INVESTIGATIONS ON CETACEAN SONAR. I. SOME RESULTS ON THE THRESHOLD DETECTION OF HOLLOW AND SOLID SPHERES PERFORMED BY THE ATLANTIC BOTTLENOSE DOLPHIN, *TURSIOPS TRUNCATUS*

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Summary

A threshold detection experiment was set up to gain insight into the sonar detection capabilities of an Atlantic bottlenose dolphin *(Tursiops truncatus)* by using as a stimulus a pair of iron spheres with identical outer dimensions, one of which was solid and the other hollow.

The subject succeeded in a detection score of 95 out of a series of 100 trials for the discrimination of a hollow sphere rather than a solid sphere with an inner-to-outer diameter of 0.6, while the score dropped to 77 for another 100 trials when the diameter ratio was reduced to 0.4. The latter ratio turned out to present practically the detection limit.

Results suggest that the animal utilized a time difference cue to distinguish between the two, i.e. the difference of time interval between the primary and secondary echoes. In the case of the 0.4 sphere, as compared to the solid sphere, this time difference was 8.5 μsec.

An inspection of the power spectrum revealed a decrease of 25% in bandwidth for the detection of the 0.4 sphere. The animal then used signal energy more concentrated around a slightly lower midfrequency of 40 kHz as compared to 44.4 kHz for the 0.6 sphere.

A comparison of the sonar signals used for fish detection with the ones that were used for the target recognition in this sphere detection problem revealed a shift within the range of optimal hearing sensitivity.

Under water video recordings showed that the direction in which the animal echolocates the spheres conforms to the midline of the snout.

Introduction

The ability of the Atlantic bottlenose dolphin *(Tursiops truncatus)* to perform difficult target detection experiments, both in open waters and in captivity, reveals that these dolphins posses a highly effective sonar system and an exceptional hearing sensitivity. A number of discrimination experiments have illustrated their ability to detect different sizes of spheres, different compositions of targets and different shapes. Remarkable detection ranges have been demonstrated (MURCHISON and PENNER, 1975). Although all of these experiments reveal the effectiveness of the bio-sonar signals of the dolphin, it is not exactly known whether this ability to echolocate depends merely on the intrinsic properties of the signal or on the processing of the echo. Finally, information about the objects is entirely contained in the echo structure, but can be dependent on the nature of the emitted sonar.

It has been reported that bottlenose dolphins use a frequency spectrum extending to about 150 kHz, with peak energy centred between 35 and 60 kHz (EVANS, 1973).

In the following article a description will be given of a detection experiment that was in some ways an outgrowth of an earlier investigation on the sonar capabilities of a dolphin in a captive environment, i.e. a concrete tank (KAMMINGA and VAN DER REE, 1976). From that study, where a hollow sphere with a diameter ratio of 0.6 was to be distinguished from a solid one, it seemed plausible that the dolphin used a time parameter and, more specifically, a difference in the arrival times of the secondary echoes from the targets, due to the elastic waves set up in the spheres when sound waves impinged on them.

From these previous experiments it was also observed that the main energy in the spectrum of the sonar click was located around the point of the optimal hearing sensitivity of *Tursiops*.

Formulation of the problem

In view of the ability of *Tursiops* to perform a difficult task involving echo location, the question arises regarding the manner in which the dolphin sonar is co-ordinated with its signal processing and how it is adapted by the animal for a specific task.
PURVES (1966) has shown that in *Phocoena, Lagenorhynchus* and *Tursiops* the sonar waves they produce is quite adequate to meet the requirements of echo location. It is therefore interesting to further investigate the possibilities of the sonar, relying on the supposed fine discrimination of time intervals. In a paper by YUNKER and HERMAN (1974) an impressive ability to discriminate small temporal differences is reported. On the other hand, if the dolphin is faced with a discrimination task that involves difficulties in the time domain, then there is equally an opportunity to study a possible adaptation of the sonar in the frequency domain. To this end, a detection experiment was set up to ascertain the ability of the dolphin to discriminate between differing shell thicknesses of a hollow sphere.
The animal is thus faced with a changed echo structure, induced by this variation. As the shell becomes thicker, the echo function for the hollow sphere approaches that of the solid sphere. This offers the opportunity, if it is possible to choose the appropriate shell thickness, to establish at the same time in this experiment the threshold for detection. Note that, following DIERCKS and HICKLING (1967), small discrepancies between the elastic constants of the material used in the experiments and in the calculations act upon the elastic behaviour of the sphere in a less degree for a thicker shell, so there is an even better agreement between the calculated and measured echo.
Based on the previous experiment, we have chosen for the thicker shell a diameter ratio of 0.4. After a time interval of six years, it would be intriguing to see if the animal performed as well as she did before, now in a more complicated situation, and to investigate the hypothesis of adaption of the sonar signal, combined with a determination of minimally detectable time intervals.
A recording video tape via two underwater cameras, taken simultaneously with the emitted sonar, would shed light on the behaviour of the animal when she approached the targets and how they were ensonified. From the previous experiment, where some recordings from above the water surface were made, there was already an indication about the way she looked at the spheres.
From series of measurements of other investigators (NORRIS et al., 1961, EVANS et al., 1964, AU et al., 1978) there is evidence that the directional pattern in the vertical plane of the emitted sonar of *Tursiops* indicates an elevation of 15 - 20%. This experiment offers at the same time the possibility to verify on a great many recordings the phenomenon of lowering the mouthline in another task than echolocating for sinking fish or in the circumstance when the attention of the animal momentarily was given to some disturbances in the water.

Experimental configuration and training

Subject

The dolphin in this experiment was again the adult female bottlenose dolphin named Doris, who has been in captivity since September 1969. She was the subject in a previous echolocation experiment some six years ago, where she showed up as a very willing animal.

Targets

The spheres used as stimuli in the recognition experiment were made of cast iron (containing 3.7% C and 1.5% Si, density 6.98 x 10^3 kg/m^3). Three spheres were constructed, each composed of two halves seamed together with a special type of water-resistant resin glue and finished with three layers of black varnish.

One of the advantages of using spheres instead of (long) cylinders which are easier to manufacture is found in the all-circular symmetry, a major property that makes a mathematical treatment of the echo structure more feasible. Another aspect has to do with the incident angle for the ensonifying signal; with a cylindrical target one is not sure that the incident wave is perpendicular to the axis of the cylinder.

Although it was tempting to have the hollow spheres with a vacuum inside, we did not manage to keep the vacuum more than a few days, due to the nature of the iron that was used. In the end, the spheres were filled with dry air, thus serving theoretically as good standard targets. The behaviour of the air is expected to correspond fairly closely to that of a vacuum, since the density is significantly less than that of iron.

Outer diameter was fixed at 15 cm, while the internal diameters of the hollow spheres had a disparity of resp. 9 cm and 6 cm. With these thicknesses of 3 cm and 4.5 cm the energy of the vibration of the shell apparently goes into surface waves.

With an outer diameter of 15 cm, the sphere then appears to have its true or 'optical' diameter at a frequency of about 32 kHz.

The wave number $\frac{\pi d}{\lambda}$ is then greater than 10, thus offering a stable back-scattering cross-section σ. Fig. 1 shows the relationship between the echo-reflecting power of a sphere and the wavelength of the incident signal. The ordinate shows the normalized cross-section area of the sphere, the abscissa the circumference in terms of the wavelength.

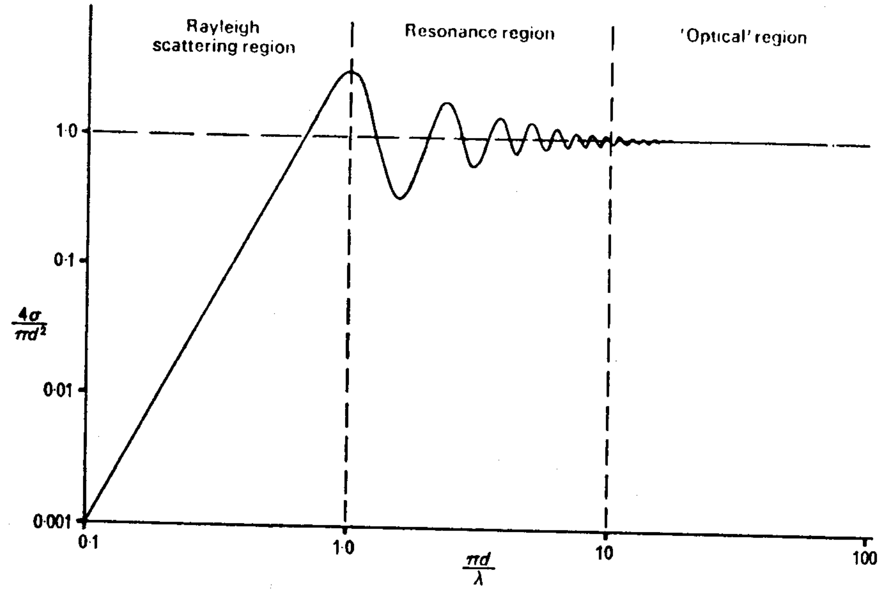


Fig. 1. The relationship between echo-reflecting power of a sphere and the wavelength of the incident signal (from: G. Sales and D. Pye, 1974).

The reflectivity R of the material is related to the acoustic impedances of the substance Zs and the water Zw

$$R = \frac{Zs - Zw}{Zs + Zw}$$

where Z = pc, p being the density and c the acoustic velocity in the material. For iron in salt water, the reflectivity is of the order of 94%. A small part of the energy thus penetrates into the object and causes resonances of the sphere. Obviously, less energy for setting up internal vebrations is available if the acoustic impedance of the material becomes greater. With regard to the aluminium formerly used (R = 84%) there is an increase in intensity of the first echoes and a different velocity of sound. These facts confront the dolphin with a different discrimination task.

Environment

Training and experiments were carried out in the same concrete tank with dimensions of 12 x 6 m and water depth of 2.60 m.

