Investigations on cetacean sonar VIII
Sonar signals of *Pseudorca crassidens* in comparison with *Tursiops truncatus*

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Summary

This paper describes the underwater sounds from a pelagic dolphin species—*Pseudorca crassidens*—as recorded in captivity. Waveforms of the sonar signals are investigated with regard to such basic features as time duration, dominant frequency and signal bandwidth. The latter two are compared to the sonar behaviour of two captive Tursiops spp: DORIS, a female animal used in previous echolocation experiments in Harderwijk, the Netherlands, and the other one named HEPTUNA, an experienced echolocator at N.O.S.C., Hawaii.

The sonar waveform of *P. crassidens* consists of only a few cycles of a dominant frequency around a fairly low 28 kHz with a time duration of about 60–75 µsec., and rather closely resembles the waveform of both Tursiops spp. Long sustained click trains were observed during approach and stationary inspection of the hydrophone, occasionally accompanied by a rather pure whistle of about 8 kHz.

Occasionally rather perturbed two-component sonar clicks were noticed with a higher frequency content around 100 kHz.

The time-duration-bandwidth product $\Delta t.\Delta f$ as an appropriate figure of merit for dolphin sonar applied to Pseudorca is in the order of 1.20 and thus equals both Tursiops spp. In this way a pelagic sonar signal is added to the portfolio of dolphin underwater sound.

Introduction

The first sounds from *Pseudorca crassidens,* albeit without further details or notes, were supplied by Schevill and Watkins (1962) in the form of a phonograph record.

In 1968, Busnel and Dziedzic published the first observations of *P. crassidens,* the false killer whale, and gave a description of underwater vocalizations as recorded in the Mediterranean. Unfortunately, however, as with most underwater-sound studies carried out at that time, the recording equipment had a rather limited bandwidth (up to 30 kHz), which inevitably affects the nature of echolocation clicks. Today we recognize that odontocete sonar signals span a frequency range up to some 140 kHz (Kamminga & Wiersma, 1981). This figure occurs for most members of the Phocaenidae family. Armed with this information about the frequency content we used 150 kHz as an upper limit, furnished by the use of a 200 kHz B&K hydrophone and a Racal tape recorder. Data were recorded during approach and inspection of the hydrophone without introducing a specific echolocation task, thus evoking sonar sounds used by the animals to ensonify a strange object in their pool.

It should not be surprising, therefore, to find frequencies over 30 kHz. Furthermore, we bear in mind that *P. crassidens* is a pelagic dolphin, evolutionarily considered as a modern representative of the family Globicephalidae (Dudok van Heel, 1981). Consequently, from an ecological point of view, we might expect the acoustic behaviour to be quite different than that of littoral animals, in response to the different demands of the open ocean. From the acoustic point of view a comparison with sonar from the well-known *T. truncatus* as an inshore/offshore dolphin would be quite interesting. Therefore we incorporate two examples in the following. A female *T. truncatus,* named DORIS experienced in echolocation in Harderwijk, the Netherlands and a male HEPTUNA, a highly experienced animal at N.O.S.C., Kailua, Hawaii.

Not supplied with full-bandwidth recordings, we in Delft welcomed the opportunity during a short stay in 1983 offered by Hubbs Marine Research Institute in San Diego to record underwater sounds with the same instrumentation as used in past measurements.

P. crassidens is relatively common, found worldwide in all tropical and temperate seas in quite large schools. They are fast swimmers, feeding mainly on squid (Watson, 1985). The *P. crassidens* is also known as a strander. Strandings, often of large schools, are well documented (Porter, 1977). Sound recordings for this paper are obtained from three
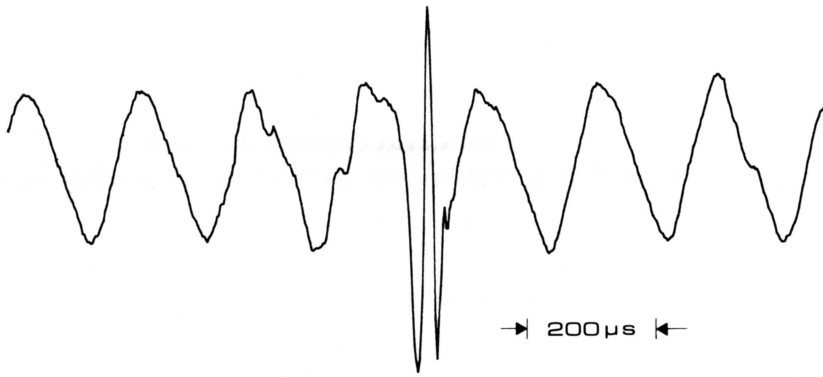
→| 200μs |←

