Investigations on cetacean sonar XI:
Intrinsic comparison of the wave shapes of some members of the *Phocoenidae* family

C. Kamminga[1], A. Cohen Stuart[1] and G. K. Silber[2]

[1]*Delft University of Technology, Information Theory Group, P.O. Box 5031, 2600 GA Delft, The Netherlands and* [2]*Marine Mammal Commission, Washington, DC 20009, USA*

Abstract

A comparison of the acoustic waveforms of three different species, *Phocoena phocoena, Phocoena sinus* and *Neophocaena phocaenoides* of the sub-family *Phocoeninae* is made with the species *Phocoenoides dalli* of the subfamily *Phocoenoidinae*. The comparison is based on the successful mathematical modelling and identification of the clicks. As remarkable as it may seem, the polycyclic sonar signals of these species have the same basic wave shape in common, despite their somewhat longer time-duration frequency bandwidth product in relation to a *Tursiops* type click which lasts only a few cycles. In-depth analysis for the type of sonar click of the *Phocoeninae* subfamily reveals both a representation by a single pulse and a decomposition into a main pulse, followed within 16–20 µs after onset by an important reverberation. Both pulses can be modelled by the Gabor time function. For the *P. dalli* species we find a decomposition into three elementary pulses together giving rise to the unusual time duration of the click of 100 µs. The time difference between those first two pulses of the click—with identical dominant frequency—is conjectured to be an important parameter in the identification of the acoustic behaviour and is probably attributable to a morphological distinction inside the animal's head. This supports acoustically the subfamilial partition. Cluster analysis applied to the two highest ranking parameters of the click description, i.e. dominant frequency and either time duration or frequency bandwidth reveals a striking overlap in similarity in the click structure of the three members of the subfamily *Phocoeninae* and a distinguishing characteristic for the subfamily *Phocoenoidinae*. A cluster of clicks for *Tursiops* (open water) is added to this scatter plot as a reference to species with a different (higher) relative frequency bandwidth. As a linear, non-parametric measure of similarity in waveform, the cross-correlation factor for normalized frequency scale between *P. sinus, P. phocoena* and *N. phocaenoides* is calculated as 0.73 and 0.76.

Introduction

The purpose of this research was to establish whether there is a parametric fit of the sonar signals of the Vaquita (*Phocoena sinus*) into the sonar plot of other members of the family *Phocoenidae*. This parametric estimation is carried out by model forming based on the proven time signal of Gabor. The modelling is justified again on the basis that we deal with time functions that have a rather short time duration–frequency bandwidth product, which is minimal for the Gabor signal. The first steps on the estimation of the Gabor model had already been done for *N. phocaenoides* sonar as an example of porpoise sonar (Kamminga *et al.*, 1986). The results were promising, although there was a constraint in that we were dealing with a higher uncertainty product than for *Tursiops* sonar signals. The higher uncertainty product inspired us finally to a structure of decomposition into more than one elementary Gabor signal, which partly explains the comparatively long time duration of the actual porpoise click (Cohen Stuart, 1994).

Following the first report on the acoustic signals recorded from *Phocoena sinus*—local name Cochito or Vaquita (Silber, 1991)—this paper treats a parametric description and subsequent comparison of the acoustic behaviour of three different Phocoenids, *Phocoena phocoena, Neophocaena phocaenoides* and *Phocoenoides dalli* with that of *P. sinus*. Attention is given to the individual sonar clicks as building blocks of the sonar click train. Thus, it is possible to investigate the actual differences or similarities in the acoustic behaviour of four members of the two sub-families of the family *Phocoenidae*. To this end, high-quality, adequate bandwidth recordings in the wild as well as in captivity of these four species are used in the

here-presented cluster analysis and intrinsic para-metric analysis of the waveforms. Given the hypothesis that membership of the same (sub)-family should be an indication of similar acoustic behaviour, one might expect without doubt that a comparison based on a quantitative approach should reveal that Vaquita fits into the same cluster as *P. phocoena* and *N. phocaenoides*. A comparison with the sounds of *P. dalli* should then be interest-ing, not only from an acoustical point of view, but also from the taxonomical side, as this species belongs to the other subfamily Phocoenoidinae of the Phocoenidae. This taxonomic point is separately treated below.

Phocoenidae vocalizations have been in the minority in the description of odontocete under-water sounds, especially as we take into account the frequency bandwidth of the recording gear needed for these high frequency echolocation signals. We note then the reports of *P. phocoena* by Dubrovskii, Krasnov & Titov (1971), Møhl & Andersen (1973), Kamminga & Wiersma (1981), Kamminga & Terry (1994). For *N. phocaenoides* we only have the observations by Evans *et al.* (1985) and a more detailed description by Kamminga *et al.* (1986) about vocalizations recorded in a restricted en-vironment (tank). For a third species, Silber (1991) presented the first description of sounds recorded from the phocoenid species *P. sinus*. Still missing altogether in this subfamily is the description of the acoustics of *P. spinnipinnis* (Burmeister's porpoise). As far as we observe for the other subfamilies we only see adequate bandwidth recordings for *Phocaenoides dalli*, recorded at sea by Awbrey *et al.* (1979) and by Hatakeyama & Soeda (1990) at sea as well as in a tank. Characteristic features of Phocoenid vocalizations are, in general, a small relative bandwidth $\Delta f/domf$ around a dominant frequency of the sonar clicks above 100 kHz with a number of cycles of more than six, and a typically low sound pressure level of an average of 160 dB re 1 µPa. Cranford (1992) refers to this class of signals as having a polycyclic waveform in contrast with the well-known Tursiops waveform with less than four cycles as a second category in the waveform classification (oligocyclic). At the time of writing, the category of the polycyclic waveforms is an incomplete minority with regard to the description of odontocete echolocation behaviour.