The two target spheres were suspended from a reinforced plastic bridge by nylon ropes of 5 mm thickness, 60 cm under the water surface. The distance between the spheres was 120 cm. In the midline between the spheres, centred at one end of the tank and opposite to the target location at a distance of 8 m was the starting position of the animal. This was the point at which the subject had to wait for a release signal of 4000 Hz, given under water from a type 8100 hydrophone used as a projector. The echolocation trial was actually begun at another place in the tank by placing a type LC 10 hydrophone mounted in a rubber suction cup on Doris' rostrum. This position on the head of the dolphin was chosen since the cleanest signal, with the least amount of disturbance to the animal, is recorded from here. In order to observe the behaviour of the animal when she was carrying out her detection task, two video cameras were installed under the water surface. Fig. 2 indicates the exact placement of the two cameras: one looking from behind the two suspended spheres and the other looking from the side.

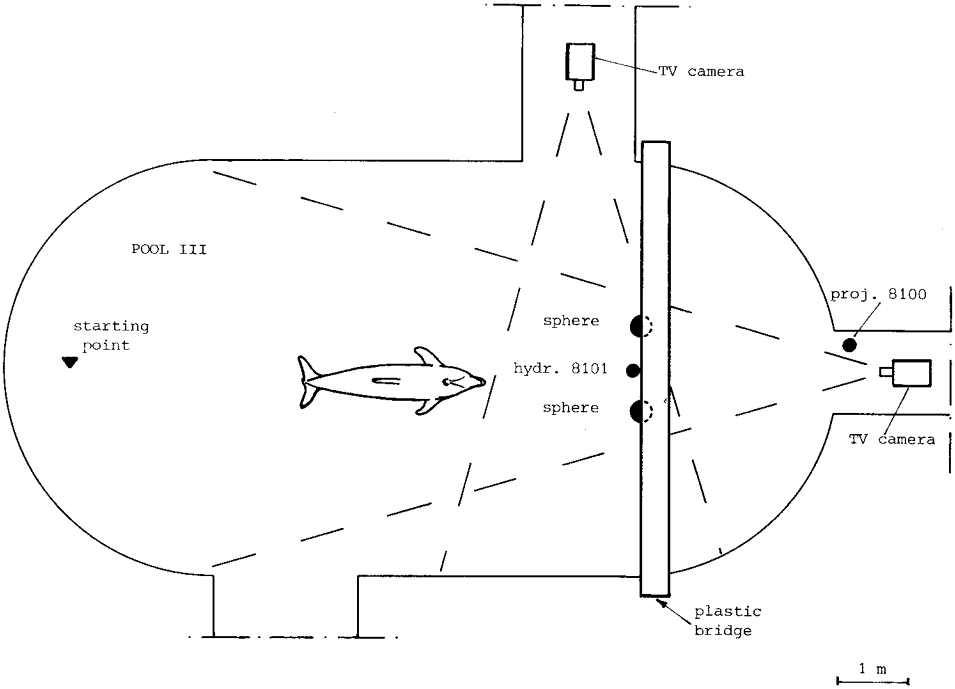


Fig. 2 Schematic arrangement at the experimental location in the pool.

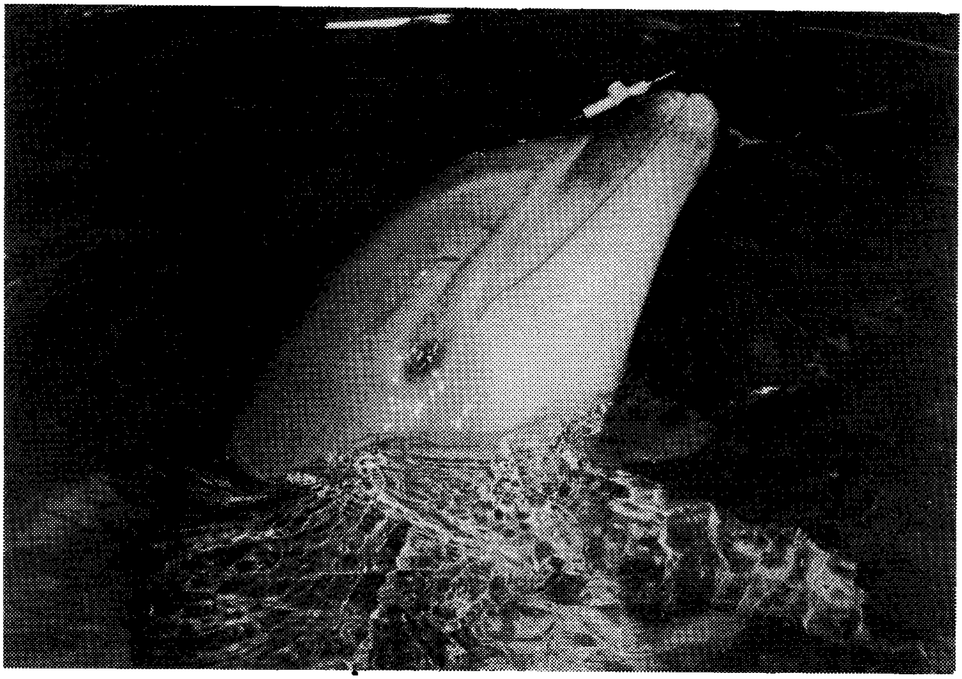


Fig. 2a Mounting of LC-10 hydrophone in the suction cup.

Training

The reward system used in this experiment was the presentation of a piece of fish as a primary reinforcer, and a signal from a dog-whistle was used as a secondary reinforcer. Training was done in two periods, the first covering 26 sessions of one-and-a-half hours each during six weeks, and the second covering 18 whole-day training sessions during another seven weeks. The training as a whole was segmented into five parts:

- The dolphin was habituated to the placing of a rubber suction cup on her rostrum. This was done half way between the starting point and the target location. This part of the training procedure was the most time consuming. After the removal of the cup, a whistle was blown and a piece of fish was presented.
- The rubber suction cup was placed again on her rostrum, this time with the LC 10 hydrophone connected to it. Doris was encouraged to swim around the tank. Sonar signals produced during this training part were used to line up the chain of instruments.
- As an introduction to the next phase of the trial, Doris was trained to approach a plastic target, hanging down from the bridge spanning the tank. To initiate the approach the attention signal was introduced. The learning got good results within a few days, independent of the position of the target on the bridge.
- Then, the starting position for the animal had to be fixed in such a way that the animal's body was positioned away from the target location. Doris was trained to remain stationary in this position, waiting for the attention signal. This phase of the training was concluded by introducing the real stimulus, the two spheres, with the hollow one having the diameter ratio of 0.6. The first sonar registrations were made during these sessions.

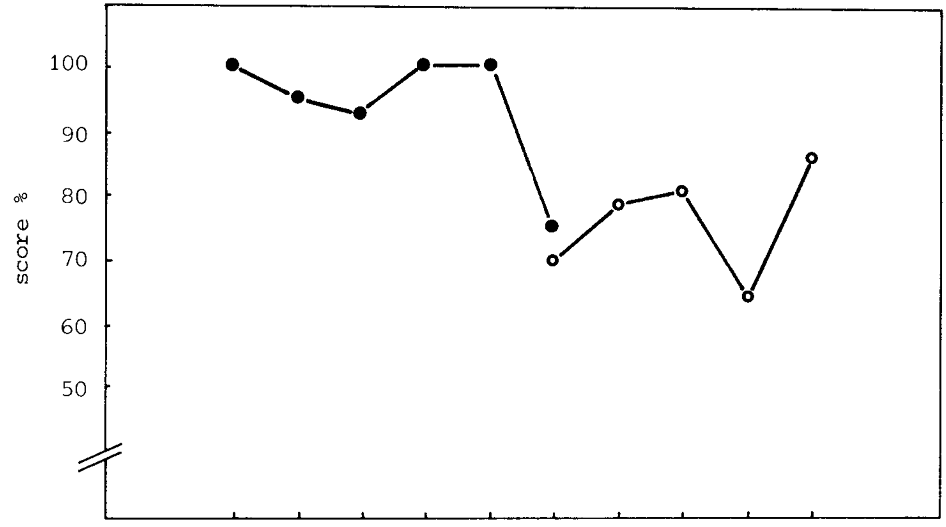
Observations during this stage resulted in the conclusion that without special training Doris was not able by herself to detect the difference between the two targets.

- The final part of the training procedure consisted of the errorless training method, giving less stress to the animal (KELLOG and RICE, 1966; BLOUGH and LIPSITT, 1972).

To visually distinguish the two spheres, the solid sphere was marked with a piece of tape. After nearly a whole day of training, Doris could indicate the marked sphere in favour of the 0.6 hollow sphere. During the subsequent 85 trials the size of the tape was gradually reduced and Doris eventually succeeded in identifying the hollow sphere from the unmarked solid one.

In the final experiment, in which in the first part the 0.6 hollow and the solid sphere were presented and in the second part the 0.4 hollow with the same solid sphere, the spheres were interchanged in a pseudo random way in every trial, thus facing the animal with a new situation every time.

A 100 trials in each series were performed. Results of each series are presented in Fig. 3; these experiments took altogether 10 days in November/December 1978.



days	1	2	3	4	5	6	7	8	9	10
trials	10	20	30	15	17	8 10	19	25	26	20
spheres	0.6 ↔ solid					0.4 ↔ solid				

Fig. 3 Daily score of recognition of the targets a 10 day period, covering a number of 100 trials for each type of hollow sphere.

Experimental apparatus

The echolocating signals of the dolphin Doris were measured in the immediate vicinity of the rostrum. This site was also chosen so that the results of the signals recorded in the previous experiment and the work of others could be compared.

The emitted sonar was recorded simultaneously at a position midway between the targets with a B & K high-sensitivity hydrophone type 8101. A part of the experimental configuration in situ is given in Fig. 4 and shows the bridge, spanning the tank.

