DISCRIMINATION OF SOLID AND HOLLOW SPHERES BY *TURSIOPS TRUNCATUS* (Mont.)

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Summary

Discrimination ability of the sonar in *Tursiops truncatus* (Mont.) the Atlantic bottle-nosed dolphin, is investigated for a pair of aluminium spheres with same external dimensions, but different texture, i.e. solid versus hollow. It is suggested that the information obtained by the animal in this echo location trial, where both sets of echoes looked similar, originates from the difference in times of arrival of the secondary echoes from the spheres, set up by its elastic resonance.
This difference is due to the fact that the wave velocity in a homogeneous sphere is smaller than in the hollow sphere.

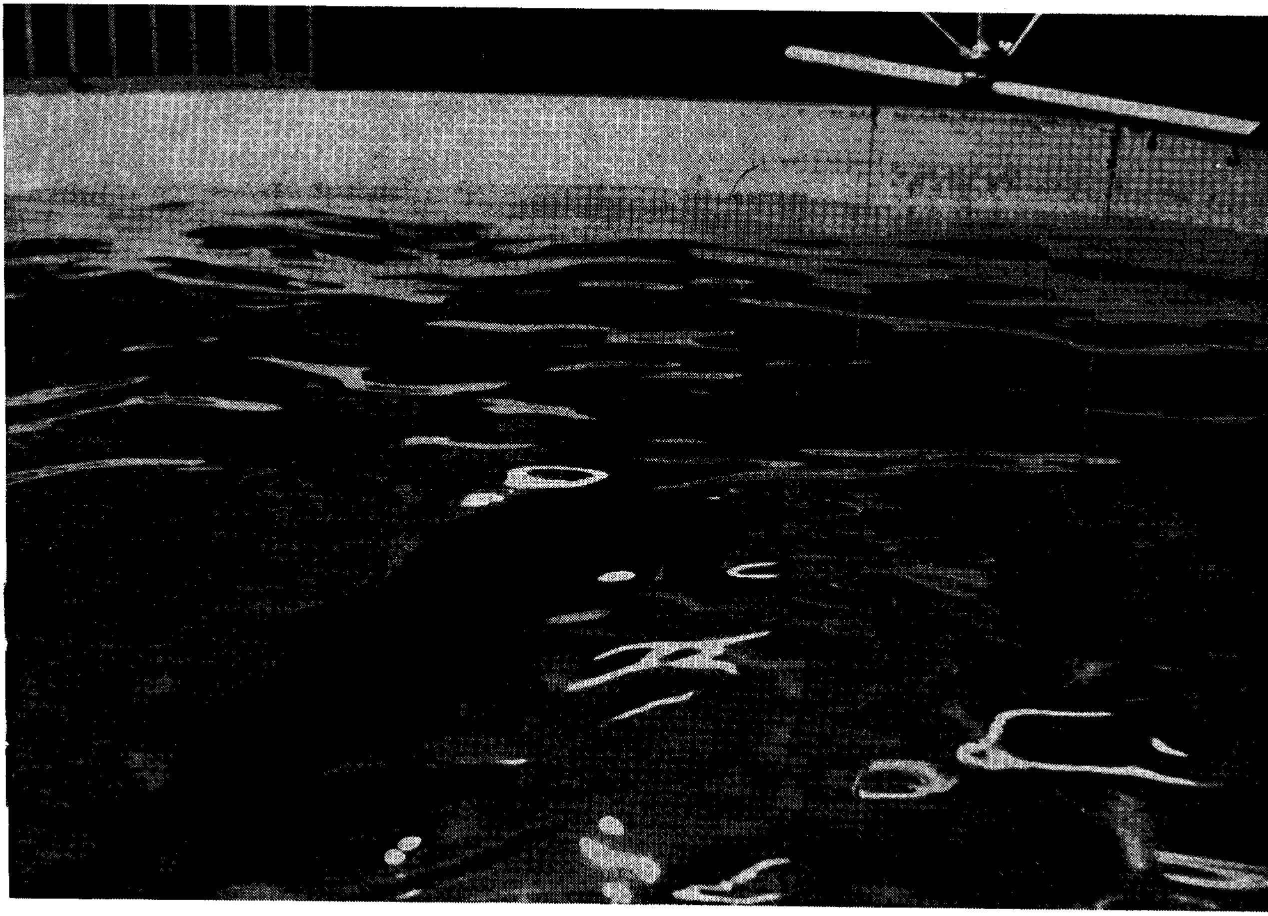


Plate 1. Doris makes her choice.