The outgoing clicks from the dolphin are submit-ted to a transmission beam pattern that has been shown to be directional to highly directional. Au *et al.* (1986) measured Tursiops in the vertical and horizontal planes an average − 3dB beamwidth of 10°C. For the harbour porpoise only, we are left with a remark by Møhl & Andersen (1973) that the presence of a high frequency was noted when the animal was pointing at the hydrophone with an angle of 30°C, as was estimated from a photograph. Given the high dominant frequency, we are left with the supposition that the transmitting beam is more directional than for Tursiops.

Taxonomy

After finding the same physiological phenomenon in different species, one has to consider the origin of the similarity. It may be of a general nature and thus can be found in all the species of a large taxon (e.g. echolocation in Odontocetes), it could be linked with a particular anatomical structure found only in the studied species or it could be related to an adaptation to a particular ecological feature (e.g. a certain biotope). In this study, we accept the second possibility as the most logical one. *Phocoena phocoena*, *Phocoena sinus* and *Neophocaena phocae-noides* have skulls which markedly resemble each other and also *Phocoenoides dalli* skulls look very much like those of Harbour Porpoises (see Van Bree *et al.*, 1977). The biotope of Dall's Porpoise on the one hand and the biotope of the Harbour Porpoise, the Finless Porpoise and the Vaquita on the other hand are very different; the first one is a pelagic species, the other ones are coastal. If our conclusion that the phenomenon is linked with the anatomy of the skull and thus is a taxonomic feature, the *Phocoena spinipinnis* and *Australo-phocoena dioptrica* should also show the same basic wave shape.

Instruments, methods and subjects

The acoustic signals of the *Phocoena sinus* were obtained by Silber (1991) in 1986 and 1987 at sea within 10–16 km off San Felipe, Baja California Norte. The geographical distribution of the Vaquita porpoise appears to be restricted to a few areas in the Northern Gulf of California. Aerial sight-ings (Silber & Norris, 1991) indicate year-round seasonal distribution of this rarely encountered porpoise. Recordings were made with RESON hydrophone TC4014 (frequency range up to 400 kHz) and backed up by a preamplifier and a Racal Store 4DS tape recorder. A 500 Hz high-pass filter was used to suppress low frequency distur-bances. System response at 30 ips recording speed thus resulted in flat frequency response (0 db) from 500 Hz to 150 kHz. Recordings were also made at a recording speed of 60 ips, thus extending the fre-quency range to 300 kHz. An example of a *P. sinus* click is shown in Figure 1.

The *Phocoena phocoena* echolocation signals were obtained in 1989 from a young animal, stranded shortly after birth and expertly raised at the Point Defiance Zoo and Aquarium, Tacoma, Washington, it was six months old when taped

Figure 1. Typical waveform of an echolocation click of *Phocoena sinus.* Signal-to-noise ratio is 31.8 dB. Recorded at sea in Baja California Norte.
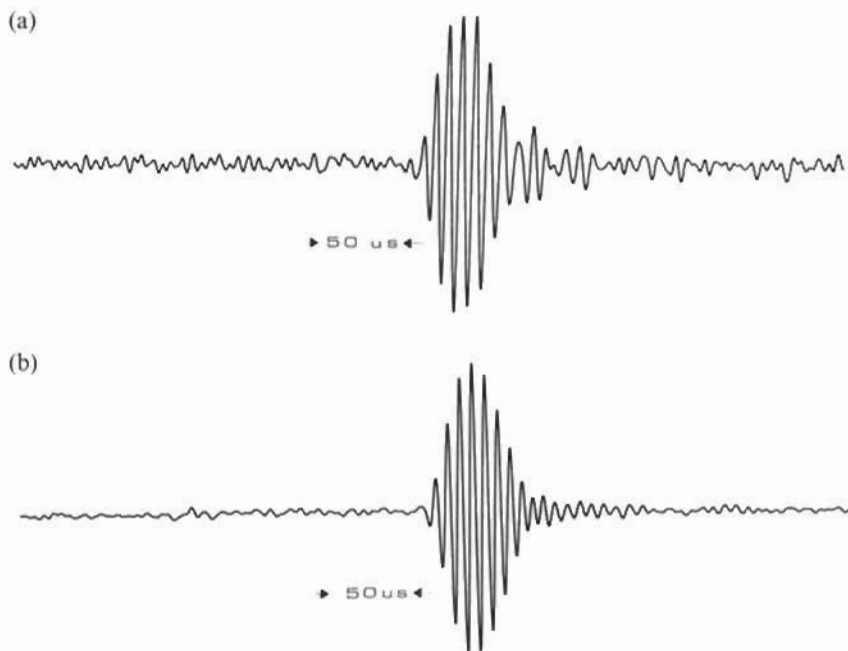
(a)

