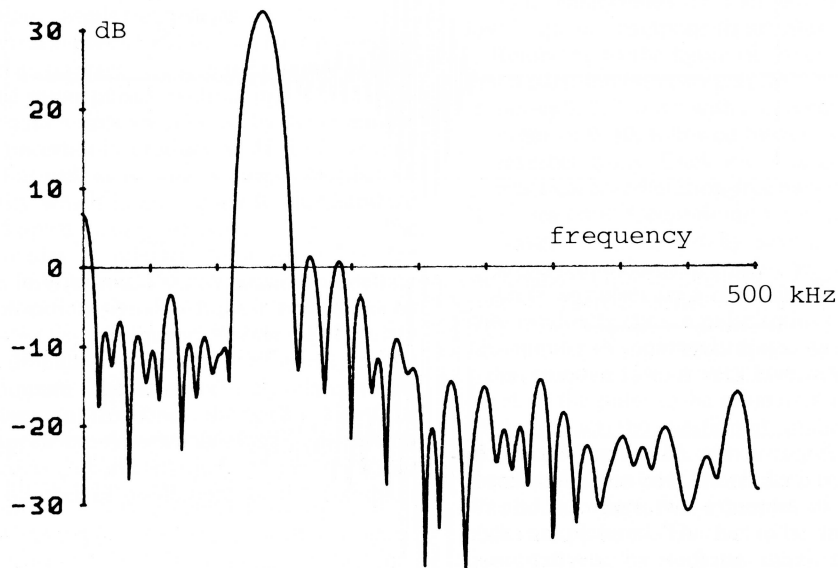
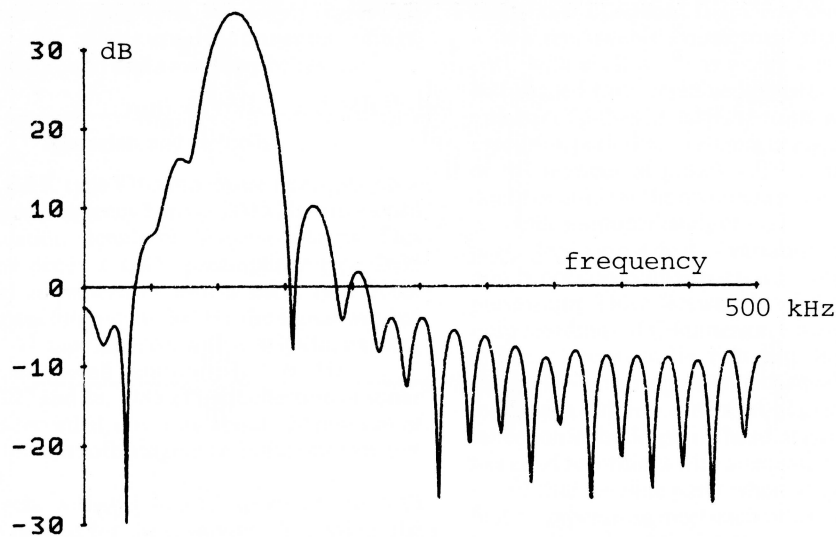
**Figure 4b.** Example of an echolocation click of a young *Phocoena phocoena* (Karl), recorded within one week of arrival at Odense, Denmark, on October 8, 1980. Dominant frequency 138 kHz.

**Figure 4c.** Representative waveform for the echolocation pulse of *Cephalorhynchus commersonii* recorded at the Duisburg Zoo on June 13, 1980. Dominant frequency 125 kHz.

dominant frequency of 113 Hz in a bandwidth of some 23.5 kHz, with a second peak 25 dB below the main peak appearing at 160 kHz. Although also

noticed earlier in the spectrum of Commerson's sonar, this phenomenon has yet to be explained. Figure 5b is a representative spectrum which portrays





**Figure 5a.** Frequency spectrum of a *Neophocaena* sonar click with a dominant frequency of 113 kHz and a 23.5% bandwidth (one-third octave). Spectral resolution is 1 kHz. A still unexplained peak 25 dB below  $f_0$  is noted.

