

INVESTIGATIONS ON CETACEAN SONAR VI. SONAR SOUNDS IN *ORCAELLA BREVIROSTRIS* OF THE MAKAHAM RIVER, EAST KALIMANTAN, INDONESIA; FIRST DESCRIPTIONS OF ACOUSTIC BEHAVIOUR.

C. Kamminga, H. Wiersma, W.H. Dudok van Heel, Laboratory for Information Theory, Delft University of Technology, Mekelweg 4, Delft, The Netherlands, and Tas'an, Gelanggang Samudra, Oceanarium Jakarta, Indonesia.

*Summary*

Time and frequency representations of hitherto unknown echolocation signals registered from several captive *Orcaella brevirostris* (Gray, 1866), including a young female *Orcaella* born in captivity, are presented. The recordings of this species from the Makaham river of East Kalimantan exhibit a basic type of sonar sound, already known from other odontocetes, i.e. small time-duration bandwidth signals, with emphasis on a small time-duration of about 25-30  $\mu$ sec.

The single-component main sonar signal consists of only a few cycles ( $N_c \approx 2$ ) of a dominant frequency around 60 kHz, with small deviations. The time duration bandwidth product  $\Delta t \cdot \Delta f$  is in the order of 1.10, one of the lowest found this far for the ten species we have investigated in recent years, and equals in this respect the high-frequency component of *Sotalia* sonar. There was little variety in wave shape. Pulse trains are rather regular in nature, and small changes in the repetition rate are noted, mostly in the order of 40-60 Hz.

The Irrawadi dolphin appears to be a lively, fervently vocalising animal. The vocalising intensity reminds one of *Inia geoffrensis*. Nevertheless, even in playful behaviour or pursuit situations, no audible whistles or pure tones were observed, not from the pregnant animal, nor from any of the others.

A detailed analysis of a couple of complete pulse trains is presented and comprises the unravelling of the sounds of two animals, vocalising together. These two pulse trains were fully processed with regard to their dominant frequency to get an exact insight in the trend. We noted only slight deviations from the value of 60 and 70 kHz. There is no substantial correlation with the pulse repetition rate.