Figure 1a. Example of the simultaneous occurrence of a whistle and a sonar click. Whistle frequency is centred at 8000 Hz.
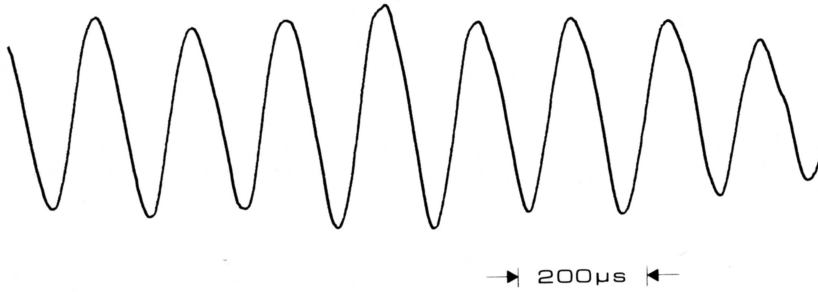

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Figure 1b. The very harmonic looking whistle of *Pseudorca crassidens*.
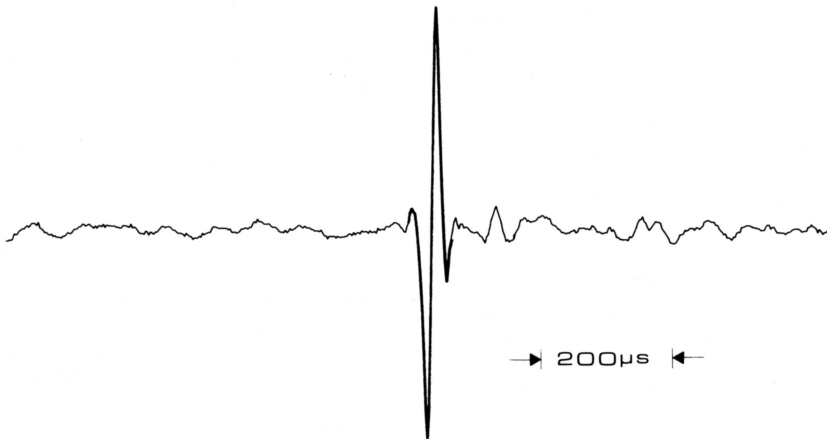

→| 200μs |←

Figure 2a. Typical waveform of a sonar pulse of a young captive *Pseudorca crassidens*, recorded at San Diego on 9 November 1983. The main sonar pulse, consisting of some 2 cycles, is represented by the thick line. An absence of internal reverberations immediately after the pulse is to be observed. Dominant frequency is 28 kHz.

rather young animals, in captivity for only a couple of months at the time of recording.

Sonar signal description

1. General aspects

The recordings we are about to describe were obtained at close range when the dolphins, singly or together, came in to inspect the hydrophone. During approach, long sustained sequences of sonar clicks, lasting for several seconds at a rate up to 300 pulses per second, were observed.