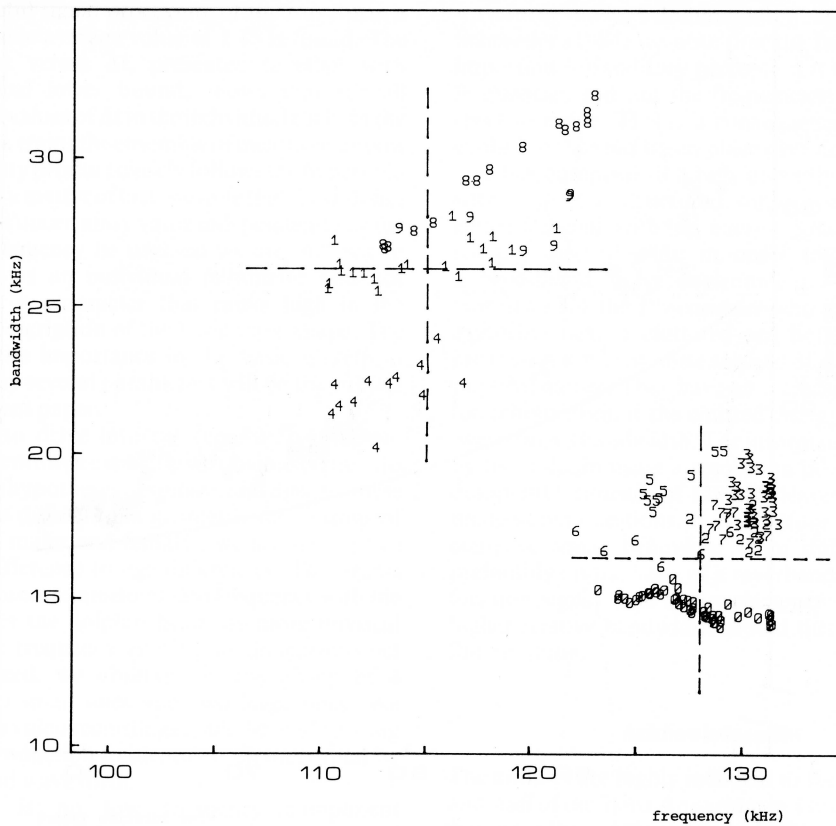
**Figure 5b.** Frequency spectrum of *Neophocaena* sonar click with the higher dominant frequency of 132 kHz and a relative bandwidth of 13%.

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## 2. Modelling

As indicated above, a possible modelling of the echolocating signal is given by the concept of the four-parameter model, the so-called Gabor-elementary waveform as known from communication theory

(Gabor, 1946). Earlier descriptions of odontocete sonar waveforms have been proved satisfactory from this point of view of signal analysis. The reader is referred to the former reports: Investigations in Cetacean sonar. One of the most powerful aspects of the Gabor signal representation lies in the fact that we are dealing with a low-parametric signal space, i.e. 4 dimensions. Together with the theoretical lower bound of the product  $\Delta t \cdot \Delta f = 1$ , resulting for



**Figure 6.** Representation of the behaviour of the two frequency parameters of the sonar signal from captive *Neophocaena phocaenoides* of the Japanese coastal population. Recorded at Toba Aquarium on April 27 and 28, 1985. Bandwidth  $\Delta f$  is plotted as a function of the dominant frequency from a total number of 172 clicks. The centres of gravity of the two clusters indicate relative bandwidths of 13% and 22%.