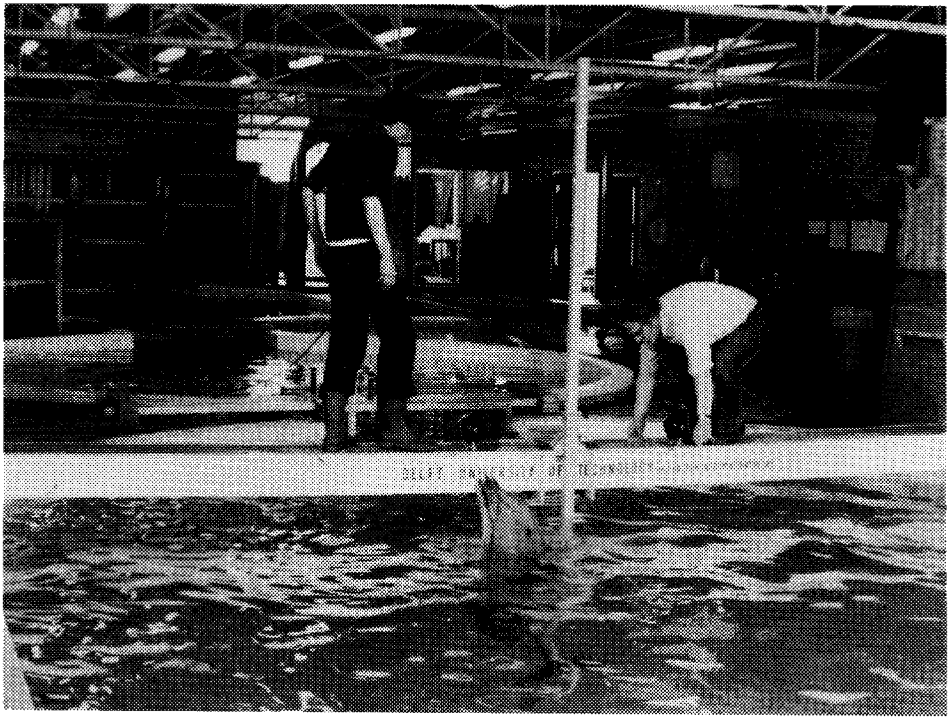


Fig. 4 View of the experimental configuration in situ.

The position of the LC 10 hydrophone, as it is mounted in the suction cup is shown in Fig. 2a; the hydrophone is to be seen pointing slightly downwards. The 8 m-long cable was connected to a point centrally located above the tank, thus allowing the animal to swim freely around the whole tank. After the rostrum signal passed through a 40 dB preamplifier, another amplifier (B & K type 2608) was inserted into the recording chain before it was fed to an instrumentation tape recorder RACAL Store 7D. The complete arrangement of the instrumentation is schematically presented in Fig. 5.

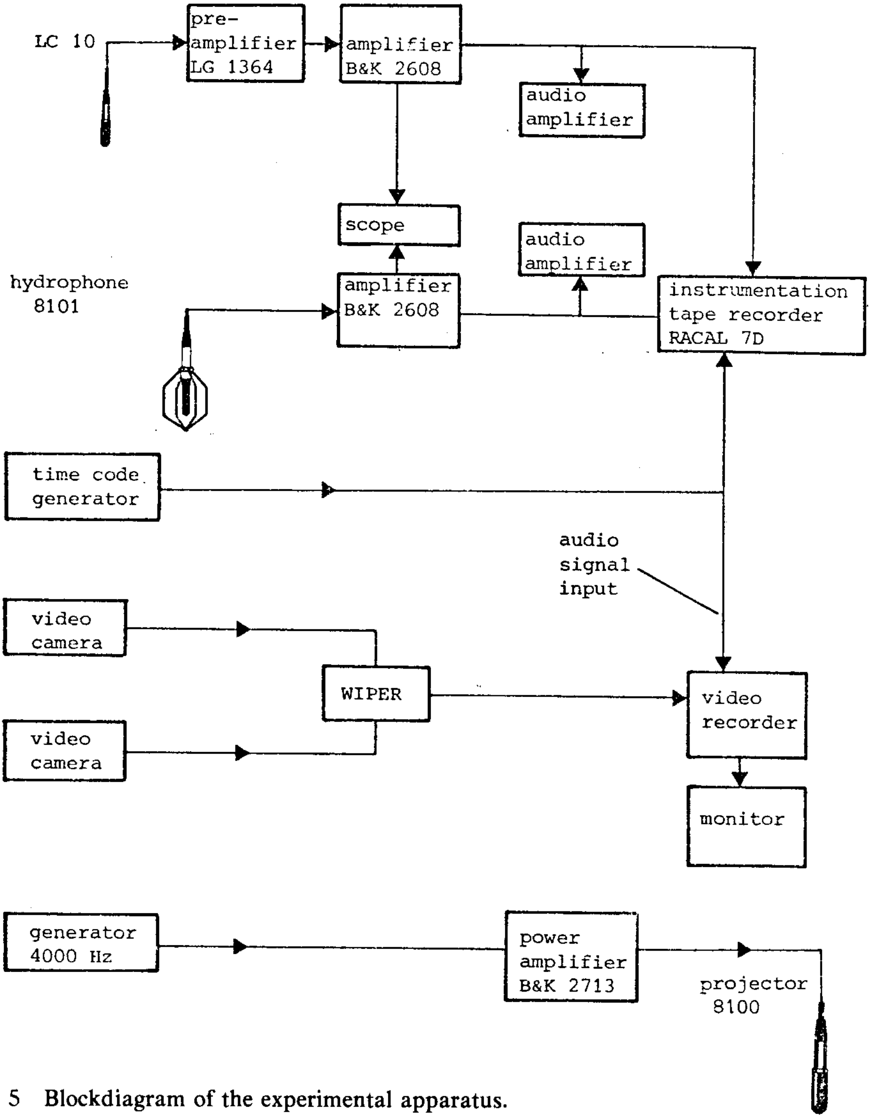


Fig. 5 Blockdiagram of the experimental apparatus.

The recording speed was 30 ips, giving a bandwidth of 150 kHz and sufficient possibilities for slowing down without degradation of the signal. On a separate track on the tape a timing signal from a time-code generator (Systron Donner) was inserted. For synchronizing the sonar signal with the behaviour, this timing signal was also recorded on the audio track of the video-recorder tape. To get a simultaneous and complete overview of the behaviour of the dolphin during the approach and the inspection of the targets, the two video signals from the wide-angle cameras (f 1.7/8 mm) were wiped together on one track. This enabled the trainer to get a monitoring view on the screen. Typical examples of the behaviour of the dolphin during the approach of the targets - from behind the spheres and from the side - are shown in Fig. 6 and 7.

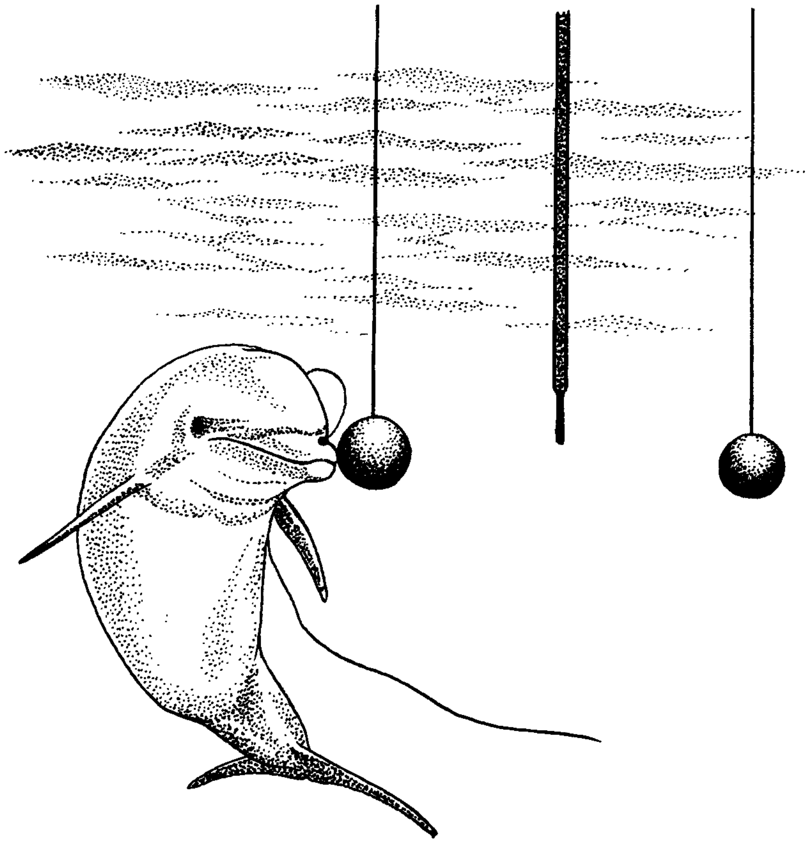


Fig. 6 Doris approaches the targets, viewed from behind the spheres.

Data handling

In order to obtain the necessary information in both the frequency and the time domain, a careful analysis is carried out of a selection of sonar pulses from a number of click trains as recorded during all the trials.

A preliminary inspection of click trains together with the behaviour was done by registering the tape recorded on a UV-recorder (Honeywell Visicorder). Out of all the recorded material four trials for each of the two series were selected for a closer inspection and computation. The signal involved in this final analysis stemmed from the LC 10 hydrophone on the rostrum. In that way, the position of the signal site during the experiment was fixed, and the signal was less corrupted by noise and reverberations.

Fig. 8a and 8b show examples of a pulse train from which several pulses are selected. These click trains were recorded during the last moments of the inspection of the targets.

The selected analogue data was then converted to digital time-series data at a sample rate of 400 kHz and fed into the PDP 11/40 computing system for further analysis.