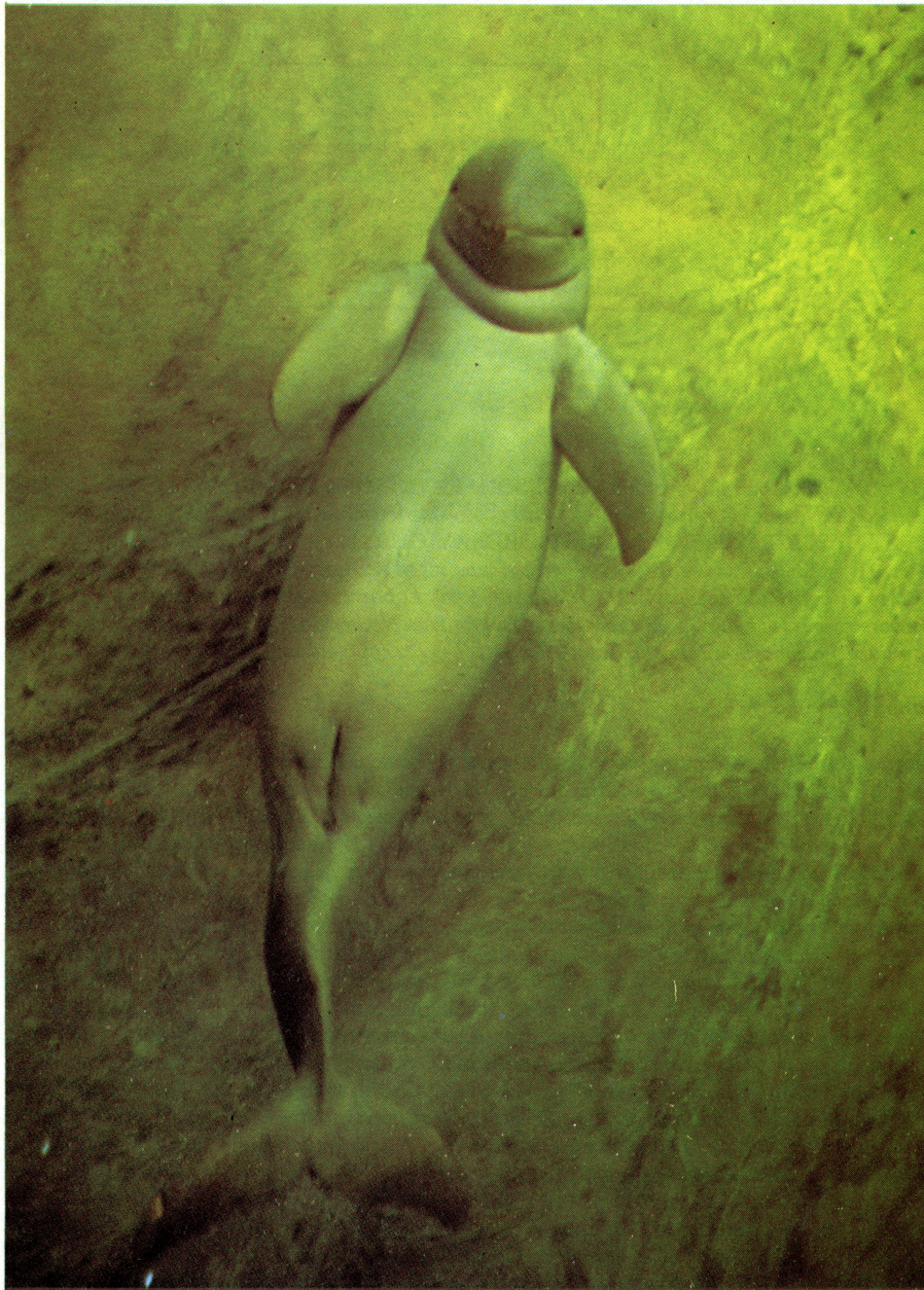


Fig.1. Pregnant *Orcaella brevirostris* swimming upside down in quarantine pool at the Oceanarium Jaya Ancol, Jakarta.



Based on previous studies of a number of species of the littoral/estuarine and riverine type (KAMMINGA, 1977; KAMMINGA AND WIERSMA, 1981; WIERSMA, 1982), an ecological classification of odontocetes has been proposed, including as well the sonar capabilities of a number of different dolphins with regard to their habitat (DUDOK VAN HEEL, 1981).

Recently, the authors, in close cooperation with the scientific staff of the Oceanarium in Jakarta, Indonesia, had the opportunity to study two more species, *Orcaella brevirostris* and *Tursiops aduncus*, from East Asia, which can now be compared with the species which were already known with respect to their bio-acoustic behaviour. The species *Orcaella brevirostris* (GRAY, 1866) is the subject of this paper, which is aimed at providing an initial outline, accentuating sound production.

In terms of evolution, *Orcaella* is classified as one of the oldest 'modern' species (DUDOK VAN HEEL, 1981) which has been 'forced' inshore by more recent newcomers. In this case two populations evolved: a riverine one and a littoral/estuarine one. Field observations show that the species has a rather large geographical distribution (Fig. 2), from the coasts of the Gulf of Bengal down to the northern coast of Australia, as well as in the Irrawadi and other rivers such as the Mekong in South-East Asia (MORZER BRUINS, 1966) and the Mahakam river, East Kalimantan (TAS'AN et al., 1980). Whether the estuarine/littoral *Orcaella* represents a subspecies with respect to acoustical behaviour remains to be seen. The habitat of the river population, considered just as we did with *Inia geoffrensis* in the light of acoustical behaviour, does not call for a complicated sonar, but rather for a short-range navigational one, suitable for functioning in a turbid environment. On the other hand for the littoral population, one might expect a similarity to *Phocaena* and *Delphinapterus*.

Thus an intriguing question emerges: Does the reciprocal of the phenomenon as found in *Sotalia fluviatilis* (comprising also of a riverine and a littoral subgroup) exist? So far, experiments in acoustical behaviour of the latter species have only been performed with the coastal subgroup, indicating two-component sonar signals.

We may remark that in both cases, *Sotalia* and *Orcaella*, the populations are regarded taxonomically to belong to the same species (VAN BREE, 1983).

At first glance the (captive) *Orcaella*, originating from the Mahakam river, East Kalimantan, bears a striking resemblance to *Delphinapterus* in its shape, its almost uniformly dark bluish grey colour and even in its playful behaviour (spraying water from the mouth), although *Orcaella* is a typical tropical aquatic mammal, confined to relatively high water temperatures in the order of 25-30°C.

An interesting anatomical feature was observed during sonar recording in the show pool where 4 animals were housed. After dead fish were introduced in the vicinity of the monitoring hydrophone assembly *Orcaella* did not always approach straight forwards, but moved ahead with an apparent bending of the neck. Unlike other Delphinidae, *Orcaella* has movable cervical vertebrae, as is common in Platanistidae and Monodontidae.

Maneuverability was also demonstrated by rolling and swimming upside down (Fig. 1).

Like other delphinids, *Orcaella* appears to have good eyesight. However, when we threw a handful of fish in their show pool near the hydrophone assembly, they would come to grab a fish, using their sonar. They would turn and "look around", but to our astonishment would not take a fish in plain view less than 100-150 cm away, as if they hadn't noticed it, but instead would first scan the near environment with sonar and only then capture their prey. Lastly, scanning for ensounding the hydrophone was observed, from nearby as well as at a distance.