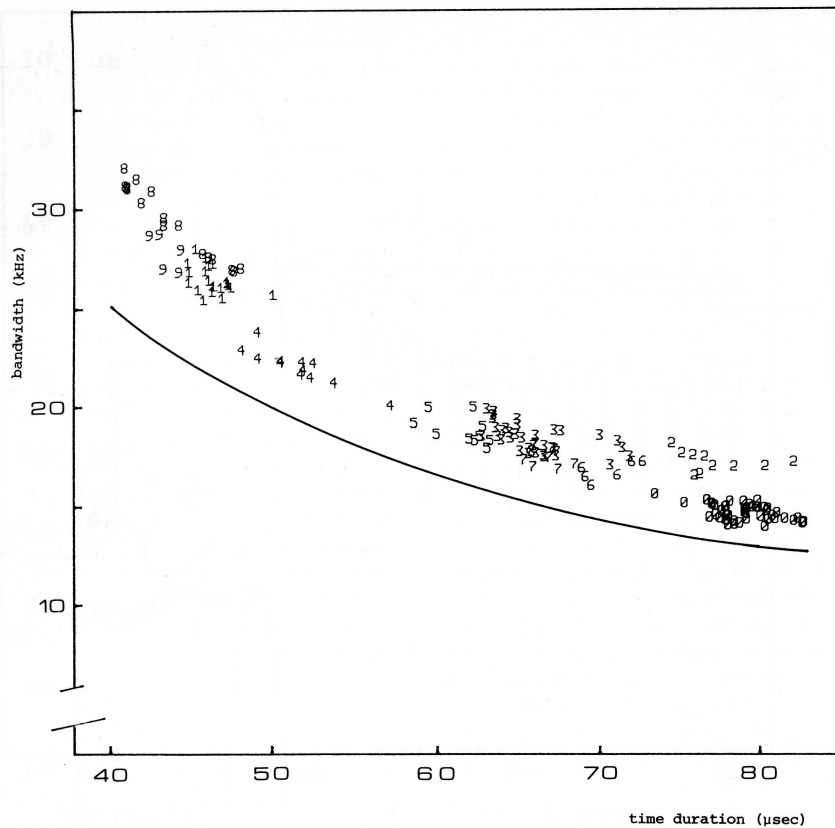
Gaussian envelopes in both the time and the frequency domain, we have tools to verify whether the sonar fits the theoretical optimal signal, and if so, how close the fit is. In fact, we are using a structural information theory of sound, i.e. a theory concerning the elementary form of acoustical waves.

### 3. Clustering

In looking in more detail at the four parameters  $t_0$ ,  $\Delta t$ ,  $f_0$  and  $\Delta f$ , one might wonder how these parameters are related to each other and how they might behave in a structural description of the collection of *Neophocaena* signals. We then refer at a first approximation to a two-dimensional representation of two selected parameters. To this end we have to substantiate an adequate mapping of the clicks in a four-dimensional space where the features are pictured at a set of orthogonal axes. Each click is then seen as a point in the resultant signal space. Evidently, the

apparent grouping following from figure 4a now has to show up quantitatively as clumps of data points. As a first approximation we refer to a two-dimensional representation to two selected parameters, which is in fact a mapping of the above-described four-dimensional space. We choose at first sight the relation of the bandwidth  $\Delta f$  versus the dominant frequency  $f_0$ . Figure 6 shows this relation for 172 clicks.

Two clusters can definitely be distinguished without any further mathematical help. The first cluster contains clicks of the lower dominant frequency of some 5–6 cycles with inherently higher bandwidths. The second cluster has all the higher-frequency-valued clicks with the number of cycles up to 10, characterized by the narrow bandwidth of 13%. To get more insight into the fundamental behaviour of the echolocation clicks, i.e. the concentration in time and the frequency domain, we calculate the relation  $\Delta t \cdot \Delta f$  for the same number of clicks as above. The



**Figure 7.** The uncertainty product of time duration  $\Delta t$  and frequency bandwidth  $\Delta f$  plotted for an ensemble of 172 pulses, from a random selection of 10 click trains. The solid line indicates the theoretical lower bound of  $\Delta t \cdot \Delta f = 1$ .

result is plotted in Figure 7, together with the theoretical lower bound  $\Delta t \cdot \Delta f = 1$ . This time no clear distinction is made in the data collection, but a very distinct approximation that follows the bound is presented for all clicks.

A question that might crop up is whether there exists a dependence of the uncertainty product with regard to different frequencies. Upon inspection of figure 6 it is clear that if  $f_0$  increases,  $\Delta f$  decreases, which implies that  $\Delta t$  becomes larger, and the reverse for  $f_0$  decreasing, or in other words, a changing  $f_0$  implies no change in  $\Delta t \cdot \Delta f$ , which is quite fundamental property of echolocation clicks when they are conceived of as elementary signals.