Introduction

During recent years our knowledge of the production of acoustical signals by Cetacea has steadily increased. Refinements in recording apparatus such as wide band instrumentation, magnetic tape recorders and very small sensitive hydrophones with adeqate bandwidth capacity have favoured near optimal possibilities for sound registration in marine bioacoustics.

Since 1971 research in the Netherlands on dolphin behaviour and the analysis of the registrations of emitted signals was made possible by a very fruitful co-operation between our Institute and the Dolfinarium, located at Harderwijk.

Following some experiments on hydrodynamics, vision and communication, a tentative experiment was started in 1972 to test the discrimination abilities of the sonar of *Tursiops truncatus* (Mont.), the Atlantic bottle-nosed dolphin. Investigations into *echo location* started in early 1956 and by the end of the sixties a lot of knowledge has been collected on cetacean signals. The paper of NORRIS, EVANS and TURNER (1967) at the Animal Sonar Systems Conference at Frascati, discusses the discrimination between nickel steel ball bearings of two sizes, one of them used as a reference sphere of 6,35 cm in diameter. This paper gives extensive information about the different clicks used by the Atlantic bottle-nosed dolphin for discrimination and orientation tasks.

In the following article a short description will be given of another investigation on the discrimination ability of a dolphin in a special situation created in a tank with inherently strongly reflecting walls. In this complex sound situation the animal is faced with the task of discriminating between aluminium spheres of equal diameter of 15 cm. (6 inches) but different texture in that one of the two spheres is solid and the other is hollow with a shell thickness of 3 cm. (1.2 inches) so that the radius ratio is 0.6.

Formulaion of the problem

Although the literature reports on discrimination experiments which are related to different sizes (NORRIS c.s., 1967) and material differences of objects (EVANS c.s., 1967 and DUBROVSKII c.s., 1971), there exists little knowledge about the discrimination ability possessed by dolphins between targets with identical physical outer dimensions and the same material, but with different construction properties that produce changes in the echo structure. It was our aim to test the hypothesis (NORRIS c.s., 1967 and NICHOLAS, 1967) that a dolphin could use his sound producing and receiving mechanism to make a distinction between two structurally different targets where the determination on the basis of energy content was insufficient.

It can be concluded from the results of our discrimination experiment that a dolphin is perfectly capable of locating the hollow sphere in a complicated environment by means of his sonar system. The remarkable ability to discriminate between a hollow and a solid sphere of the same average target strength indicates that the dolphin uses a signal of a specific structure in combination with a fine discriminating hearing system to accomplish the task of separating the two sets of echoes received from the spheres.

To arrive at a short explanation of this phenomenon we will follow the problem of insonified spheres as described by HICKLING (1964), DIERCKS and HICKLING (1967). These papers give an extensive mathematical treatment of the analysis of echoes from solid and hollow metal spheres in water, when these are radiated by a commonly used monochromatic sonar pulse. They show, that metal spheres exhibit in their echo characteristics a rigid body aspect as well as an elastic behaviour. The primary reflection from the outer surface is similar to a reflection from a rigid body. If the incident sound pulse only contains a few cycles, then the echo pulses that follow the first are caused by the resonances of the sphere as the incident sound partly penetrates into the sphere. Obviously, it is to be expected that the hollow sphere complicates the echo problem and in particular it is noted that there exists a shift in the time of arrival of the secondary echoes with respect to the situation in which a homogeneous sphere is used. Furthermore, the structure of the echo exhibits only a definite structure that is different from other ones, i.e. - the primary reflection is time-separated from the secondary echoes - if the length of the incident sonar waves does not exceed the diameter of the sphere in situ.