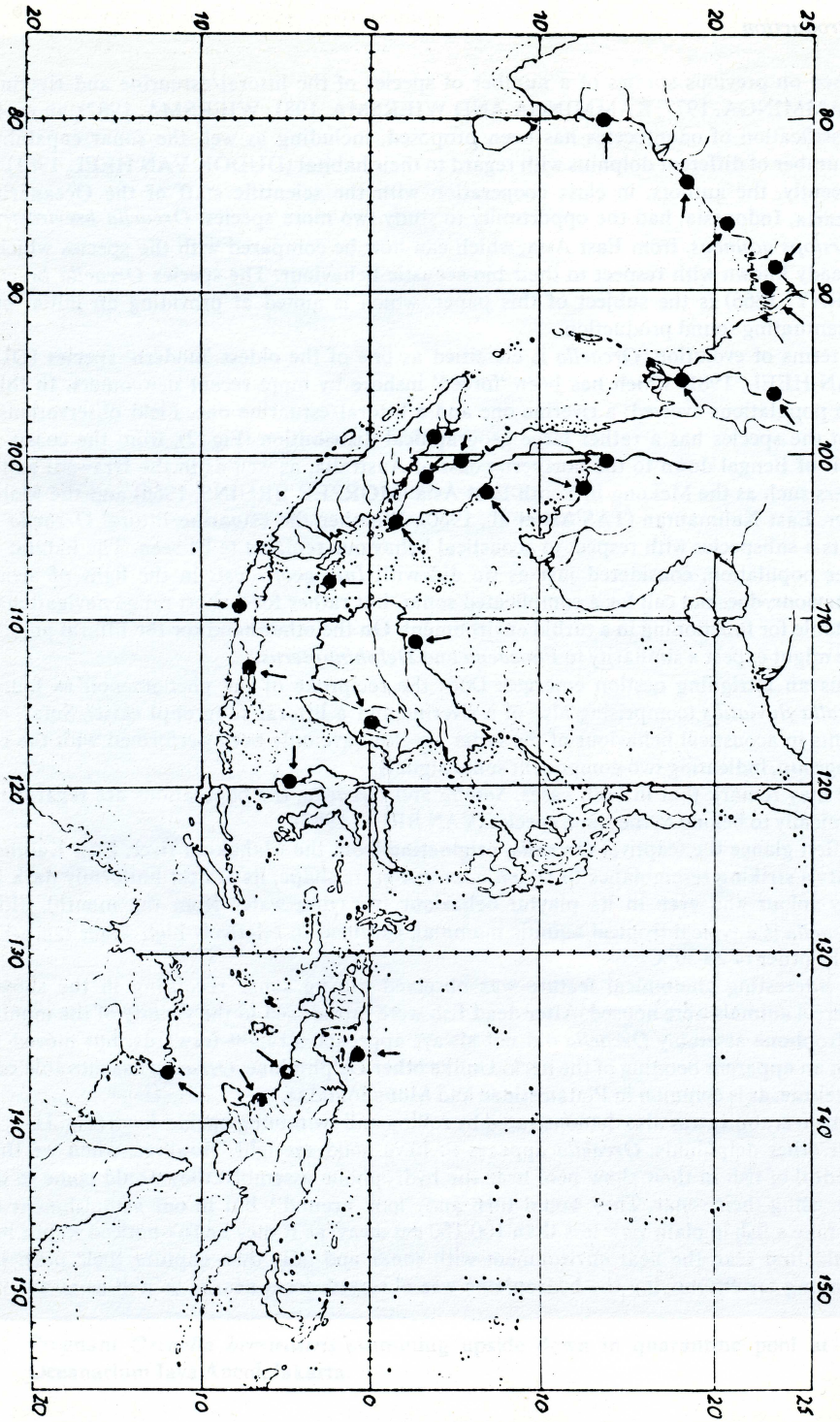


Fig. 2. Map showing the localities where *Orcella brevirostris* has been sighted. (After MOZZER BRUYNS, 1966).



QUARANTINE TANK (ORCAELLA)