### Discussion and Conclusions

After inspection and elaborate studies of many click trains of *N. phocaena* the resemblance to the sonar behaviour of other members of the *Phocoenidae* family becomes more and more apparent. We had the opportunity to add to the group of high-frequency

sonar-producing dolphins a (third) member that turns out to fit right in the already-existing description of *Ph. phocaena* and *C. commersonii*. Many questions, however, remain unsolved. One of the most pressing problems is to gather from outside observations and analysis exact data that could be used to obtain insights into the reverberational characteristics that occur inside the head of the dolphin. The difference in echo patterns between the two categories, with their slightly differing dominant frequencies, is remarkable. From the physicist's viewpoint, it is very peculiar how a physiological system is capable of generating such a modulated sine wave, so well known in basic descriptions of electrical networks. The very consistent wave shape of the sonar click indicates that the sonar behaviour we are dealing with a very stable system, generating a basic wave form, despite the fact that for *Neophocaena*, as for the other two members of the group, the uncertainty product does not present the ultimate limit as was found for the very few cycled waveforms of the Irrawadi dolphin (Kammaing et al., 1983).

After careful signal processing of the waveform a very acceptable average value of 1.15 is found. The graph of  $\Delta t$  versus  $\Delta f$ , presented together with the theoretical lower bound, shows that for all encountered values of  $\Delta t$  in the individual clicks in the different click trains the ensemble of measurements of the uncertainty product closely follows the hyperbola  $\Delta t \cdot \Delta f = 1$ . As a matter of fact, we note that the dolphin produces this uncertainty value independently of the dominant frequency he uses, so we are inclined to designate  $f_0$  as an individual parameter and not primarily as a parameter that ranks high in the parametric description of the basic wave shape. The ranking of the importance in the basic waveform description by several parameters will be the subject of a subsequent paper.

In trying to delve into the separation into two definite clusters more explicitly we obviously run into speculations/hypotheses about sex and age. As there is no obvious difference in geometric dimensions of the skulls of males and females, we are inclined to assign the difference to age differences. This seems plausible if we correlate dominant frequency with the dimensions of the dolphin head: by more physical evidence, the frequency goes up as dimensions get smaller. Indeed, we observed in the group of 4 dolphins two small ones and two large ones. We regret that no video recordings could be made during our sound production to identify each individual by his own sound wave form.

As there is no low frequency component observable in our data, we reject a hypothesis of the bi-frequency behaviour of the *Neophocaena phocaenoides* of the Japanese coastal population. By the fact that yet no statements can be made on the *Neophocaena* that inhabits the Yangtze River in China, full bandwidth recordings of this species will definitely be needed for a most interesting comparison of sonar behaviour in one family, consisting of sub-populations.

Finally, we are convinced that the analysis of *Neophocaena* sounds leads to the conclusion that *Phocoenids* and *Delphinids* are not significantly different and that the sound of *C. commersonii* fits nicely in the acoustic cluster of *Phocoenids*.

### Epilogue

From a report by Evans *et al.* (1985) we note that another member of the Phocoenidae family (*Phocoenoides dalli*) produces acoustics signals very similar in waveshape and dominant frequency to those of *Ph. phocaena* and now *N. phocaena*, although we did not observe double pulses in the latter one.

The very narrow relative frequency bandwidth (13–25%) of both *Phocoena phocoena* and *Neophocaena phocaenoides* leaves us with the question of the advantage of using a like-shaped echolocation

waveform and high dominant frequency. In line with Schroeder (1984) we note that the fact that is most important for auditory perception is the presence of frequencies and not the frequencies missing in the spectral range. This is a consequence of biological evolution that has taken place over millions of years and has equipped dolphins and other odontocetes with a specific structured sonar system, using an emitted signal with its energy concentrated in a narrow spectral band in order to compete with a broadband noisy environment. This holds in particular for the *Phocoenidae* who are feeding and exploring near a cluttered sea bottom in coastal areas with different noise sources of a biological and physical nature. They have an increased success rate for echolocation if the emitted energy is not spread over a broad bandwidth. The information processing by the dolphin using a resolution power given by a dominant frequency of 128 kHz leaves us with more unanswered questions. It is therefore worthwhile to compare sonar behaviour from different species, preferably on the basis of a reverberation-free echolocation signal. The low-cycle sonar signals with a higher relative bandwidth should then be given our full attention.

### Acknowledgement

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Finally, a time-consuming operation such as analysing recording of sonar sounds needs perseverance and continuous discussion, both of which were contributed by two doctoral students, Mr J. van Wezel of the University of Amsterdam and Mr W. Krijgsman of the Information Theory Group of the Delft University of Technology.

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