(b)

Figure 2. (a) Typical waveform of a young *Phocoena phocoena* about six months old when recorded at the Point Defiance Zoo and Aquarium at Tacoma, Washington. Signal-to-noise ratio 31.7 dB. (b) An echolocation click of a rehabilitated by-catch *Phocoena phocoena*, recorded at the bio-acoustics facility of the Odense University at Strib, Denmark. Signal-to-noise ratio 26.4 dB.

acoustically at that location, and from adult *Phocoena* at the acoustics facility of the Odense University at Strib, Denmark in 1983. The latter animals were rehabilitated victims of by-catch in Danish waters. Although our recordings in Odense revealed, besides the ever-present high frequency of around 125 kHz in the sonar clicks, also the 2 kHz and 20 kHz component, we opted for uniformity in comparison in choosing for the click trains without the low frequency components and then collected some 56 typical examples of clicks. Figure 2a shows

an example of the Tacoma porpoise and Figure 2b pictures the adult Phocoena.

Furthermore, to exclude possible differences in hydrophone/amplifier configurations, only the recordings made with the combination B&K hydrophone 8103 and the B&K charge amplifier 2635 were used in the final comparison with other Phocoenid signals.

The data obtained for the representation of the acoustic behaviour of *Neophocaena phocaenoides* (Finless porpoise) of the Japanese coastal popula-

Figure 3. An echolocation waveform of *Neophocaena phocaenoides* from the coastal population of Japan, recorded in the Toba aquarium, Toba City, Japan. Signal-to-noise ratio 37 dB.
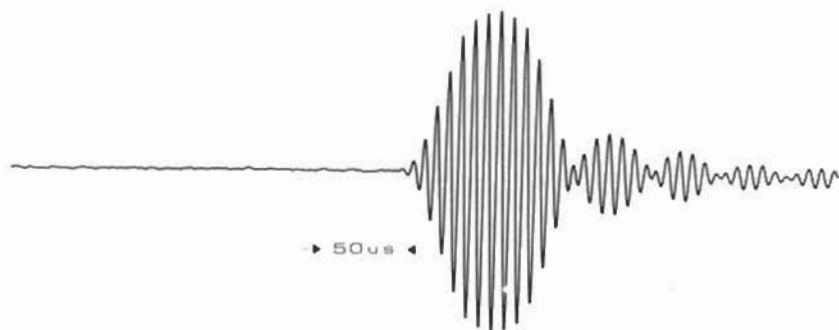

Figure 4. Waveform of an echolocating *Phocoenoides dalli* at sea, in Monterey Bay, California. Signal-to-noise ratio is 42.2 dB.

tion was recorded in the Toba Aquarium, Toba City in Japan (Kamminga *et al.*, 1986). These recordings were carried out with the same combination of hydrophone and amplifier as the *P. phocoena* sounds. *N. phocaenoides* is a surprisingly quick and lively animal, emitting abundant click trains with stable pulse forms and with a pulse repetition rate of over 250 Hz. Due to the probably pencil-formed sonar beam, there was much variation in the amplitude of the reverberational part of the click in the approach to the hydrophone in the centre of the pool. The 23 clicks used in the final scatter plot as typical examples of this species are from earlier careful processed click trains. The example chosen for the model fitting is shown in Figure 3.

The fourth member in the *Phocoenidae* cluster is from hitherto non-published research on *Phocoenoides dallli* sonar behaviour at sea. Recordings were made in Monterey Bay by Kamminga, Engelsma and Norris in December 1989. We observed plenty of sonar activity from this animal, when several animals approached the vessel to inspect the hydrophone, B&K type 8105, from

nearby, the result was an extremely high signal-to-noise ratio of over 40 dB, as is to be seen noted in Figure 4. Perusing literature for a description of dalli sonar, we note two papers, by Hatakeyama & Soeda (1990) and Awbrey *et al.* (1979). A similarity of the clicks from *dalli* with those of *Phocoena* had been noted by Kamminga (1988). Given the fact that for this species we could not rely on the previous carefully chosen material from our archives, another procedure was followed. The here-used 15 typical examples of sonar clicks were chosen from four click trains. This selection was not carried out in a random way, but samples were chosen from a persistent, stable part of the click train, i.e. we were looking for the lowest number for the relative frequency bandwidth $\Delta f/domf$. This method had previously been used with the varying orientation of the dolphin towards the hydrophone for a free ranging Inia (Kamminga *et al.*, 1993).

The last cluster that is incorporated in the collection of clicks for wave shape comparison originates from the echolocation data of a free ranging Tursiops (Kamminga, 1990) recorded in 1986 off the Coast of Brittany, France.