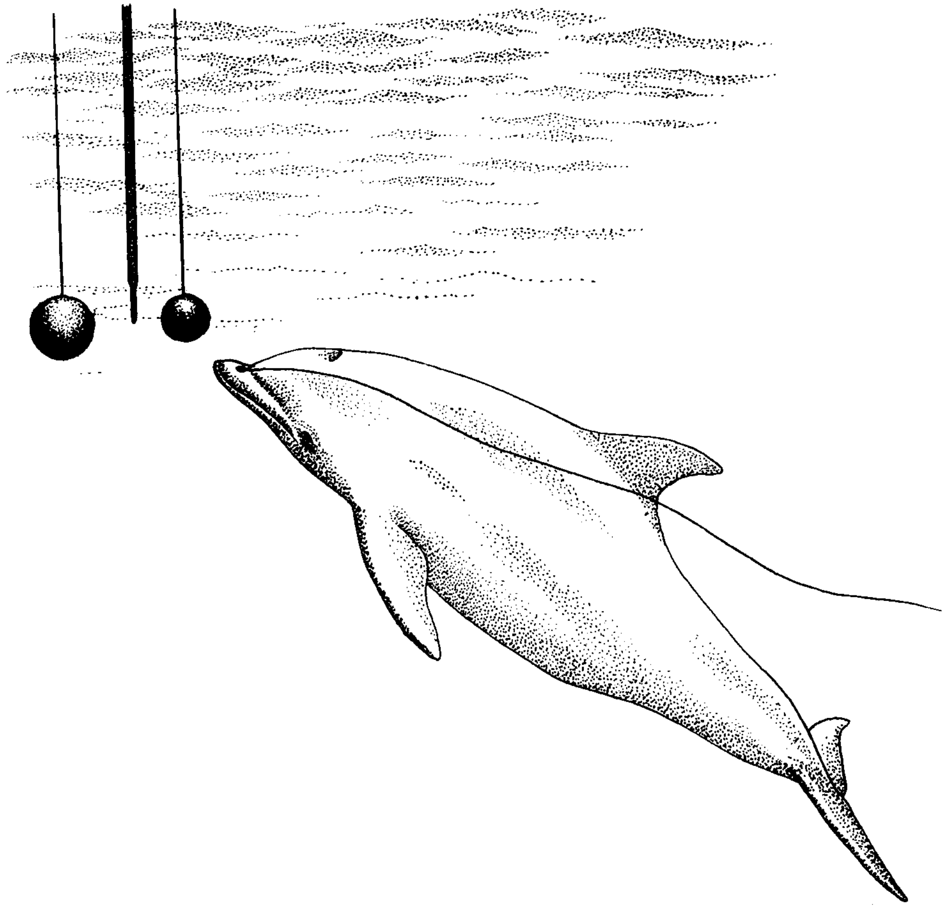


Fig. 7 Doris approaches the targets, as seen from the side.

Results and discussion

Following the last training phase, Doris had to solve the problem of identifying the hollow 0.6 sphere in favour of the solid one. This was done in a 100 trials, during which the spheres were presented in a position that was pseudo-randomly changed every trial. After this session, the 0.6 sphere was replaced by the 0.4 sphere and another 100 trials formed the second session of recogniton, this time being more complicated due to the thicker 4.5 cm shell. Results of both series are presented in Fig. 3 in which the trend of the scores achieved during first six, and then five days are marked.
The succes level turned out on an average to be 95% for the 0.6 sphere and dropped to a statistically significant lower level of 77% for the 0.4 hollow sphere.
As is shown in Fig. 9 there is no overlap in the two-sided 5% confidence intervals.

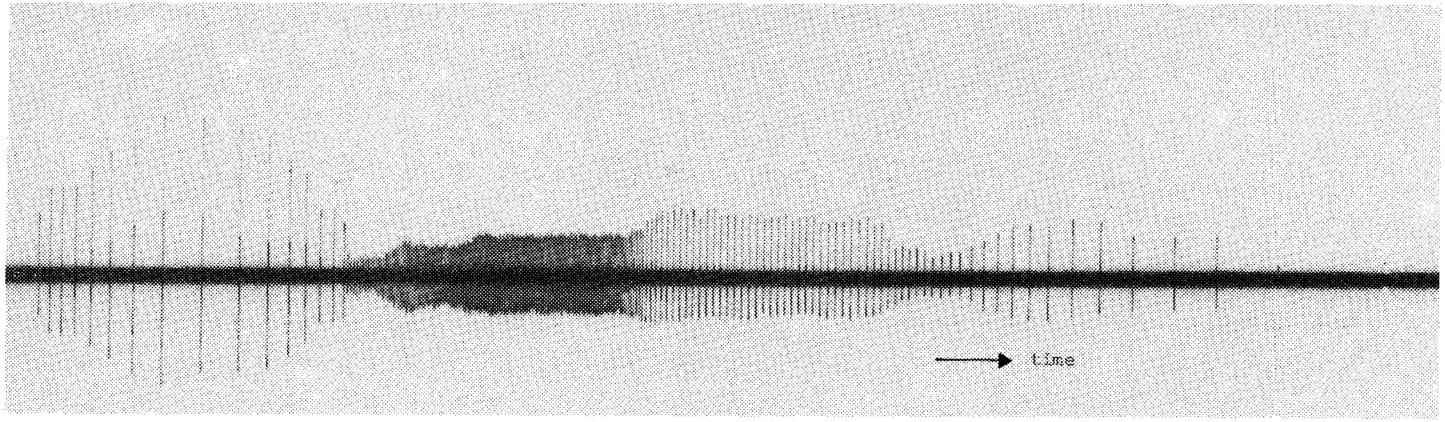


Fig. 8a An echolocation click train during the last phase of inspection of the targets; 0.6 ↔ solid sphere.

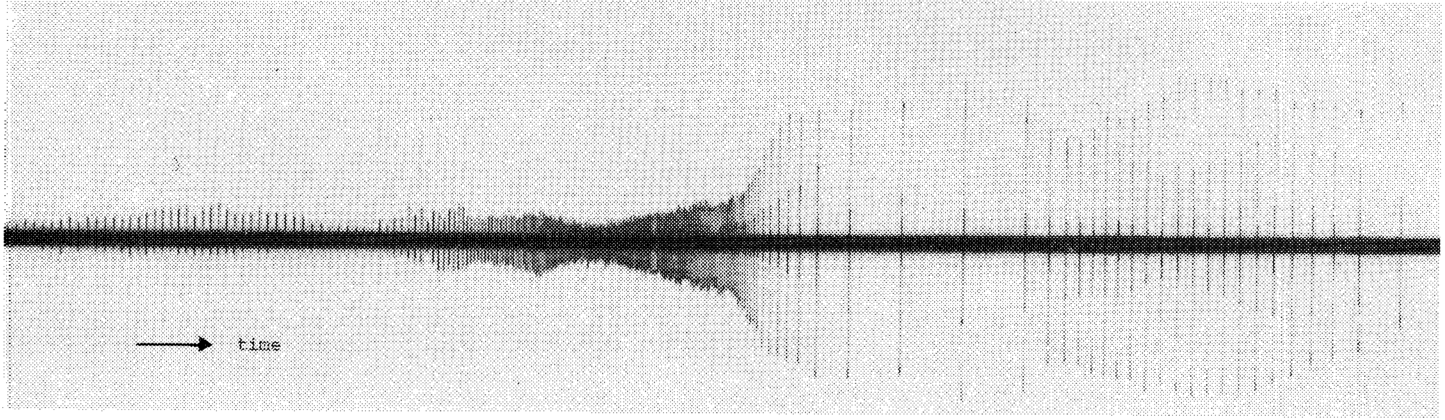


Fig. 8b An echolocation click train during the last phase of inspection of the targets; 0.4 ↔ solid sphere.

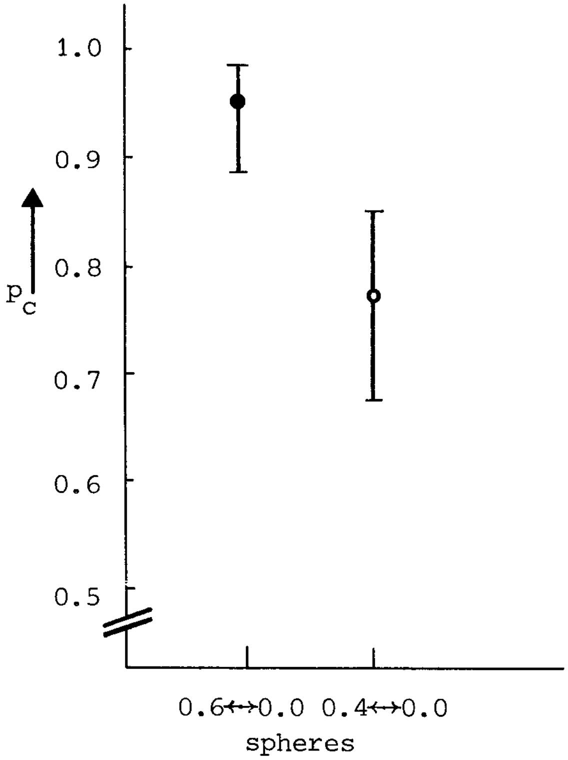


Fig. 9 Two-sided confidence interval for $P_{correct}$.

Sonar signals

1. Observations

A random selection of 4 recordings out of a correct identification for both the 0.6 and 0.4 spheres was made for further analysis in the time and frequency domain. Sonar signals registered by the LC 10 were preferred for already mentioned reasons.

There tends to be some variation in the click wave shape for the sonar as recorded in the vicinity of the rostrum.

Some three representative prototypes could be distinguished. The most frequently occuring pulse in all pulse trains is plotted in detail in Fig. 10. In this type, pulse duration is of the order of 60-100μs. The second pulse type occurs mostly at the beginning of a pulse train. This main pulse duration is shorter than for the type 1 pulse, now about 20μs for the pronounced oscillation downwards, with a total duration again of 100μs. Fig. 11 gives a plot of prototype 2. Occasionally a third type of click is observed at the end of a click train and comprises several oscillations. Complete duration is still of the order of 100μs, as is to be seen in Fig. 12.