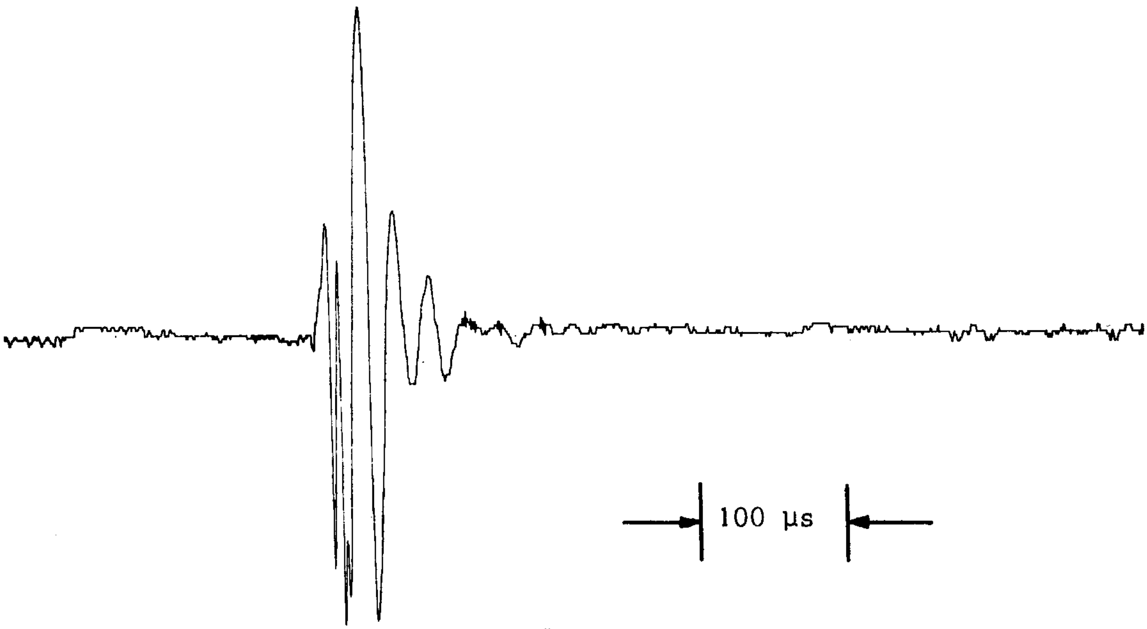


Figure 1. Example of a dolphin sonar pulse in digitized form. Sample frequency rate 2 MHz.

In figure 1 is shown a single sonar pulse taken out of a complete pulse train as produced by the dolphin in the case of correct response during the discrimination task, recorded at the top of the rostrum. From this wave form it is clear that the dolphin uses a sonar pulse which has a length of about 100 μsec, thus equalling practically the diameter of the sphere, i.e. 15 cm, if we express the duration in a non-dimensionalized form $\Delta t = \frac{c \Delta t}{2a}$ with

c = speed of sound
Δt = time duration of incident sonar pulse
a = radius of the sphere

The difference in time of arrival of the secondary echoes is due to the fact that the wave velocity in a homogeneous sphere is less than in the air-filled hollow sphere. As the shell-thickness equals 3 cm we might expect that mainly surface waves are produced by the resonances in the sphere. It is plausible to state that this phenomenon of time difference between the practically indentical secondary echoes in the two cases is used mainly by the dolphin as a distinctive clue to carry out the discrimination task.
In fact, the results of this study are also in agreement with the suggestion already made by EVANS and POWELL (1967), who suggested that next to differences in echo strenth the phase structure in the reflected waveforms would be significant for the dolphin to make a decision.
To investigate further the nature of the time differences, an artificial replica of this discrimination experiment was designed and carried out in a non-reverberating fresh water pond.
The measurement setup of this replica experiment is shown in the blockdiagram of figure 2.

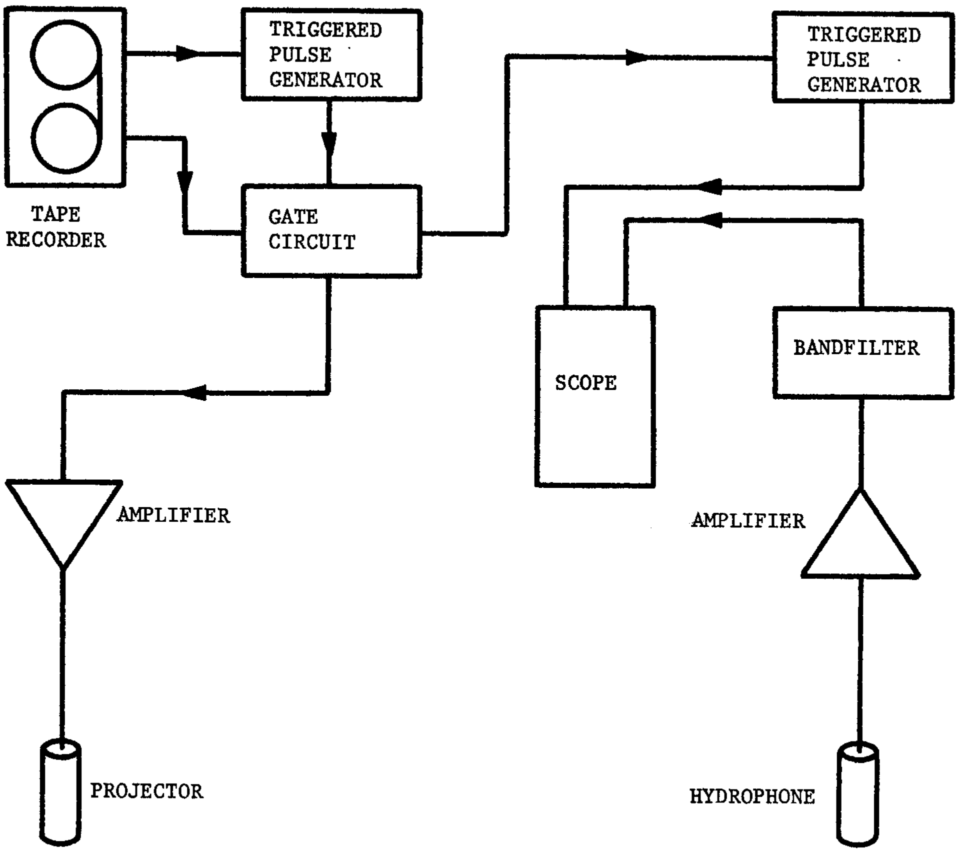
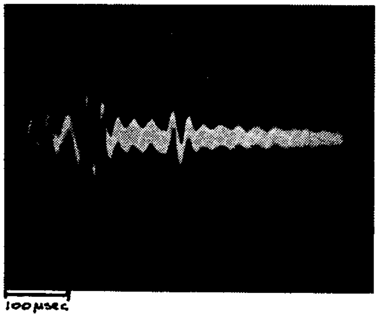