Signal processing and analysis

The Vaquita signal

After a first aural detection, the previously taped *Phocoena sinus* sonar clicks were digitized at a sampling rate of 1048 kHz by a 14 bit A to D converter in the HP 3565 signal processor, and backed up by a HP/9000/425 workstation. For the spectral analysis, a standard 512 point FFT was used on an interactively selected arbitrary number of data points that covered the first (main) part Δt of the echolocation click without including reverberations, zero-padded to the left and to the right of Δt. This procedure has proved to be very effective in the case of oligocyclic clicks (Kamminga *et al.*, 1990). However, it is also a justified analysis method for *Phocoenid* type sonar clicks as shown below. The typical waveform for a sonar click of the Vaquita is again depicted in Figure 5a. The phase change, where a reverberation follows the main pulse, is clearly visible and is used further throughout the calculation of the time envelope to indicate this main part of the click. The time duration Δt is conveniently taken as $\Delta t = 2\pi\sigma_t$ with σ_t taken as the standard deviation of the envelope of the time function. In this manner there is more agreement about the impression as to what the time duration of a click effectively means. Further, as we are dealing in general with recordings that have signal-to-noise ratios in the order of 20–40 dB, the left marker of Δt indicates the point where the click emerges out of the background noise. For a Gaussian curve, the number $2\pi\sigma_t$ corresponds with a probability of occurrence of 3.10^{-3}. The actual time duration turns out to be a value of 70 µs. The click shown in figure 5a has a signal-to-noise ratio of 31.8 dB.

The frequency spectrum of the windowed click is presented in Figure 5b. The logarithmic scale is used to get a better impression of the dynamics in the spectrum and a better view of the frequencies surrounding the dominant frequency. Bandwidth is again defined by $\Delta f = 2\sigma_f$, i.e. the standard deviation of the frequency spectrum relative to the dominant frequency, which definition differs only slightly from the currently used 3 dB value.

The next step in the processing and analysis stage of the Vaquita sonar click is the application of the parametric description of the click waveform in terms of the Gabor representation (Kamminga *et al.*, 1990, 1993). Emphasis in this description is laid on the features of dominant frequency (domf), time duration (Δt), uncertainty product ($\Delta t.\Delta f$) and number of cycles ($Nc = \Delta t$. domf). An important parameter for agreement as to whether the Gabor model fits the actual sonar click is given by the energy ratio of the residue to the model. A satisfactory fit would occur if the residue is similar in
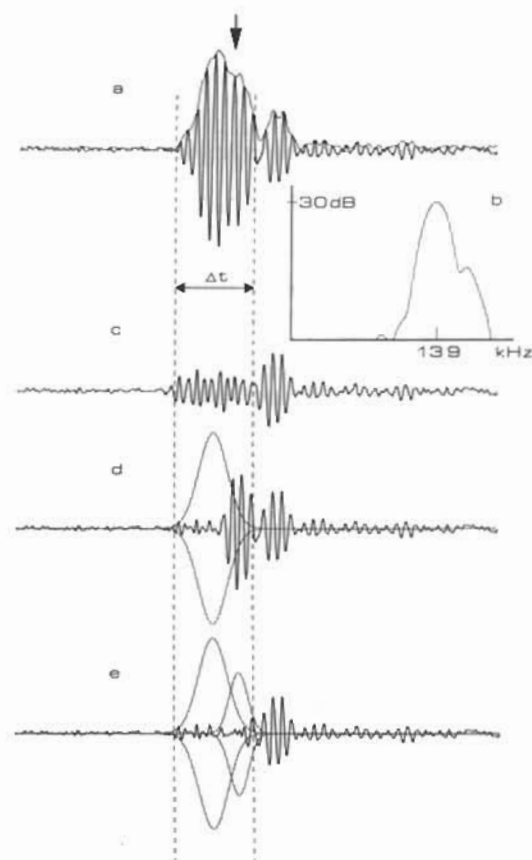
Figure 5. (a) Echolocation click of *Phocoena sinus*, shown with the positive half of its envelope sketched in. Δt indicates the main part of the click that equals 70.5 µs time duration. (b) Fourierspectrum of the sonar click of time duration Δt on a logarithmic scale. Dominant frequency 139 kHz. The small side lobe at 170 kHz is due to an internal reverberation that is shifting into the main part Δt. (c) The residue of 5% that remains after one Gabor model over Δt is attempted for a fit. The dominant frequency of 139 kHz is clearly visible. (d) Envelope and residue of 0.5% after the first of two Gabor models is fitted over the left part of the pulse duration Δt. The residue shown is the remaining part (right) of the main pulse. (e) Envelopes of the two Gabor models, shifted in time over 20 µs that compose the original sonar click. Final residue is 0.7%, which transforms to a signal-to-noise ratio of 21.5 dB.

magnitude and dynamic behaviour to the noise preceding the pulse. If the residue is more or less similar to the noise preceding and following the click, the fit is considered to be satisfactory since further improvement is questionable. Another viewpoint on the significance of the residue could be given when we convert this figure into a signal-to-noise ratio. In doing so, we then obtain a

logarithmic measure which, when compared next to the actual signal-to-noise ratio of the actual click, indicates the difference that is left to arrive at a satisfactory fit. The analytical expression for the Gabor time function as used in the Marquardt-Levenberg fitting procedure is given by

$$f(t) = \exp{-\alpha^2(t-t_0)^2} \cos\{2\pi f_0(t-t_0) + \varphi\}$$
with $\alpha = \pi/\Delta t$.