There is only a slight deviation from the three prototypes in all the observed click trains, which allows averaging in the frequency as well as in the time domain.

Besides the sonar clicks emitted by the dolphin to 'interrogate' and compare the targets, there were also several registrations that contained primary and secondary reflections from the

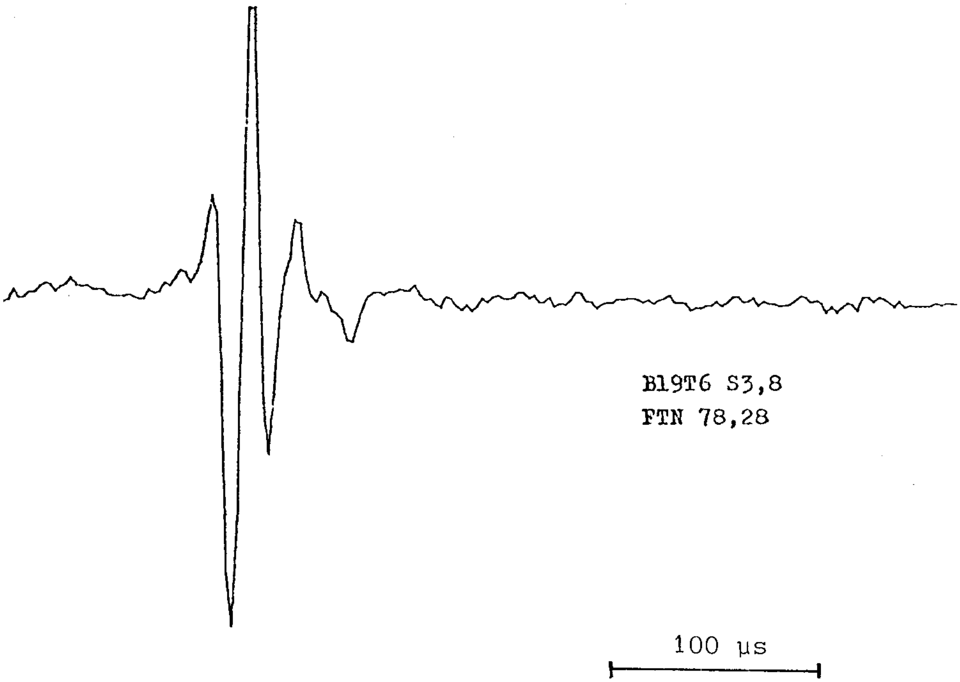


Fig. 10 Example of a single echolocation pulse, type 1.

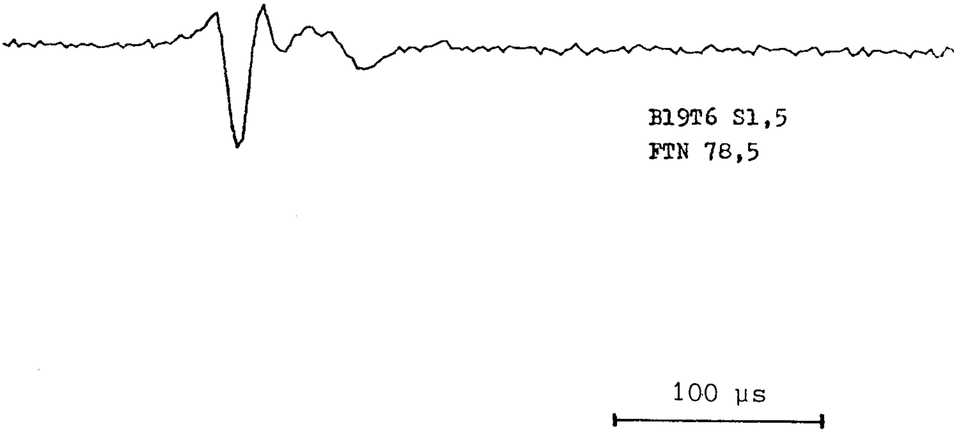


Fig. 11 Example of a single echolocation pulse, type 2.

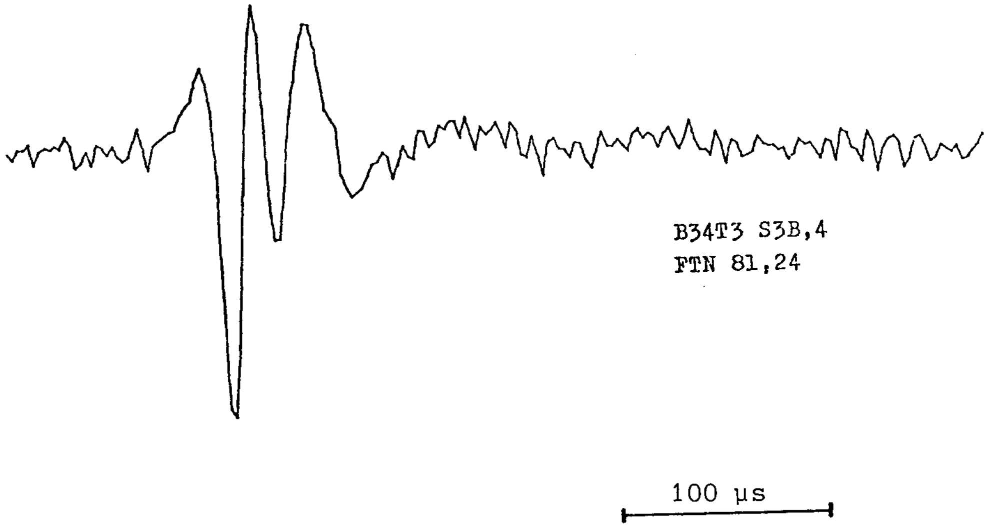


Fig. 12 example of a single echolocation pulse, type 3.

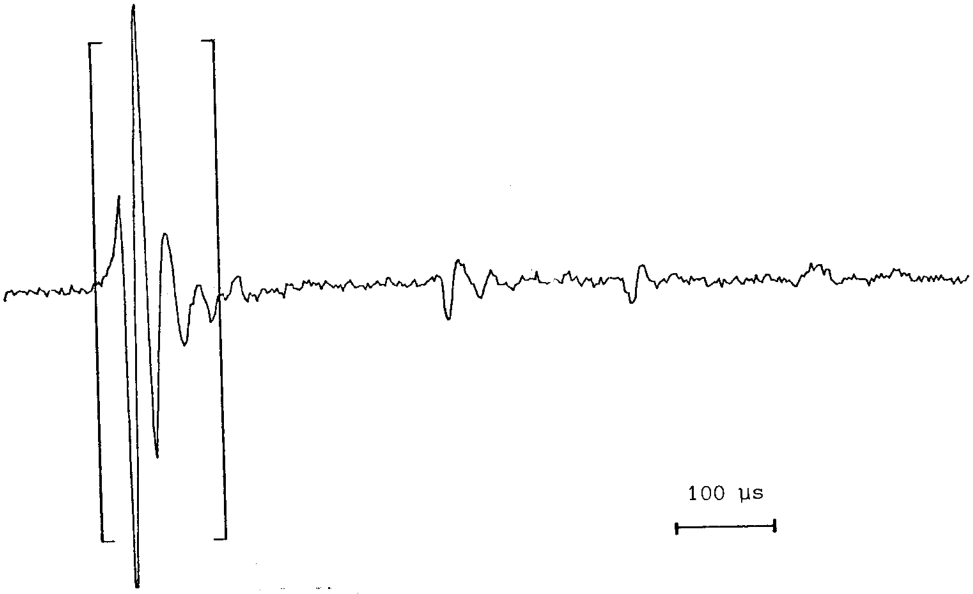


Fig. 13 The reflected signal from a solid sphere, containing both the primary and the secondary echo, together with the emitted pulse. The latter is placed between brackets.

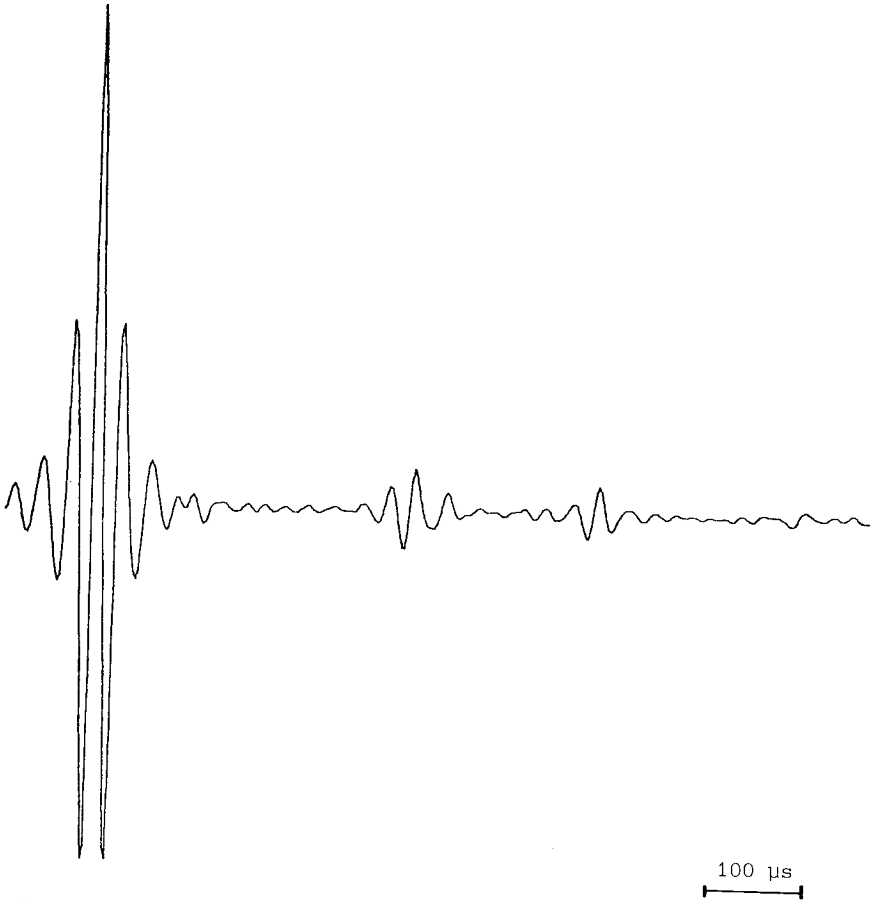


Fig. 14 Crosscorrelation of the returned signal with the emitted sonar pulse in the case of the solid sphere.