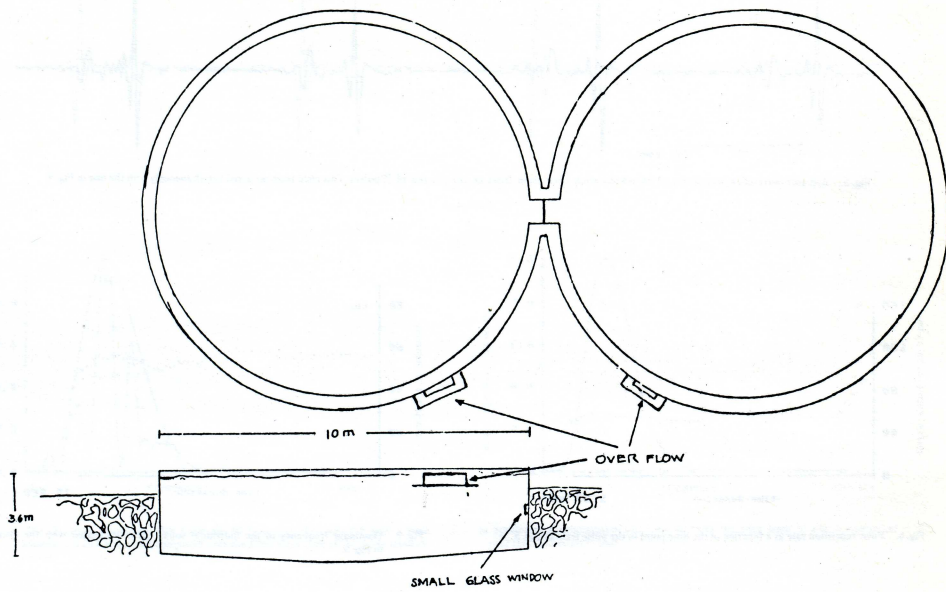


Fig. 3. Configuration of the quarantine pool.

SHOW TANK (ORCAELLA)

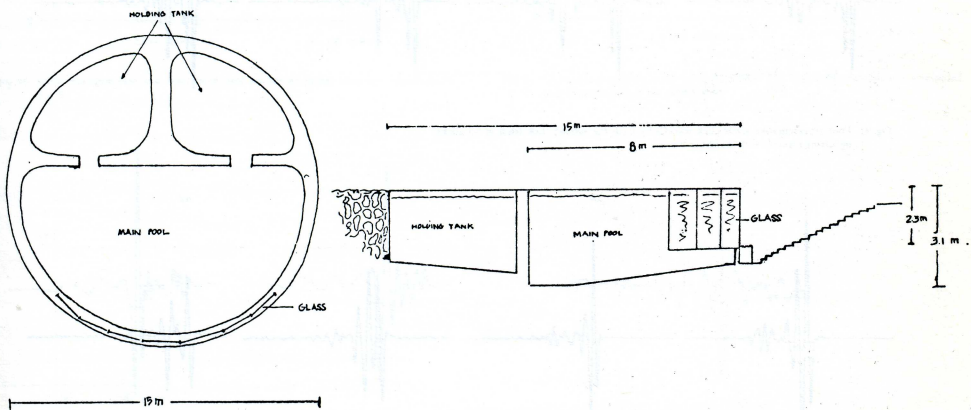


Fig. 4. Configuration of the show pool.





Fig. 5. Representative-click waveforms of an echolocation click train from *O. brevirostris* of 75 pulses. This click train occurred simultaneously with the one in Fig. 9.

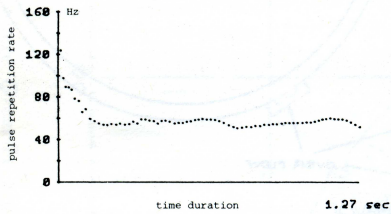


Fig. 6. Pulse repetition rate as a function of the time point in the pulse train of Fig. 5.

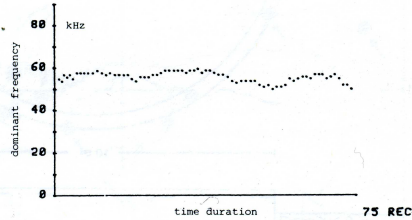


Fig. 7. Dominant frequency of the individual sonar clicks associated with the click train in Fig. 5.

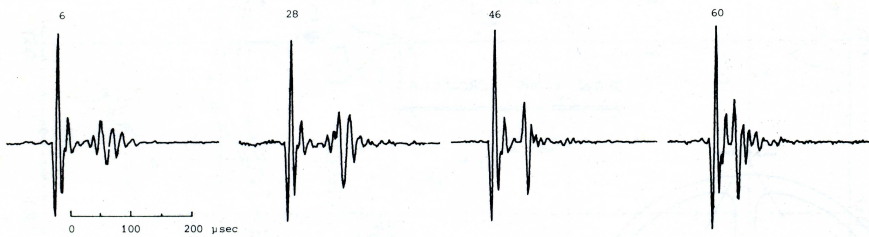


Fig. 9. Four representative sonar click waveforms from the second click train of 65 clicks, occurring together with the one in Fig. 5.