A closer look at the main pulse via its envelope clearly shows an asymmetry, indicating the presence of internal reverberations, which is also indicated by the 170 kHz side lobe in the spectrum and the deviating high uncertainty product of 1.60. An attempt to fit a single Gabor pulse to the Vaquita click yields a residue of 5% that visually differs significantly from the background noise, showing the harmonic oscillation from the main part of the click. The situation is pictured in Figure 5c. If we calculate the signal-to-noise ratio of this energy residue to the main part Δt of the click, we arrive at a value of 13 dB, which given the actual SNR of 31.8 dB leaves space to reconsider our model fitting. We now take the Gabor estimation for a possible composition of several pulses, starting with modelling in a region of interest that is situated to the left-hand side of the discontinuity in the envelope. This is indicated by the arrow marker in Figure 5a. Subtracting the model from the original click leaves us not only with a residue of 0.5%, but also with a substantial part of the main click (see Figure 5d) on the right side of the point of asymmetry. Under the assumption that this part—the first reverberation—is an echo from the very first part of the main click, we now fit again the Gabor model. This modelling could easily be started with the obtained parameters of the first part. Subtracting the second Gabor model from the main click then reveals that the second half of the main pulse vanishes to 0.8%, which leaves us with the result that we have obtained a decomposition of the original, asymmetric pulse into two Gabor pulses. This at first glance hidden reverberation explains the asymmetry in the sonar waveform and eventually the higher uncertainty product of 1.60 for the Vaquita click. The total energy residue of the main click after the decomposition into two elementary signals is in the order of 0.7%. This residue can be explained by the fact that the reverberation outside the main pulse has its influence on the model fitting of the second Gabor pulse within Δt. The two signals and the residues are presented by their envelopes in Figure 5e. The time shift between these two Gabor pulses is $20 \mu s \pm 0.5 \mu s$. This value indicates that the first reverberation is an echo with the same frequency as the first part, in the very near vicinity of the sonar source. The measured click values do

Table 1. Measured signal parameters of *Phocoenidae* sonar clicks, together with model values (between brackets)

	domf (kHz)	Δt (µs)	Δf/domf
Phocoena phocoena	137 (137)	65	0.15
Phocoena phocoena	129 (132)	69.5	0.15
Phocoena sinus	139 (144)	70.5	0.23
Neophocaena phocaenoides	130 (130)	75	0.13
Phocoenoides dalli	134 (136)	109	0.09
Tursiops truncatus	75	30	0.50

st=time duration main part of click, Δf=bandwidth, Δf/f=relative bandwidth, domf=dominant frequency

not differ significantly from the model values. The model parameters are listed in Table 1.

Continuing our analysis, we took the *Phocoena* signal from *Phocoena phocoena*. Two typical examples are involved in the final presentation of the behaviour of Δt versus domf, the young Pacific animal, 6-months-old, called Magic, and the adult North Sea by-catch animal.

The 'Magic' signal
The prominent wave shape of this young *Phocoena* with a time duration $\Delta t = 65 \mu s$ is presented in Figure 6a. Inspection of the envelope of the sonar click does not reveal at first sight a possible decomposition into two separate elementary waveforms; this is due to the value of $\Delta t.\Delta f = 1.15$, which is unusually low for a polycyclic click of 8.5 oscillations. However, a closer look at the parametric model-forming shows that a building up, similar to the above-described Vaquita click, is valid. The final residue turns out to be 0.3%. The time separation between the two elementary Gabor building blocks is now $18 \mu s \pm 0.5 \mu s$. We note a lower amplitude of the first reverberation with regard to the Vaquita signal. The other parameters are listed in Table 1 for comparison.

The Odense signal
Proceeding along the same lines of reasoning now applied to the adult *Phocoena* signal, it is quite obvious to find an analogous situation of two elementary overlapping Gabor signals, shifted in time of $16 \mu s \pm 0.5 \mu s$ that compose the sonar click. The final residue shows a value of 1.3%, which is due to the original signal-to-noise of 26.4 dB. The uncertainty product $\Delta t.\Delta f = 1.30$ points towards the possibility of a composite signal. The typical waveform is given in Figure 7a. The parameter values of Table 1 indicate the strong correlation between the two examples of *Phocoena* clicks
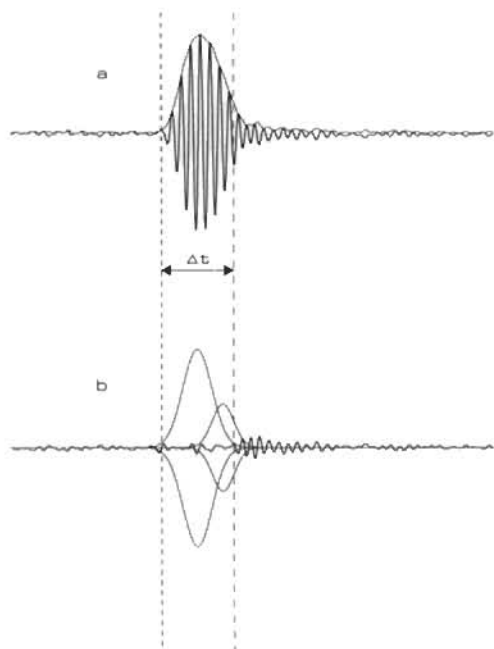
Figure 6. (a) Waveform of the 'TACOMA' young porpoise together with its envelope. Again $\Delta t = 65\,\mu s$ is the time duration of the main part of the sonar click. Dominant frequency is 137 kHz, signal-to-noise ratio is 31.7 dB. (b) The residue of 0.3% that is left after two Gabor models are fitted in the same way as for the Vaquita click, pictured with the two envelopes of the Gabor models fitted to the main pulse. Time separation between the two Gabor building blocks is now 18 μs.