Figure 2. Blockdiagram of measurement setup in the simulated experiment in the tank.

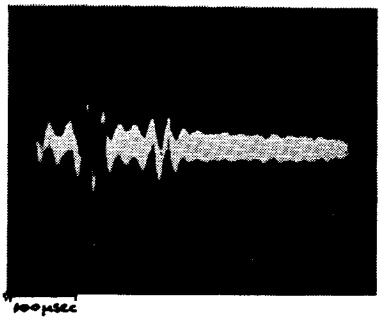
Instead of a source signal consisting of a tone burst of a certain frequency, we used as sonar signals the taped emitted echo locating sound pulses as recorded from the dolphin whilst she was performing correctly the discrimination task in the tank of the Dolfinarium. One of these pulses was stored in a memory and used as a pulse repetitive signal.

Is is worth noting that this source pulse is in contrast with the source pulse used by DIERCKS and HICKLING (1967), which consisted of a few periods of a truncated sinusoid.

The distances of the projector LC 32 and the hydrophone LC 10 from the sphere to be sonified were respectively 99 cm and 33 cm, the hydrophone being in line between the LC 32 and the sphere.



SOLID SPHERE



HOLLOW SPHERE

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Plate 2. Echoes from a hollow aluminium sphere (upper trace) and a solid sphere (lower trace).

Results of this experiment are indicated in plate 2, where first and secondary echoes are shown as a result from hitting the spheres with the sonar wave from figure 1. As might be expected, both sets of echoes look similar. The first echoes are identical and are the reflections from both spheres. However, the secondary echoes in the two cases show a prominent time difference of about 33 μsec with only a slight difference in amplitude.

Training

The object of the training was to teach the dolphin to select the hollow sphere (Plate 1). As a starting point of this training the solid sphere was marked visually to differentiate it from the hollow sphere by covering it with pieces of thin aluminium foil. Every time a succes level of 90% was achieved, part of the covering foil was eliminated. This process was continued by progressive stages, until no foil at all was left on the solid shere. At this stage the success level was above 90% of all cases, although both spheres were presented simultaneously. The beginning of each training run was indicated by an underwater attention signal — 1 sec of a 1000 Hz pure tone — through a hydrophone projector. During the training session we used the learning method by reinforcement.

After working up, testing and a training period of some three months "Doris", one of the three selected dolphins of the population at the Dolfinarium, was capable of identifying the hollow sphere. Doris was an adult female of at least ten years old and living for several years in captivity at Harderwijk. Of the other two animals one fell ill and the other appeared to be still too young and not fit yet for prolonged concentrated work and we decided not to employ them any further.