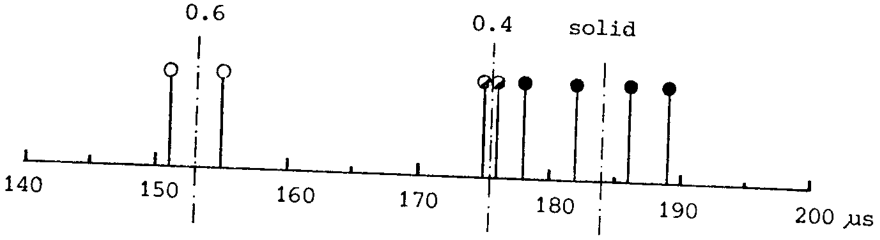


Fig. 15 Mean values of the delay times between the primary and the secondary echoes from a solid sphere, a 0.6 hollow sphere and a 0.4 hollow one.

sphere while the animal was very near the object; i.e. a distance of 10 - 12 cm.

A typical example of a complete echo signal from the solid sphere containing both the first and the secondary reflection is given in Fig. 13. A closer look on the returned signals from the spheres brings the attention to the fact that the first and the secondary reflection are not always 180° out of phase, a fact which had to be expected from the calculations of HICKLING, 1964.

It is possible to get a more noise-free and pronounced wave shape of these reflections from the sphere by means of crosscorrelating the echo signal with the emitted pulse. An example of the output of such a crosscorrelation is shown Fig. 14, this time for the solid sphere.

Several of these echoes are analysed in this way to determine the time interval between the first and the secondary reflections from the sphere, as there are strong indications that the time of interval between primary and secondary echoes forms the parameter on which the decision for a recognition is based.

To this end, these time intervals are measured as the distance between the maxima of the envelopes of the first and the secondary reflection in the crosscorrelation of the echo signal with the emitted pulse.

In Fig. 15 final data on the delay times between the two reflections are presented. These delays indicate that for the case of the 0.6 sphere a difference of 31 μsec exists, while the 0.4 sphere exhibits a value of 8.5 μsec with regard to the 184 μsec time delay between first and secondary reflection of the solid sphere.

The time spread in delay time for the case of the solid sphere is supposed to be due to the already mentioned fact that the phase relationship between the first and the secondary reflection was not always the same.

2. Spectral parameters

Characterization of the power spectrum of the individual sonar clicks is done by means of three parameters.

I. The first moment of the spectrum, related to the center of gravity,

$$\bar{f} = \frac{\int f\, S\,(f)}{\int S\,(f)}$$

II. For a modified spectrum, by skipping the narrow maximum around 18 kHz, a central frequency f_c is defined by the mean of the frequencies f_H and f_L, defined as the 3 -dB points of the power spectrum.

III. Spectral bandwidth $B = f_H - f_L$.

From fc and B another parameter can be deduced, the so-called relative bandwidth $W_{rel.} = \frac{B}{f}$. This parameter enables a quick comparison for spectra with different central frequencies and different bandwidths and can be used when an absolute value of one of the quantities does not provide sufficient information.

For the three prototypes of sonar clicks individual spectra are presented in Fig. 16 through 18. Similarity in the successive types of pulses in click trains justifies a procedure of averaging. In that way, the resulting averaged spectrum gives a better impression of the spectral information that is contained in a pulse train, as is to be seen from Fig. 19, 20 and 21.

After the succesful first part of the experiment, during which the animal managed to perform the correct recognition of a target, the aim was to investigate the ability of the dolphin to adapt her echolocating signals used in the two different situations of target identification. At a first glance, it was observed that peak frequencies in the echolocation sonar during this experiment

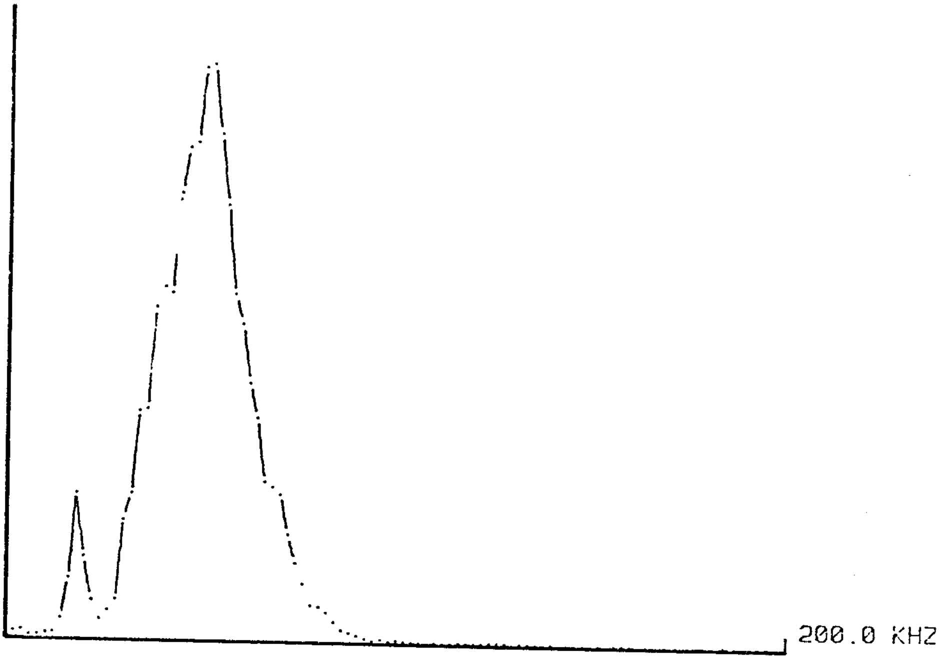


Fig. 16 Power spectral density of a single echolocation pulse type 1.

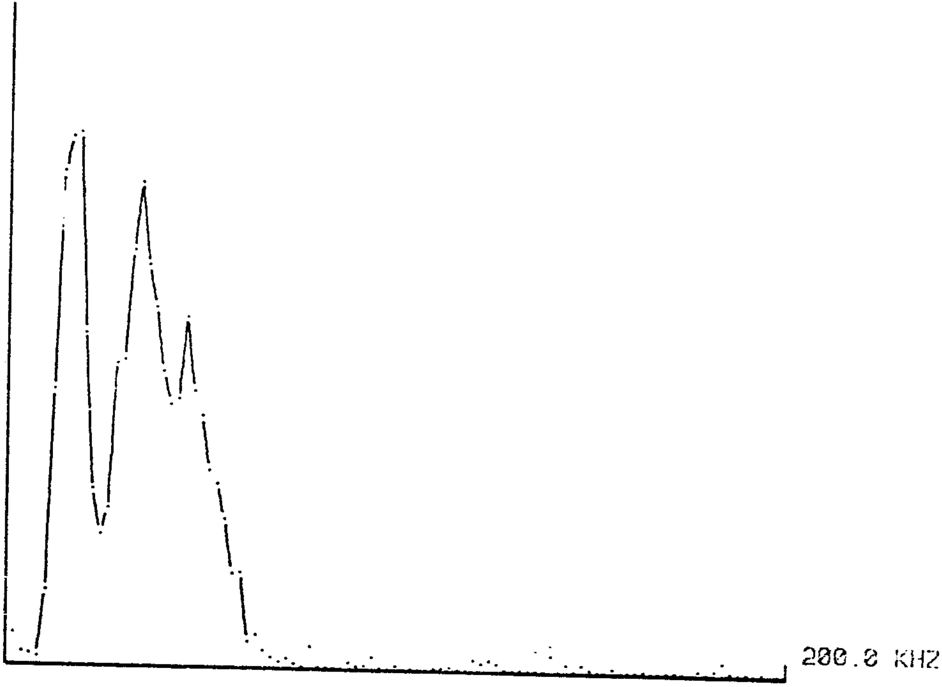


Fig. 17 Power spectral density of a single echolocation pulse type 2.

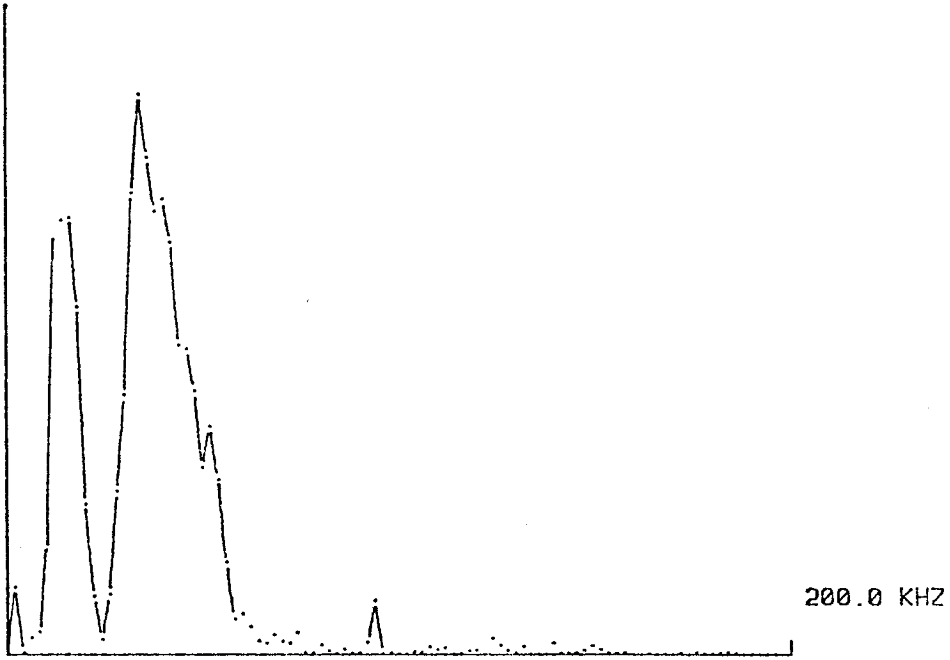


Fig. 18 Power spectral density of a single echolocation pulse type 3.