from geographically different locations, which is numerically supported by $\rho = 0.95$.

The finless porpoise signal

The typical waveform of *Neophocoena phocoenoides* is shown in Figure 8. At first glance, the time representation of this click does not reveal any asymmetry, which is illustrated by the smooth envelope, nor does the spectral representation show a certain amount of skewness. Taking into account the low uncertainty product $\Delta t.\Delta f = 1.15$ for this polycyclic signal of $Nc = 8.6$ oscillations, we should confine ourselves first to the fitting of one Gabor signal. This estimation procedure then leaves us with an energy residue that remains after the model is subtracted from the actual *Neophocaena* signal of 0.12%, which equals 29 dB and means an excellent fit in the case of the signal-to-noise ratio of the click of 34 dB.

The Dall's porpoise signal

The echolocation signal of free-ranging *Phocoenoides dalli* is depicted in Figure 9a, together
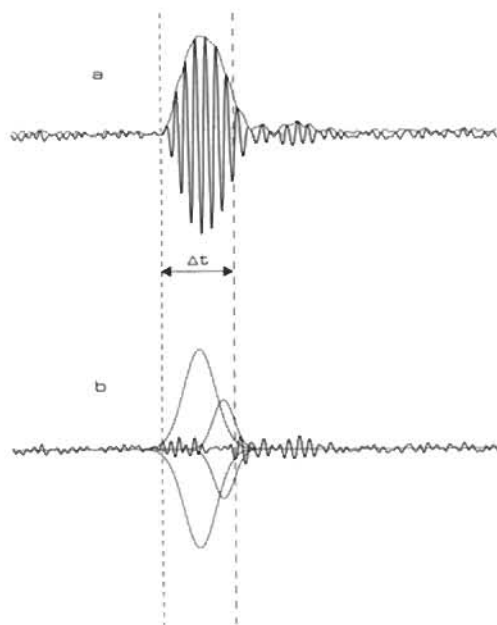
Figure 7. (a) Typical example of the 'Odense' *Phocoena* click with time duration $\Delta t = 69.5\,\mu s$. Dominant frequency is 129 kHz. Signal-to-noise ratio is 26.4 dB. (b) Final residue of 1.3% that remains after fitting two overlapping Gabor models on the main pulse. The overlapping envelopes of the two Gabor models that are now shifted 16 μs in time.

with its spectrum that exhibits the lowest relative bandwidth, 9%, we have ever found in the family *Phocoenidae* and the dolphins in the genus *Cephalorhynchus spp*, also showing a polycyclic sonar waveform. This is caused not only by the high dominant frequency of 133 kHz, which also becomes clear when looking at the unusual long click duration of 105 μs for the prominent first part. The unorthodox time duration of the *P. dalli* recorded in the Bering Sea, was also noticed by Hatakeyama & Soeda (1990). The presented waveform pictured by Awbrey (1979) of the same species indicates two phase changes in the click time duration of 250 μs, a phenomenon which is also visible in the spectral representation.