Occasionally, a rather constant whistle of about 8 kHz occurred along with the sonar pulse. An example of the click train and the simultaneous
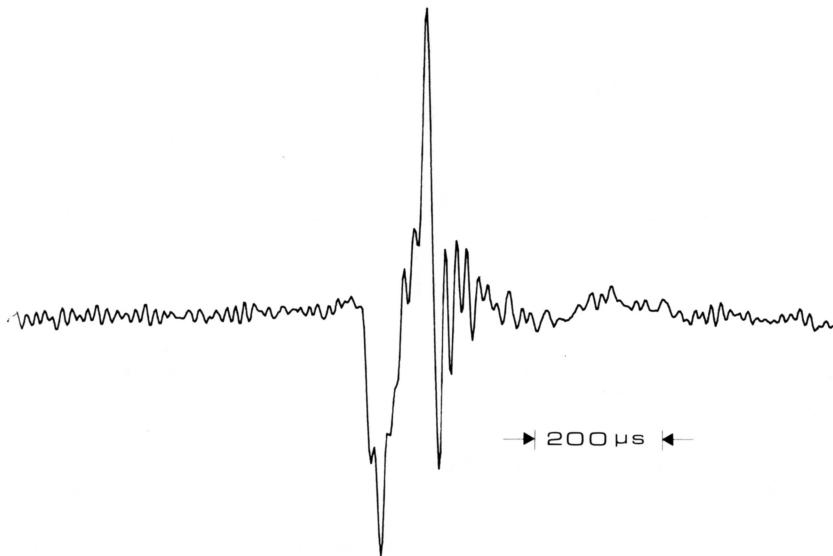
Figure 2b. Example of another waveform of a sonar pulse of *P. crassidens,* recorded at San Diego on 9 November 1983. Note the spurious high frequency oscillation (100 kHz) present over the entire waveform.
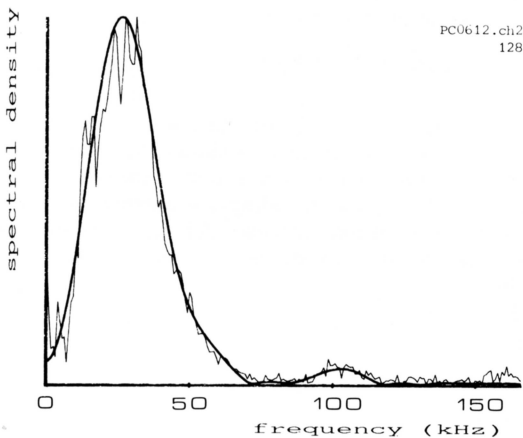

Figure 3. Frequency spectrum of the sonar click of figure 2a. The thick line indicates the spectrum of the sonar pulse alone. The thin line represents the spectrum as a result of taking a time window of 1.28 msec. Bandwidth is 18 kHz.
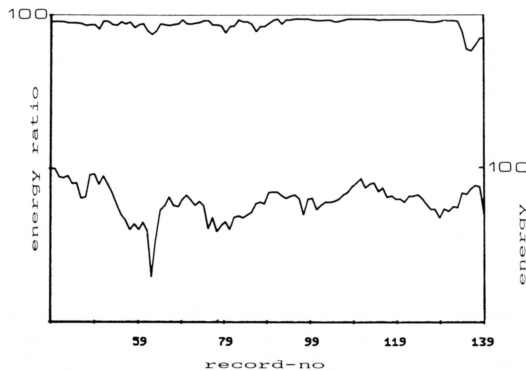

Figure 4. Energy content in the Pseudorca signal. Upper curve shows the energy ratio of the main click and the sonar signal emitted including the reverberations. In a time window of 250 µsec, 94–98% of the energy appears to be comprised in the main click. Lower curve shows the course of the energy in the same time window for a sample of 100 consecutive pulses.

whistle is given in Figure 1a. The very harmonic structure of the whistle alone is shown in Fig. 1b, where only a slight amplitude modulation is noted. Typical click wave forms are presented below in Fig. 2.