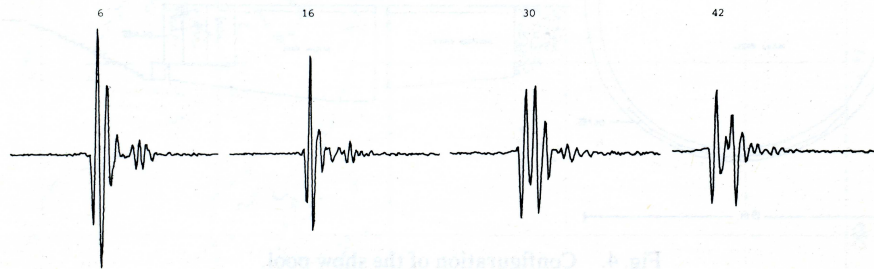


Fig. 12. Typical sonar waveforms of the pregnant *O. brevirostris*. Note the split-pulse phenomena in pulse 42. Total number of pulses is 99 during 1.15 sec.



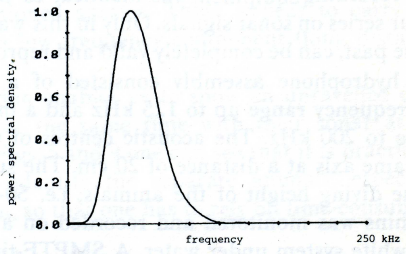
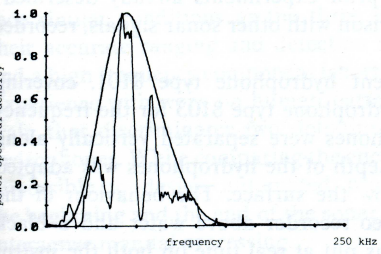
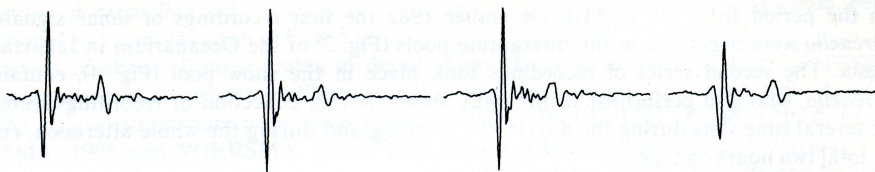


Fig. 8. a. The spectrum associated with pulse no. 60 from Fig. 9, computed over a time window of 1.024 msec. and computed over the 1/2 sec main part of the pulse (smooth curve).

b. Spectrum of echolocation click no. 46 from the click train in Fig. 5, computed over the 30 μsec main part.

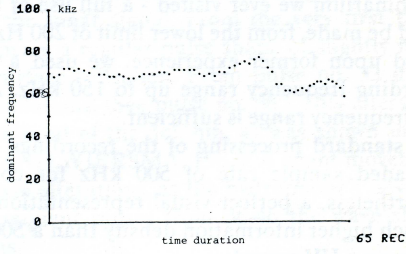
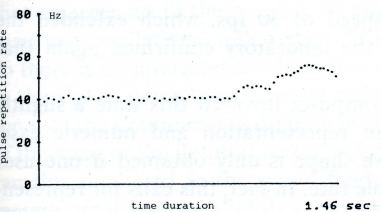


Fig. 10. Pulse repetition rate as a function of time for the 65 pulses from the pulse train in Fig. 9.

Fig. 11. Dominant frequency in the pulse train from Fig. 9 as a function of time, computed over the main part of the sonar pulse.

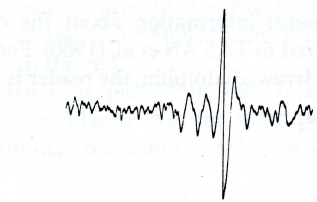
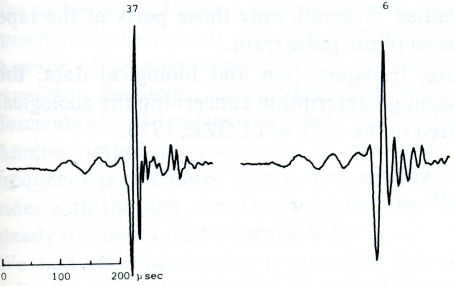


Fig. 13. a. Example of an echolocation waveform of a young female *O. brevirostris* preceded by 2 1/2 periods of a low level 18 kHz component (left) and a waveform from one of the show-pool population, showing the same phenomenon, but this time 180° out of phase (right).

b. Sonar waveform from *Sotalia fluviatilis guyanensis* with an identical low-level, low-frequency component of 2 1/2 periods. Recorded on Sept. 19, 1977 after six weeks of captivity.



In the period from 6th to 11th December 1982 the first recordings of sonar signals from *Orcaella* were registered in the quarantine pools (Fig. 3) of the Oceanarium in Jakarta, Indonesia. The second series of recordings took place in the show pool (Fig. 4), containing 4 *Orcaella*, who also performed in the daily shows. A rich collection of recordings were made at several time slots during the day: in the morning and during the whole afternoon, covering in total two hours on tape.