Our excellent signal-to-noise ratio of 42 dB (recorded at sea) allowed us to perform a very consistent and precise model-forming and analysis of this type of click. Inspection of the envelope of the click already indicates (as in the Vaquita signal) that we could expect more than one Gabor model pulse. Careful analysis along the same lines as those above shows that the building up of this long duration click can be done by three Gabor pulses. The number of 1.30 for $\Delta t.\Delta f$ might be again an indication to search for a composite signal. The
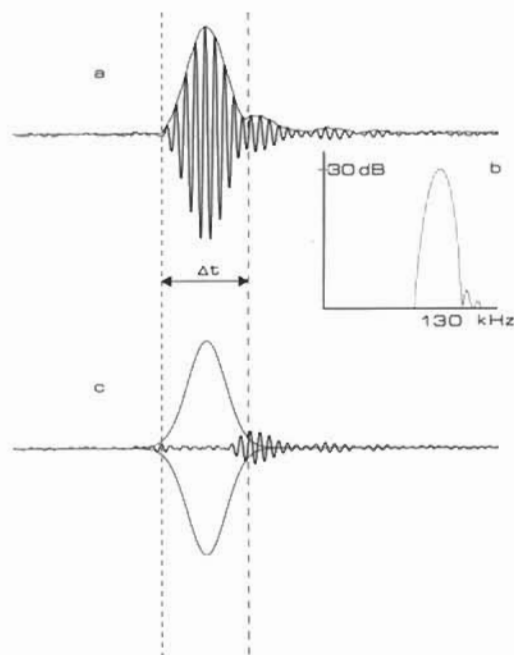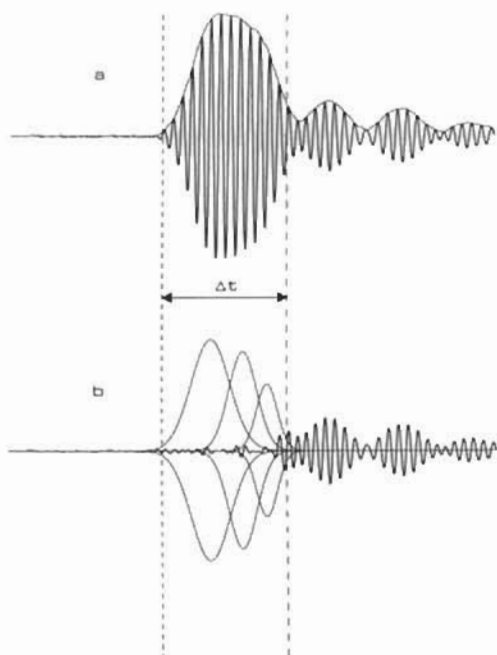
Figure 8. (a) Sonar click of *Neophocaena phocaenoides*. Time duration of main part, indicated by Δt equals 65.5 µs. (b) Frequency spectrum of main part of click from figure 8a on a logarithmic scale. Note the symmetry that occurs around the dominant frequency of 130 kHz. (c) The residue after subtracting one single Gabor model, fitted over Δt from the actual click, shown together with the envelope of the model.

Figure 9. (a) *Phocoenoides dalli* echolocation click. Note the deviating long time duration $\Delta t = 105$ µs. The number of cycles in Δt is $N_c = 14.5$. (b) Final residue of 0.6% after fitting three elementary Gabor pulses to the main part Δt of the sonar click. Time shift is 24 µs and 18 µs between the elementary Gabor pulses.

final residue, indicating the fit of these three added-together model pulses shows an agreement of 0.30% with the actual click (Figure 9). The time shift between the first and the second pulse is 25 µs ± 0.5 µs, significantly larger than for the Vaquita click and *Phocoena phocoena*. A first impression of the similarity of *P. sinus* waveform with *Neophocaena* and *Phocoena* indicates that we should look for cross-correlation as a linear wave-shape criterion. For the correlation with *Phocoena phocoena* a value of 0.76 is obtained while for *N. phocaenoides* a value of 0.73 indicates a good agreement.

Cluster analysis

We now present our collection of data of the total of 137 actually measured clicks in a scatter plot to further explore the underlying structure of the click data. The successful modelling of the sonar clicks validates the experience-based method of the previously given selection of features in time and frequency. We then project the four-dimensional feature space of α (related to the time duration by $\Delta t = \pi/\alpha$), t_0, domf and φ onto the two dimensional subspace of domf and Δt. The results of this mapping give a good insight into the data structure of various members of the *Phocoenidae* family. A final remark on this type of cluster presentation is on the justification of this projection on two features. Given the minor importance of the features t_0 (the mid-epoch of the envelope) and φ (phase of the dominant frequency with regard to t_0) the intrinsic dimensionality of the complete feature space will be chiefly determined by domf and Δt. The final plot of these two highest ranking features is given in Figure 10.

Conclusions and discussion

The Phocoenid echolocation signals, presented for cluster analysis of their highest ranking features, domf and time duration, show quite clear separation into two clusters. The *Phocoena phocoena*, *Phocoena sinus* and *Neophocaena phocaenoides* clicks comprise one cluster. The species *Phocoenoides dalli* is distinctively separated, comprising the other cluster mainly due to the feature time duration, which is more than 50% larger than the average of the *Phocoeninae* cluster, the longest time
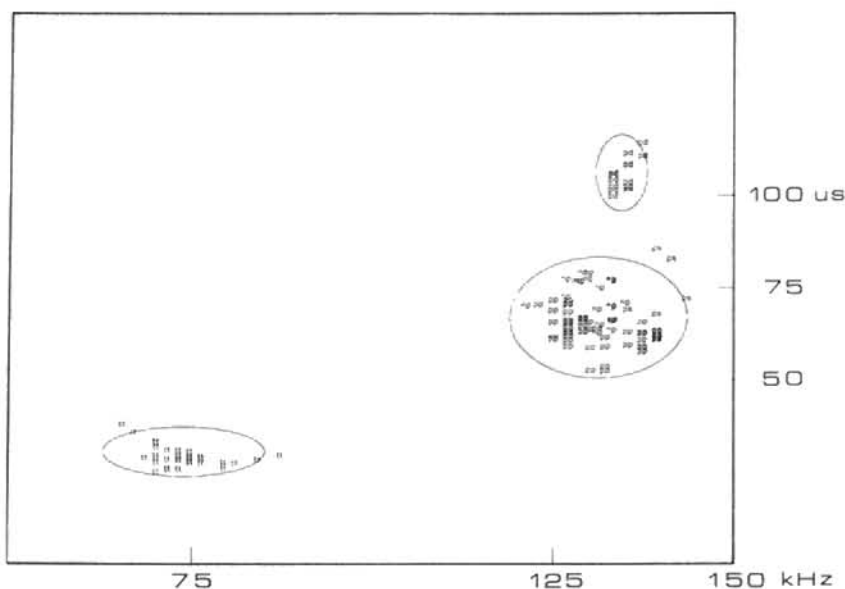
Figure 10. Scatter plot of a total of 137 actual measured *Phocoenidae* sonar clicks, projected on the features time duration Δt and dominant frequency. Note there is a splitting up into two clusters, agreeing with two subfamilies. For comparison, a cluster of *Tursiops* sonar clicks from a wild animal is added. tt = *Tursiops truncatus*, pp = *Phocoena phocoena*; np = *Neophocaena phocaenoides*, pd = *Phocoenoides dalli*; ps = *Phocoena sinus*.