The sonar click in figure 2a is a representative stable sample out of a click train of more than 600 clicks. This representative waveform was finally obtained by examining and interactively processing the total number of clicks on a graphics display at film speed. The spectral representation was obtained by performing an FFT on a number of 512 data points obtained from the recorded signal and sampled with a frequency of 400 kHz (depicted by the thin line in the graph), as well as on the data points of the main part of the waveform only (depicted by the smooth, thick line). This final time duration spanned by the main waveform was obtained by an iterative method. A sliding window technique was applied around this main part whilst
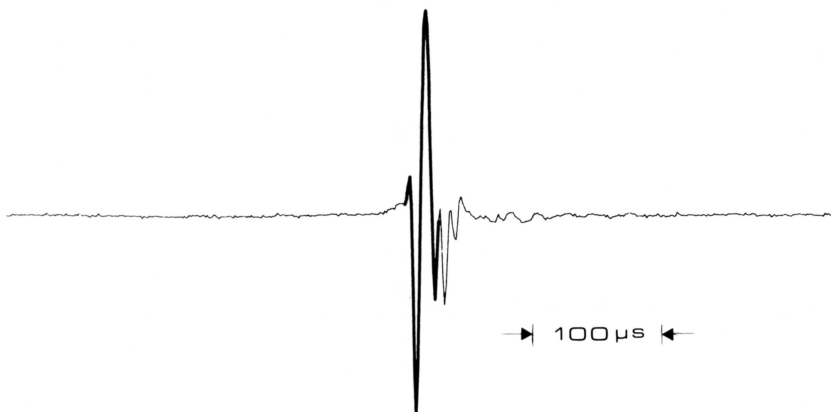
Figure 5. Example of an echolocation click of *Tursiops truncatus* (HEPTUNA) recorded at N.O.S.C. (Hawaii) on 9 September 1985. Dominant frequency 65 kHz for the two-cycle main sonar pulse, indicated by the thick line. Note the reverberational part following the main pulse.
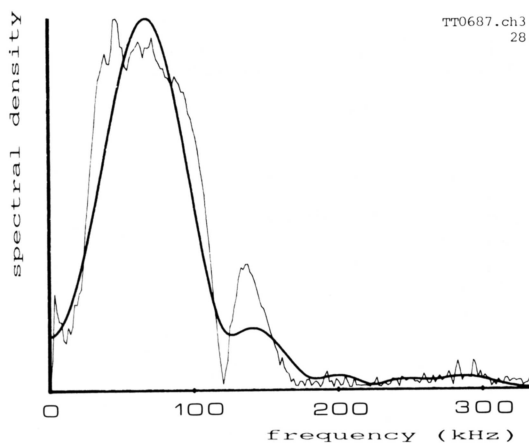

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Figure 6. Spectral representation of an echolocation pulse of HEPTUNA in figure 5. The thick line indicates the spectrum of the main part with a bandwidth of 50 kHz. The thin line represents the spectrum computed on an extended time window of 640 μsec, including reverberations and noise.

looking for the minimum value of the time-bandwidth product $\Delta t.\Delta f$. In this way we obtain the closest fit to the underlying Gabor waveform model. Mostly, two types of waveforms occurred, both with a prominent dominant frequency around 28 kHz, as is shown by the spectral representation in Fig. 3. The second type of sonar click appeared to have a slight high-frequency content as well, concentrated at 100 kHz.

In looking at the spectrum of the main part of the sonar pulse, the 28 kHz dominant frequency shows up well, with a bandwidth of 18 khz It is left up to the reader to decide whether this type of sonar signal should be classified as a narrow or a broad band type

of signal. From the engineering point of view another parameter, the relative bandwidth, can be introduced, because absolute bandwidth is limited in meaning when dominant frequency is not considered.

It is shown further on that the sonar pulse does not suffer practically from any type of reverberations, a fact that has not been significant for our recording of other species in the past.

To emphasise the effectiveness of the main part of the sonar pulse with regard to its reverberations, the energy content in both configurations is calculated. The upper curve in figure 4 shows the ratio of the energy in the stable time duration of the sonar pulse and the sonar pulse includings its reverberations in a time window of some 250 μsec. A figure of 94–98% of the energy turns up for the main part of the sonar click.
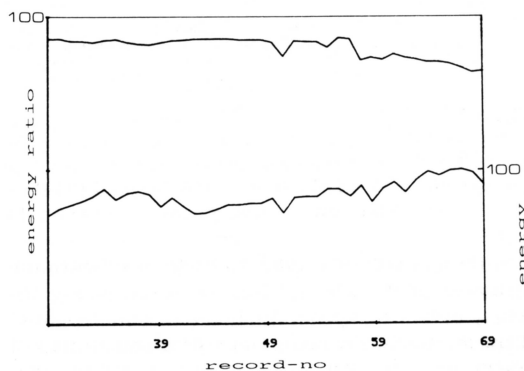