The pregnant *Orcaella* (Fig. 1) was kept separately in a tank, which was adjacent to and connected with another tank housing, with two other specimen and a young female *Orcaella*, born in captivity in July 1979.

The recording equipment was identical to that in our prior experiments already described in our series on sonar signals. Only in this way a comparison with other sonar signals, recorded in the past, can be completely valid and reproducible.

The hydrophone assembly consisted of a measurement hydrophone type 8101, covering the frequency range up to 125 kHz and a miniature hydrophone type 8103 for the frequency range to 200 kHz. The acoustic centres of the hydrophones were separated vertically along the same axis at a distance of 20 cm. The suspension depth of the hydrophones was adapted to the diving height of the animals, i.e. 50-60 cm below the surface. The behaviour of the dolphins was monitored and recorded on a colour video recorder above water and a black and white system under water. A SMPTE-time code was put at real time on both the instrumentation recorder and the audio channel of the video recorder to obtain synchronisation of sound and behaviour. The lower bound of the accuracy for timing was 20  $\mu$ sec.

Due to the excellent noise conditions - the Jakarta Oceanarium is the best soundproof dolphinarium we ever visited - a full use of the available signal-to-noise ratio of the recorder could be made, from the lower limit of 200 Hz on.

Based upon former experience, we used a recording speed of 30 ips, which extended the recording frequency range up to 150 kHz. Analysis in the laboratory confirmed again that this frequency range is sufficient.

Our standard processing of the recordings by a mini-computer involved this time a slightly upgraded sample rate of 500 kHz for convenience in representation and numeric ease. Nevertheless, a perfect visual representation of the wave shape is only obtained if one uses a much higher information density than a 500 kHz sample rate. In fact, this calls for representation on a UV-recorder.

For more details, the reader is referred to KAMMINGA AND WIERSMA (1981) and WIERSMA (1982).

During the selection of the pulse trains to be studied in detail, only those parts of the tape were chosen that covered nominal output during most of the pulse train.

For more general information about the capture, transportation and biological data, the reader is referred to TAS'AN et al. (1980). For a thorough description concerning the zoological aspects of the Irrawadi dolphin, the reader is referred to the work of LLOZE, 1973.



The nature of *Orcaella's* echolocation clicks shows some intriguing facts that could best be illustrated by examples given in Figs. 5 to 13.

The analysis of about 50 pulse trains in detail shows the total absence of a low-frequency sonar component as is present in *Phocoena phocoena*, *Delphinapterus leucas* and *Sotalia fluviatilis guianensis*, inshore population (DUDOK VAN HEEL, 1981, KAMMINGA AND WIERSMA, 1981 and WIERSMA, 1982). This refutes a bi-frequency sonar behaviour for *Orcaella*, as far as the river population is concerned. The habitat of this *Orcaella* population, just as in *Inia*, does not call for a complicated sonar; instead a short-range navigational one will do, suitable for functioning in a turbid environment.

As yet, no statement can be made about the estuarine/inshore population, which might face similar conditions as the three earlier mentioned species. These appear to carry out their accurate ranging and detection tasks with a low frequency component (long distance) and a high frequency component (short range).

Experience with work on human pattern recognition enables us to show an unravelled click train that discriminates two dolphins "looking" at the same time with their sonar at the hydrophones. While comparing the click trains in Figs. 5 and 9 one can see that it is practically impossible to design automated procedures to identify the separate animals, especially the beginning and the end of the sonar data stream, so that one has to rely on time-consuming interactive manual processing.

Moreover, in this case a video recording does not tell which animal is vocalising either. Fig. 5 shows in detail a sample of eight pulses, taken from one of the two click trains that occurred together. These samples, taken at irregular intervals out of the total number of 75 clicks over a duration of 1.27 sec. give a typical insight into the changing wave shape around the main, consistent 25-30  $\mu$ sec. part of the sonar signal. From the very first pulse that emerges up to the number 30 click there appears a regular pulse shape of slightly more than two oscillations, followed at 75  $\mu$ sec by a surface reflection. From pulse no. 32 up to 46 there is an interference within less than two oscillations. (See pulse no. 36.) This alteration in the signal stems from internal reflections in the head of the dolphin, as was shown in the sonar of the Commerson's dolphin (KAMMINGA AND WIERSMA, 1982). A slight movement of the head of the dolphin accounts for typical phase alterations, as the hydrophone's position remains unaltered in the sound field. In the subsequent pulses from 36-46 the wave shape remains unaltered for slightly under two oscillations.

This same phenomenon reappears from pulse no. 61 up to 72 and onwards. It is now clear that a randomly chosen click does not have validity as a 'typical example'; sonar behaviour has to be studied over a complete pulse train. This illustrates again that averaging a large number of pulses yields a misinterpretation of the dolphin's echolocation pulse shape.