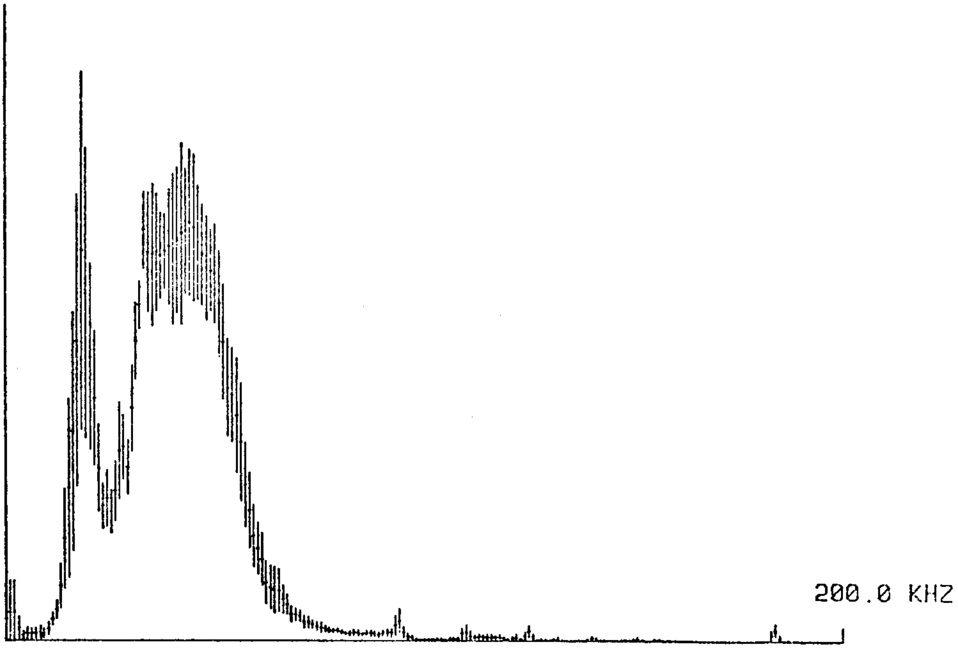


Fig. 19a Average power spectrum of the echolocation pulse type 1, identification of the 0.6 hollow sphere.

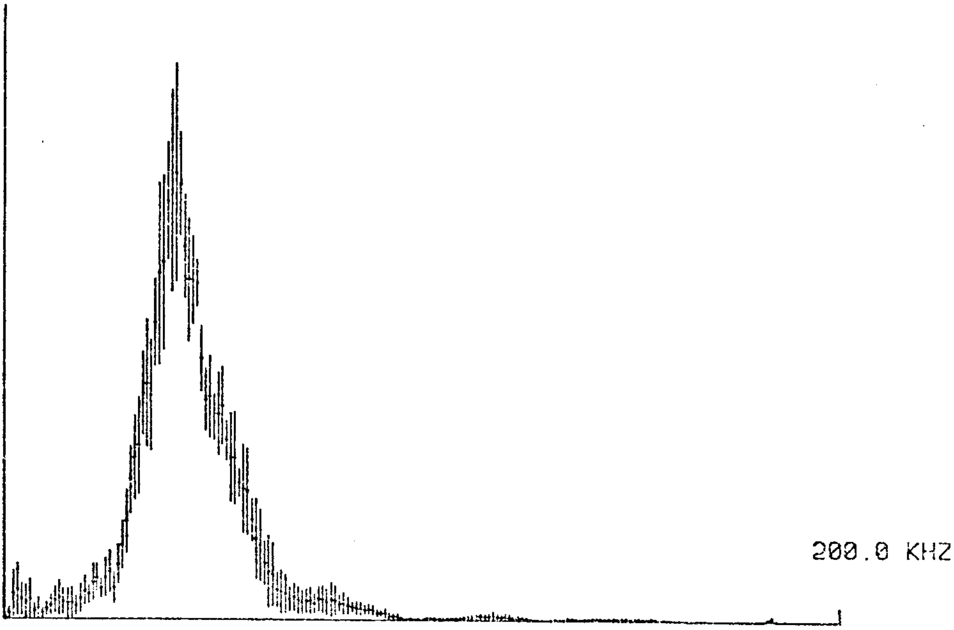


Fig. 19b Average power spectrum of the echolocation pulse type 1, identification of the 0.4 hollow sphere.

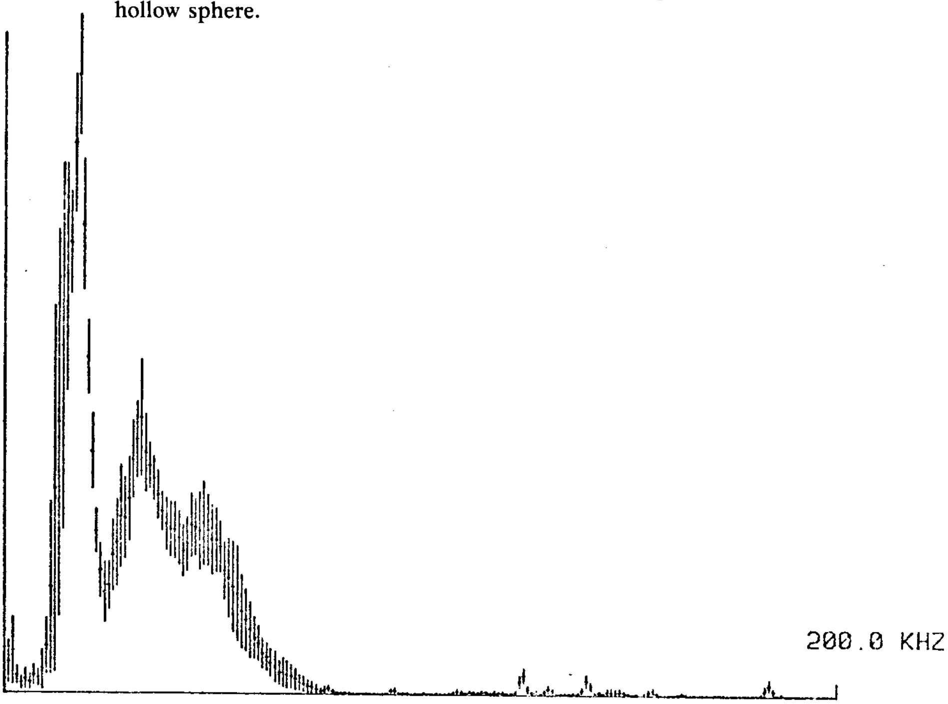


Fig. 20 Average power spectrum of the echolocation pulse type 2, identification of the 0.6 hollow sphere.

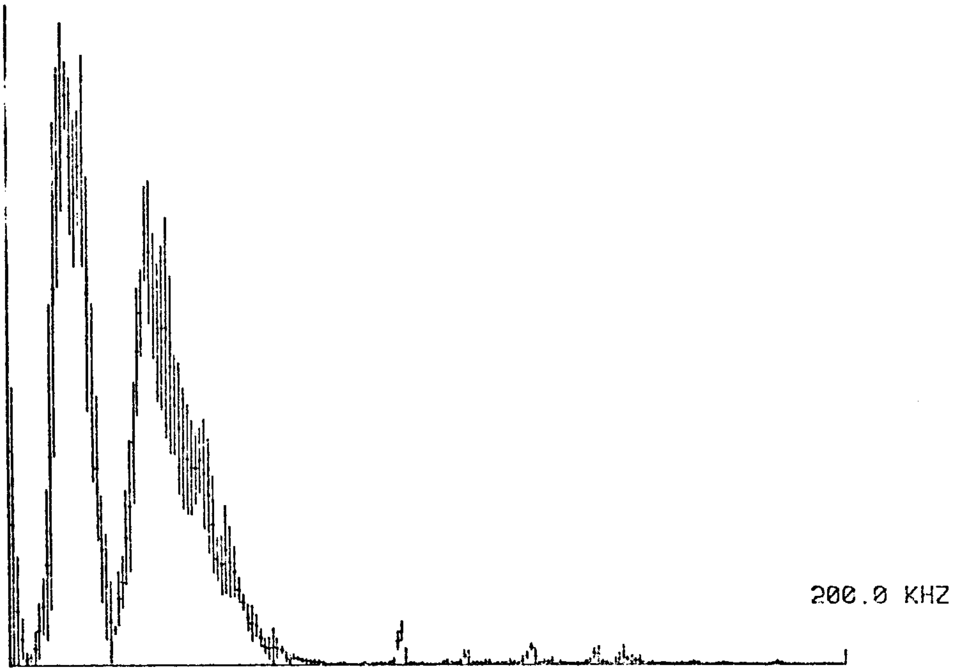


Fig. 21 Average power spectrum of the echolocation pulse type 3, identification of the 0.6 hollow sphere.

were not significantly different from the peak frequencies in the sonar signal used normally for fish detection. The hypothesis of whether the animal adapts the spectrum both in frequency and bandwidth is studied statistically from the same random selection of LC 10-recordings as indicated above.

The first approach to this problem consisted of a comparison of the location of the center of gravity for the power spectra from both series.

Although there is a minor difference in shape of the histograms as indicated in Fig. 22, a non-parametric test for the hypothesis that both distributions have the same location, is not rejected (WILCOXON, two-sided, $p > 20\%$).