Figure 7. Energy content in the emitted signal of HEPTUNA. Upper curve shows the energy ratio of the reverberational part to the main sonar pulse. The difference appears to be 7–17%. Lower curve indicates the increasing energy in a time window of 125 μsec., due to increasing reverberations following the main pulse.
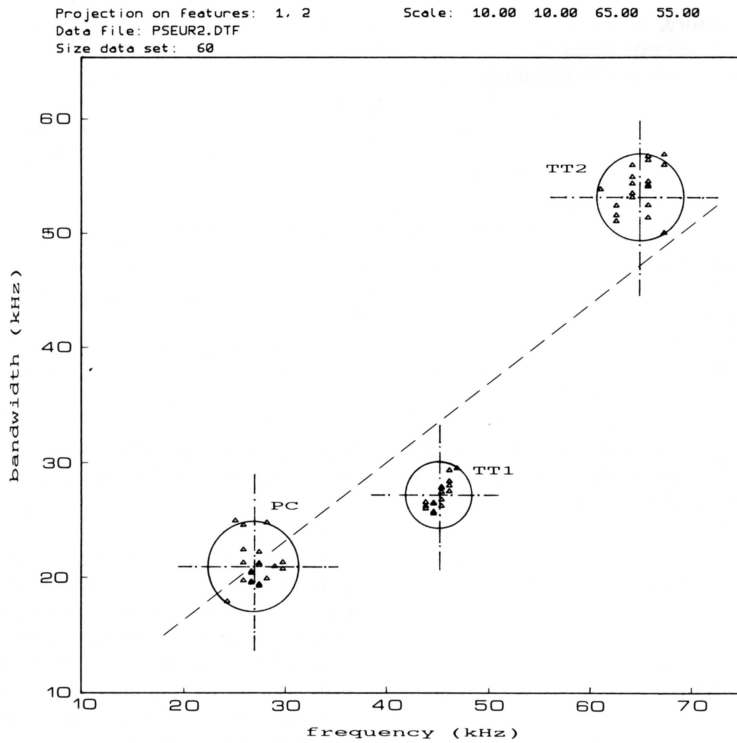
Projection on Features: 1, 2   Scale: 10.00 10.00 65.00 55.00
Data File: PSEUR2.DTF
Size data set: 60

Figure 8. Cluster representation of the two highest ranking dimensions of the sonar signals of *Pseudorca crassidens* and *Tursiops truncatus*. The dotted regression line emphasizes the linear relation of identical waveforms with different dominant frequencies. The circular clusters are presented to enhance visual clarity and do not imply the same form in the four dimensional signal space.

PC—*Pseudorca crassidens*
TT1—*Tursiops truncatus* (DORIS)
TT2—*Trusiops truncatus* (HEPTUNA)

The lower curve in figure 4 shows the course of the energy in the same time window for a sample of 100 consecutive pulses. From these results we might conclude that in fact only the consistent part of the pulse could act as an echolocation signal, thus giving an exact indication of the time duration.

Thus having obtained a clear indication of what the sonar waveform of *P. crassidens* looks like, we can go on to compare it to other delphinid sonar waveforms, inevitably including another low-cycled signal.

Although Watkins (1985) states that 'vocalization of marine mammals is broadband and used at the frequencies that appear to fit their activities best' there are practically no full bandwidth recordings of pelagic dolphins which have been analysed in order to correlate sonar sounds with related behaviour in the animal's own marine environment. Also, we are not aware of recent signal analytic studies that prove a best fit of sonar sounds with regard to adaptation to habitat, although this seems a most plausible
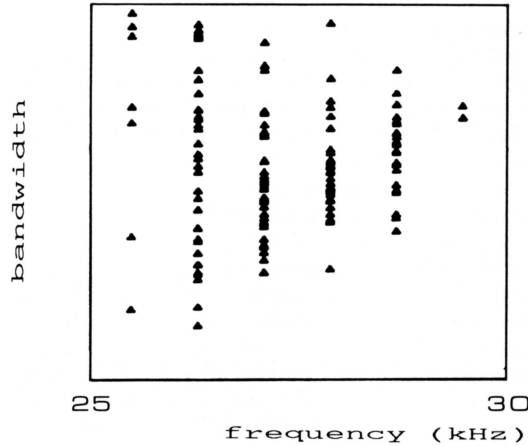
Figure 8a. A detailed view of the structure of a Pseudorca signal cluster consisting of 100 sample points. The accuracy of the spectral resolution of 0.8 kHz, dependent exclusively upon the sample frequency of the time signal, shows up clearly in the line structure.

proposition. Furthermore, a discussion about the nature of underwater sounds being broadband is needed to clarify discrepancies in the more recent literature on this topic.