A graph of the pulse repetition rate in real-time intervals is presented in Fig. 6. After an initial repetition frequency of 120 Hz - the beginning of the inspection of the hydrophone - it descends after 10 pulses to a steady rate of 50 Hz until the end.

Another important parameter of the sonar behaviour is plotted in Fig. 7. The dominant frequency is calculated over a time window of 30  $\mu$ sec placed over the main part, and coincides with the first zero crossing after the discontinuity. We found in this way a surprisingly steady frequency, just under 60 kHz.

We had the opportunity to examine the skull of an Irrawadi dolphin, belonging to the collection of the Institute for Zoological Taxonomy, University of Amsterdam, and to compare it with various skulls of each *Tursiops truncatus*, *Lagenorhynchus albirostris* and *Delphi-*



*napterus leucas*. The logical conclusion of this examination could only lead to the assumption of a dominant frequency around 60 kHz in *Orcaella*.

A typical example of the spectral shape is given in Fig. 8b and shows the same aspect already shown in earlier works (WIERSMA, 1982). At first glance there appears to be no correlation between the plots in Figs. 6 and 7, but this has not been investigated in detail.

The other pulse train, as indicated in Fig. 9, occurring with a lower pulse repetition rate of 40 Hz during the first second of its total duration of 1.46 sec, is shown by taking four pulses out of the total number of 65 pulses. An even more consistent pattern for the first 30  $\mu$ sec appears.

The same phenomenon of wave shape consistency over slightly more than one and a half periods of the dominant frequency is present again, pertaining this time to the entire pulse train. More so than in the foregoing analyses of cetacean sonar, one is amazed by the way in which a biological system could produce a signal of such a short time duration, less than two periods, a fact that will have to be mulled over by interested physicists, in search of examples of real-world oscillations occurring unexpectedly in nature.

A comparison of the pulse repetition rate in Fig. 10 with the evolution in dominant frequency as presented in fig. 11 does tempt one to expect some correlation between the two graphs in the final part of the pulse train. Looking back at Figs. 6 and 7 this is a rather speculative idea. A comparison of Figs. 7 and 11 now reveals a dominant frequency just above 70 kHz, decreasing at the very end to 60 kHz.

To round off the description of this click train, an example of the spectral representation of the main part of the sonar pulse no. 60, denoted by the smooth line in Fig. 8a, is given together with the spectrum of the entire signal plus additive interpulse noise, over a time window of 1.024 msec. The spectrum obtained in this way clearly shows three more peaks, due to reverberations that follow the proper echolocation click. Note that both spectra are normalised, i.e. the smooth line is not to be conceived of as the envelope; the broadening of the spectrum is an intrinsic property of the Fourier transform that enlarges as the time function gets shorter, thus illustrating in some way the general uncertainty relation. As is evident from these spectra in Figs. 8a en 8b, the spectral behaviour of different Irrawadi dolphins do not vary considerably in relation to the other cetaceans we have studied. Once again it turns out that the frequency range of cetacean sonar is limited and that no significant frequency components as high as 256 kHz occur, which would not be appropriate for a bio-echolocation system.

Table 1 gives some indication of the intrinsic parameters of the pulse train portrayed in Fig. 9.

Table 1.

pulse no.	$\Delta t$ ( sec )	$f_c$ (kHz)	$\Delta t \cdot \Delta f^*$	$N_c$
4	24.8	75	1.10	1.86
6	25.2	73.9	1.15	1.86
28	24.9	73.8	1.09	1.83
60	25.3	73.	1.21	1.85

\*theoretical lower bound by definition is  $\Delta t \Delta f = 1$ .



The sonar clicks of the pregnant *Orcaella* are presented in Fig. 12 in four samples out of 99. Because this animal was the only one in a pool, we were freed from the tedious procedure of unravelling different vocalisations. After the description given above, the inspection of the wave forms is left to the interested reader.

The last two things worth mentioning concern a sonar pulse from the young female *Orcaella* (Fig. 13a, left) and one pulse extracted from the enormous amount of recordings taken in the show pool (Fig. 13a, right). The click of the young *Orcaella* definitely contained some low-frequency (18 kHz) side effect before the actual echolocation pulse started. The energy in these two oscillations of low amplitude is too low to function as a second frequency component (2% of the total energy). The same phenomenon was observed many years ago in the first recordings of *Sotalia fluviatilis guianensis* in 1977 (Fig. 13b). Today's knowledge of the sound production system of cetaceans is insufficient to explain this side effect and remains to be mulled over by the anatomist, in search for the biological features of vocalisations.