duration for polycyclic waveforms that we have ever found, and which is in fair agreement with the earlier published waveforms. Figures for time duration by Awbrey *et al.* (1979) are not comparable due to a different definition of click duration. Thus far, we note a splitting up for echolocation waveforms that is in agreement with the taxonomical division in subfamilies. It would be intriguing to compare sounds of the remainder of the Phocoenid species; *P. spinnipinnis* and *A. dioptrica*. However, to date, there have been no recordings made of these rare and rarely observed species.

Similarity is still a concept that is observer related and implies a certain degree of subjectivity. However, similarity statements can be made more rigorous by applying objective measures from mathematical physics and pattern recognition. The evaluation of a partitioning of a data set into clusters, especially in the case of bio-acoustic data, should not only be based on mathematical distance measures but also have a firm connection with the original taxonomic problem. The problem treated in this article was originally formulated as whether: (1) recordings of *Phocoena sinus* sounds would conform to the Gabor model description, and (2) *Phocoena* sinus clicks would fit into a scatter plot together with earlier-described *Phocoenid* clicks.

Both questions have been adequately investigated in this research and are answered affirmatively.

From Table 1 it appears that for the sample clicks presented, we do not find a large variance in the dominant frequency, nor in the time duration with only *P. dalli* as an outliner with its 105 μs length.

Observing the data in the scatter plot in Figure 10, we obtain a good insight into the restricted behaviour of the dominant frequency, which ranges from 120 kHz to 143 kHz. This is in contrast with, for example, Tursiops, where more than an octave variation in domf was found (Kamminga & Beitsma, 1990) at a lower range on the frequency scale. To enhance the nature of domf, a clicktrain of a wild Tursiops is pictured on the left. This shows the nature of one of the differences in Tursiops sonar signals from that of Phocoenidae. Most clear is the difference in time duration, as Tursiops concentrates along a lower value of 30 μs. The difference that can be observed in figure 10 is caused by the sample frequency that presents an accuracy of 1 kHz. We are still mulling over the question as to why *P. dalli* uses this extremely long duration click of 8–12 cycles. This might be just a simple method to get more energy in the transmitting beam. Probably it has also to do with the fact that *P. dalli* is a pelagic animal, while the other observed members are more coastal species. However, focussing on the spectral representation, which shows a remarkable concentration around domf (relative frequency bandwidth of 9–12%) indicates

that for a detection problem the animal could rely on a better resolution in frequency than the other members of the Phocoena. It seems reasonable to attribute a certain dolphin preference for doing the signal processing in the frequency domain. It would be interesting to search for a concordance in the hearing system of this species. It is tempting, to calculate the frequency resolution constant for this long-duration click, following Woodward's definition (Woodward, 1963). However, the variance concept ('sharpness') could be used as a measure of the resolution of the spectrum when compared with the width of the envelope of the time function, thus indicating that there could be a certain preference for the Dalli dolphin to operate in the frequency domain. The location of *Phocoena sinus* in the scatter plot shows that the clicks of this species fit nicely in the cluster that is formed by other members of the Phocoeninae subfamily. This is further supported by the correlation factor as a shape criterium applied to *N. phocaenoides* and *P. phocoena*, giving a figure of 0.76 and 0.73, which becomes more or less visible on inspection of the typical examples of these clicks.

Finally, we are still left with the phenomenon of decomposition of the wave form of the Phocoenid members. It is remarkable that *N. phocaenoides* shows to be an exception because of the symmetrical time envelope which allows one to suffice with one Gabor model, which might be indicated by the relative low number for $\Delta t.\Delta f$ of 1.10. With regard to the other members, the difference in the time shift of the first and second Gabor pulses of the decompositon of the click are too significant to be ignored. It is tempting to indicate the time shift between them as a probably morphological feature that distinguishes the species. Further research, especially in the direction of functional forehead anatomy should be carried out, preferably with modern techniques like CT and MRI tomography.

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