Thereupon we considered the more important part of the power spectrum by neglecting the narrow low frequency peak that is occurring from time to time.

In Fig. 23 and Fig. 24 the histograms of the introduced spectral parameters, central frequency f_c and bandwidth B, are plotted for both series of signals.

Using again the two-sided WILCOXON test ($p < 5\%$), there is a difference in the location of f_c. This central frequency is slightly higher for the 0.6 sphere in favour of the 0.4 sphere. The mean value of f_c moved downwards from a value of 44.4 kHZ for the 0.6 sphere to a value 40 kHz in the case of the 0.4 hollow sphere.

There does exist a difference for the bandwidth B too (WILCOXON, two-sided, $p < 0{,}2\%$). In the case of the identification of the 0.6 hollow sphere, the mean value of the bandwidth B turns out on 24 kHz ± 5 kHz, while the identification of the 0.4 hollow sphere reveals a value of $B = 18$ kHz ± 4 kHz. This decrease is of the order of 25% and leads to the final conclusion that a spectral difference in the two cases exists, with signal energy definitely more concentrated around a lower central frequency for the identification of the 0.4 hollow sphere, this being a more difficult task for the dolphin to execute than the 0.6 hollow one.

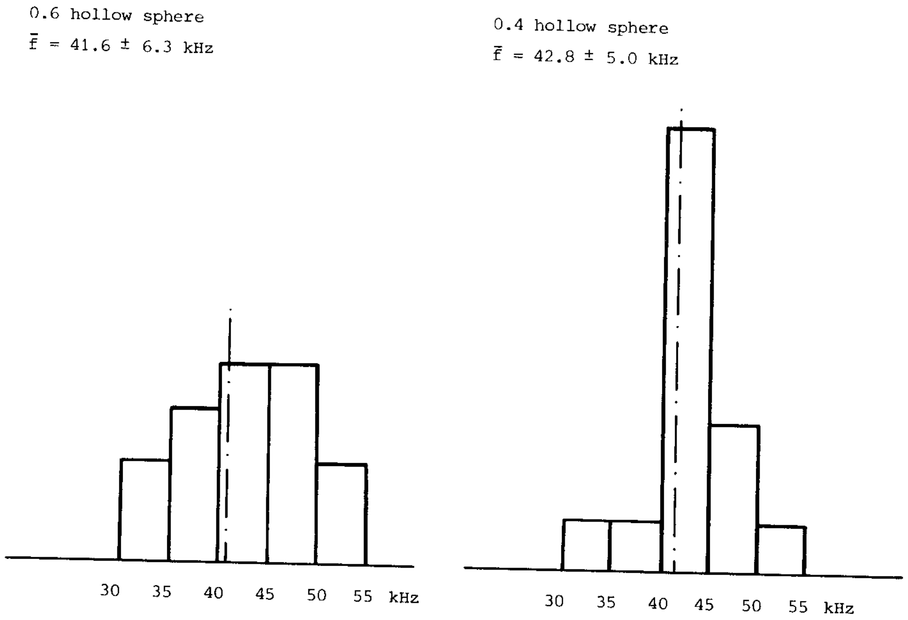


Fig. 22 Histogram of the center of gravity $\bar{f}$ of the power spectral density for the identification of the 0.6 hollow sphere c.q. 0.4 hollow sphere.

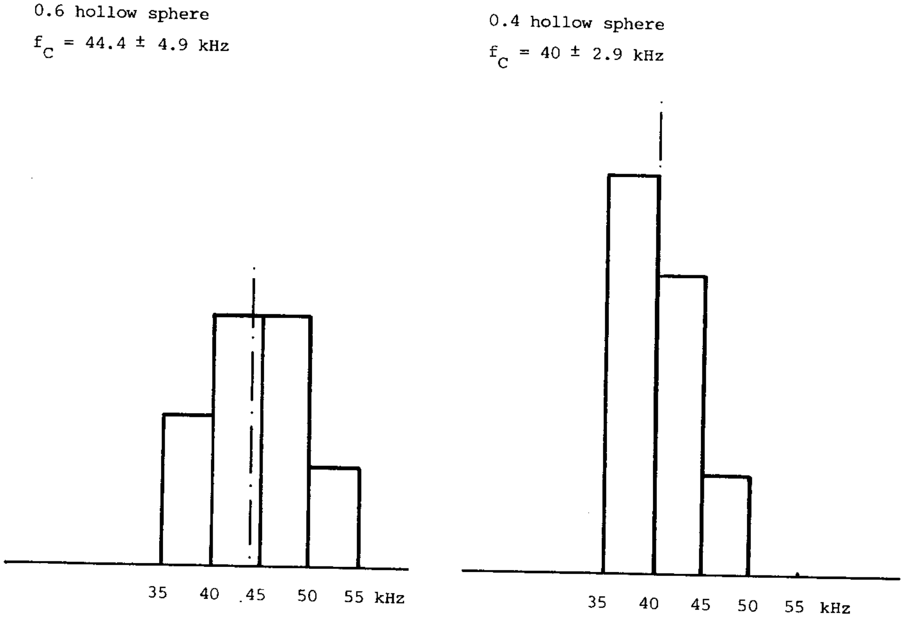
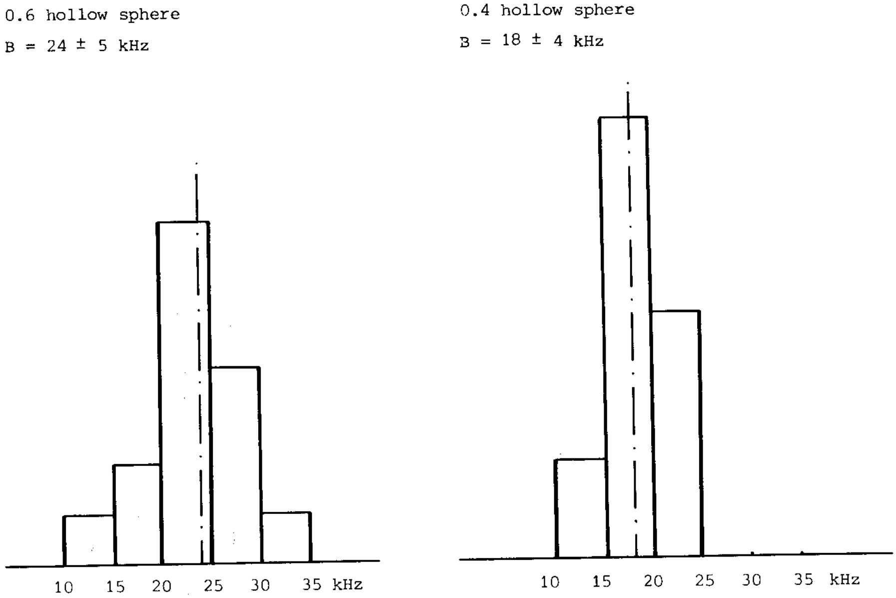


Fig. 23 Histogram of the central frequency of the power spectrum for the identification of the 0.6 hollow and the 0.4 hollow sphere.


0.6 hollow sphere

B = 24 ± 5 kHz

0.4 hollow sphere

B = 18 ± 4 kHz

Fig. 24 Histogram of the spectral bandwidth B of the sonar signal used during the identification of the 0.6 hollow and the 0.4 hollow sphere.

In general, the bandwidth of the sonar signals in the described experiment, the previous experiments and all other registrations of the animal in the past, is located precisely in the vicinity of the optimal hearing sensitivity of *Tursiops*. Why the animal uses such a relatively narrow band signal, as has been already raised by ALTES (1971), remains still an open question. Whether the animal is capable to achieve an adaptation in a more pronounced form of her sonar signal in some specific detection task, demands an extension of our knowledge of the sound producing mechanism. Investigations in this domain of research are beyond the possibilities of the authors.

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References

ALTES, R.A., 1971. Computer derivation of some dolphin echolocation signals. Science, 173, 912-915.

AU, W.W.L., FLOYD, R.W., PENNER, R.H. and MURCHISON, A.E., 1974. Measurement of echolocation signals of *Tursiops truncatus* (Montagu) in open waters. J. Acoust. Soc. Am., 56, 1280-1290.

BLOUGH, D.S. and LIPSITT, L.P., 1972. The discriminative control of behavior. In: KLING, J.W. and RIGGS, L.A., ed., Experimental psychology. Methuen, London.

DIERCKS, K.J. and HICKLING, R., 1967. Echoes from hollow aluminum spheres in water. J. Acoust. Soc. Am., 41, 380-394.

EVANS, W.E., 1973. Echolocation by marine Delphinids and one species of freshwater Dolphin. J. Acoust. Soc. Am. 54, 191-199.

HICKLING, R., 1964. Analysis of echoes from a hollow metallic sphere in water. J. Acoust. Soc. Am., 36, 1124-1138.

KAMMINGA, C. and REE, A.F. van der, 1976. Discrimination of solid and hollow spheres by *Tursiops truncatus* (Montagu). Aquatic Mammals, 4, 1-10.

KELLOG, W.N. and RICE, C.E., 1966. Visual discrimination and problem solving in a bottlenose dolphin. In: NORRIS, K.S., ed., Whales, Dolphins and Porpoises, 731-754. Univ. of Cal. Press, Berkeley.

MURCHISON, A.E. and PENNER, R.H., 1975. Open water Echolocation in the Bottlenose dolphin *(Tursiops truncatus)*: Metallic Sphere Detection Threshold as a Function of Distance. Proceedings of Conference on the Biology and Conservation of Marine Mammals, University of California, Santa Cruz, Dec. 4-7.

PURVES, P.E., 1966. Anatomical and experimental observations on the cetacean sonar system. In: BUSNEL, R.G., ed., Animal sonar systems. Jouy en Josas, France, 1967.

YUNKER, M.P. and HERMAN, L.M., 1974. Discrimination of auditory temporal differences by the bottlenose dolphin and by the human. J. Acoust, Soc. Am., 56, 1870-1876.