### Epilogue

Like several other species *Orcaella brevirostris* appears to have an elementary sonar signal, consisting of about 2 sinusoidal cycles. These may be optionally followed by some disturbing reverberation, which sometimes even obscures almost the entire waveform. The spread in frequency due to the rather abruptly truncated time signal, however, remains extremely limited. In fact, the product of time duration and frequency spread is often as low as is the theoretical limit. Usually, manmade systems with similar goals attempt to achieve a very high value for this product, the philosophy being that with the emission of a singular pulse an optimum simultaneous resolution is aimed at for both range and velocity.

Technically speaking, although it would not be so complicated to design a system for 'dolphin-like' signals an enormous amount of processing would have to be done at the receiver site to obtain a reasonable resolution, at least in range. This is probably what the dolphin is doing: the animal uses a rather unsophisticated signal, and the intelligence in the overall system is concentrated in the receiver (not the ear, but the brain). There remains, however, the rather unique feature of a physiological system which produces such sharply pitched very time-limited signals. From the point of realisability it probably is not particularly easy to generate these signals in a biological system, for no other known living creature is capable of producing such sounds. Since dolphin echolocation is unquestionably effective and since their sonar signal has only a minimum number of degrees of freedom, the processing takes place inside the brain, where the performance originates. This implies that with respect to the problem of mass-stranding of some pelagic species no anatomical explanation need be sought (DUDOK VAN HEEL, 1962, 1966 and 1981). Although an additional feature is added to the sonar system of some species living in inshore waters (such as a second frequency component, KAMMINGA AND WIERSMA (1981) and WIERSMA, 1982), this is unlikely to be in itself the main or only explanation for the absence of mass-strandings in these species. Probably the brain processing software in "modern" pelagic species fails for some reason. Either due to absence of additional information (the missing second frequency component), a lack of attention, occurrence of an unknown and unexpected situation, psychological factors or a combination of two or more of these parameters. The fact that some species undergo mass-strandings while others do not cannot be accounted for on purely technical or anatomical grounds. Instead, there must be something wrong with the animal's interpretation of the perceived echoes, which we can label, for the time being, as an "acoustical illusion".

### Acknowledgement

The authors are highly indebted to the direction and staff of the Jaya Ancol Oceanarium in Jakarta for their fruitful cooperation in this research on the rather unknown *Orcaella brevirostris*. We thank the Netherlands Organisation for the Advancement of Tropical Research (WOTRO) as well as the Dutch Ministry of Agriculture for their financial support, the Indonesian Institute of Science (L.I.P.I.) for the goodwill supported in preparing our scientific visit to the Oceanarium and not in the least the support of the Royal Dutch Embassy by Mr. F.H.J. Kuipers. Thanks to KLM, for our precious scientific apparatus was taken in good care during transport to Jakarta and back home.

Special thanks are due to all those research workers that contributed to complete the feature description of the acoustical behaviour, in particular Dr. P.H.J. van Bree of the Institute for Zoological Taxonomy of the University of Amsterdam, Prof. Y. Boxma and staff of the Information Theory Group of the Delft University of Technology and Prof. J.W. Verheyen of the State University of Utrecht.

### References

- VAN BREE, P.J.H., 1983. Personal communication.
- DUDOK VAN HEEL, W.H., 1962. Sound and Cetacea. Neth. J. Sea Res. 1(4):407-508.
- DUDOK VAN HEEL, W.H., 1966. Navigation in Cetacea. In: K.S. NORRIS (Ed.) Whales, Dolphins and Porpoises. Univ. Cal.Press, Berkely and Los Angeles, no 27, pp 597-602.
- DUDOK VAN HEEL, W.H., 1981. Investigations on Cetacean sonar, III. A proposal for an ecological classification of odontocetes in relation with sonar. Aq. Mammals, 8(2):65-69.
- KAMMINGA, C., 1979. Remarks on dominant frequencies of cetacean sonar. Aq. Mam. 7(3):93-100.
- KAMMINGA, C., and H. WIERSMA, 1981. Investigations on Cetacean sonar II. Acoustical similarities and differences in odontocete sonar signals. Aq. Mammals, 8(2):41-62.
- LLOZE, R., 1973. Contributions à l'étude anatomique, histologique et biologique de l'*Orcaella brevirostris* (Gray, 1866) (Cetacea-Delphinidae) du Mékong. Thèse Toulouse.
- MORZER BRUINS, W.F.J., 1966. Some notes on the Irrawaddy Dolphin, *Orcaella brevirostris* (Owen, 1866). Zeitschrift f. Säugetierkunde 31(5):367-370.
- TAS'AN, ANNY IRWANDY, SUMITRO, SUKIMAN HENDROKUSOMO, 1980. *Orcaella brevirostris* (Gray, 1866) from Mahakam River. Jaya Ancol Oceanarium, Jakarta.
- WIERSMA, H., 1982. Investigations on Cetacean sonar, IV. A comparison of wave shapes of odontocete sonar signals. Aq. Mammals, 9(2):57-67.