As an appropriate example we turn our attention to *T. truncatus,* whose acoustic behaviour has been described so often and so well. Two examples will be used for this evaluation. We first take the sonar signal from the *Tursiops truncatus* DORIS (Hol & Kamminga, 1979), which exhibits a dominant frequency of 46 kHz during a detection task. Second, we incorporate the sonar signal from a highly-experienced animal at N.O.S.C. in Kaneohe Bay (Hawaii): HEPTUNA, an 18 year old male who performed well in former echolocation tasks (Au and Penner, 1981; Au and Turl, 1983, 1984). The sonar waveform of HEPTUNA, recorded in a target present/absent task (in a stationary position with its head in a hoop), is presented in figure 5. Note the internal reverberation that shows up immediately after the main part of the waveform.

When the same signal processing technique as outlined above is applied, a time duration of 25–30 μsec shows up at a dominant frequency of 65 kHz.

The spectral representation is given in figure 6. The energy content in the reverberations now attains a figure of some 7–15% of the total energy in a time duration of 125 μsec. Figure 7 indicates the energy relations in a sample of clicks in a pulse train by the same method as those obtained for Pseudorca. In comparison to the sonar signal from figure 5, we note the reverberations present in a substantial time span. The lower curve in figure 7 indicates increasing energy in the time window of 125 μsec. due to the increasing amplitude of the reverberations.

2. Signal space

Applying the parametric description of the waveform, following the powerful Gabor-model, we next restrict ourselves to f_0 (dominant frequency), Δf (effective bandwidth) and Δt (time duration). The latter two are connected in the figure of merit $\Delta t:\Delta f$ which gives a value of 1.00 as a theoretical lower bound for a Gaussian modulated sine wave. The two remaining parameters Δf and f_0 are plotted in figure 8 for the three types of sonar waveforms, each represented by 20 random samples. In fact, three definite clusters can be distinguished in this graph. It is noted, that we are now dealing with very consistent waveforms having the same number of cycles. This implies that we obtain for increasing dominant frequency, a linear relationship in the form $\Delta f/f = $ constant.

Also, time bandwidth products for the two signal types of *P. crassidens* and Heptuna are concentrated around a fairly low band of 1.20, while the *T. truncatus* Doris exhibits a deviating, unexplained figure of 1.20–1.40.

To obtain insight into the accuracy of the spectral representation, a detailed view of an enlarged part of another Pseudorca cluster is shown in figure 8a. Some 100 samples in the box show a spectral resolution of 0.8 kHz, which is due exclusively to the sample frequency of 400 kHz of the time signal.

Conclusions and Discussion

A closer look at the signal waveforms of the clicks of *P. crassidens* and *T. truncatus* shows that, leaving out the reverberational part of the waveform, they all look very much alike, showing a main sonar pulse with $N_c \simeq 2$ periods and only differing in their dominant frequency. If the number of oscillations remains the same, this implies that the bandwidth is also altered.

Figure 8 emphasises this latter property as we observe the regression line through the origin with respect to the centres of gravity of the three clusters. Due to careful processing of the individual clicks with regard to their minimum attainable $\Delta t:\Delta f$-product, rather compact clusters show up. As a consequence of the linear relation between Δf and the dominant frequency we come to the following conclusion. As far as the comparison of these three sonar signals is concerned, the dominant frequency is the highest ranking feature involved and may be the distinguishing feature in sonar behaviour. Any extensions of this assertion should be verified on a larger collection of different species with a low-cycled sonar behaviour to see whether they fit along a straight regression line or in a certain band in the graph instead of behaving like a scatter plot. In inspecting the placement of individual clusters we noted that the dominant frequency for *T. truncatus* ranges from 40–75 kHz, a much larger range than that found for the three Pseudorcas, concentrated between 25 and 30 kHz.

As was depicted in figure 3, the second type of sonar click waveform in *P. crassidens* shows a noticeable high-frequency component of some 100 kHz. This high-frequency behaviour can by no means be compared with the two-frequency property found earlier in *Phocoena phocoena* (Kamminga and Wiersma, 1981). Due to the fact that the high-frequency component is spread out over the entire pulse, even before and after it, this could be a by-product of the sonar production as well. Moreover, the appearance of this type of waveform is not too frequent.

With respect to the occasionally recorded simultaneous presence of sonar and whistles, we note a tight and stable interconnection between those two sources in terms of their phase relationship.

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