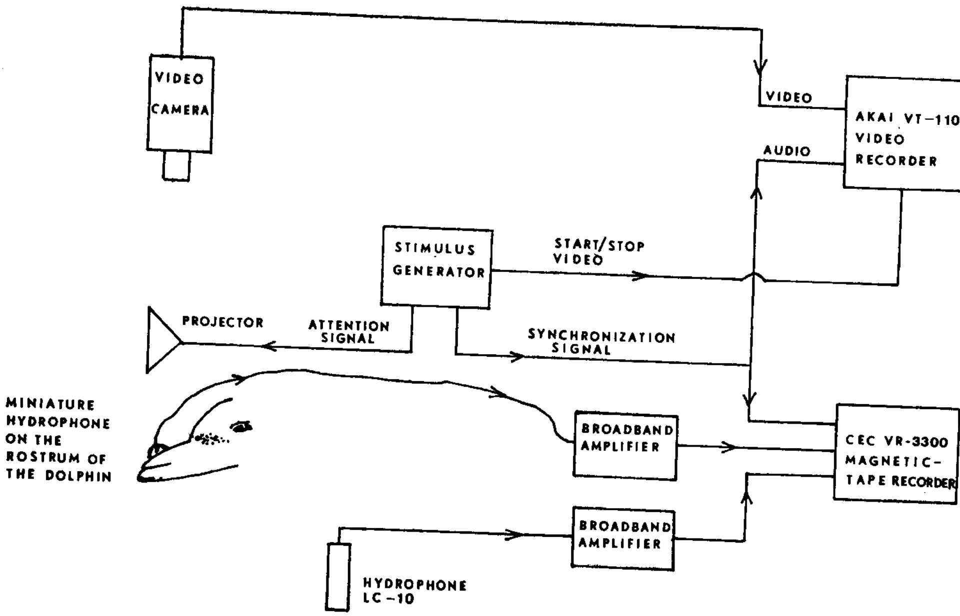

Figure 3. Blockdiagram of measurement for the discrimination task in the Dolfinarium tank.

Experimental setup and data collection

The experimental setup for the discrimination task in a tank is shown in the block-diagram of figure 3. The registration of the sonar signals emitted by the dolphin during the experiment took place by means of a very small sensitive hydrophone

(designed and constructed by Ir. H. A. J. Rynja) consisting of the piezo-electric ceramic material lead-zirconate-titanate (RYNJA, 1974) The sensitivity attained the value of 220 dB re IV/μPa.
This hydrophone was placed on the rostrum of the dolphin by means of a small rubber suction cup (DIERCKS c.s., 1971). It was noticed that the rostrum produced a cleaner sonar signal than the melon.
Signal transmission to the CEC type 3300 instrumentation wide-band taperecorder was provided by 9 m (30 ft) miniature coaxial cable. This small cable was no inconvenience at all to the dolphin which could move around freely in the tank during the performance runs.
The hydrophone comprised a flat frequency response up to 120 kHz, which determined the bandwidth of the entire measuring system, as amplifier and taperecorder — running at a tape speed of 60 ips — provided a bandwidth of about 200 kHz.
The described method of signal registration resulted in a relatively good signal-to-noise ratio of 30 dB.
During each trial run a videorecording of the behaviour of the dolphin was made in synchronization with the sonar signal.
Despite the zoomlense on the videocamera it was not possible to cover the whole area of the training tank so we missed the beginning of the approach of the dolphin to the spheres.
Training and experiments in the Dolfinarium were caried out in a separate tank with dimensions 12 x 6 m (40 x 20 ft) and 2,60 m (8,5 ft) water depth. Figure 4 indicates

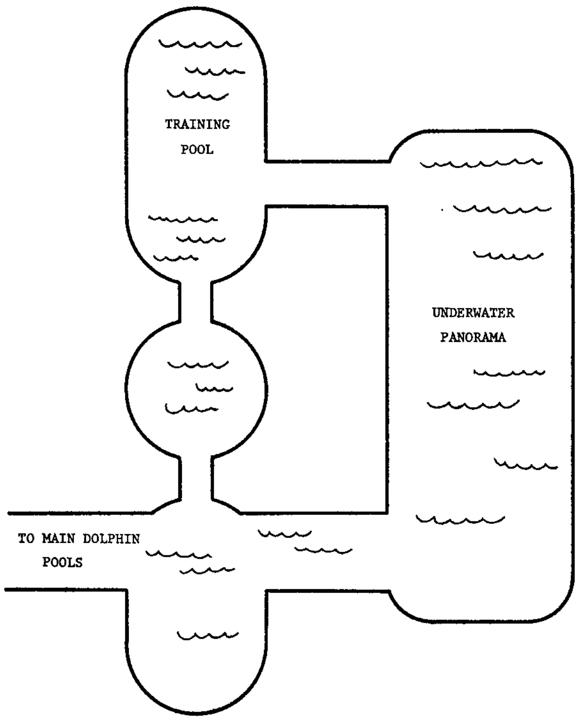

Figure 4. Location of the training tank in the Dolfinarium.

the situation in the services buildinp of the Dolfinarium. Plate 1 shows the experimental situation in the tank. Here the dolphin is seen to touch the left — in this case the hollow — of the two spheres. The suction cup on the rostrum and thin co-axial cable trailing in the water are distinguishable. The two spheres are suspended on nylon wires from a bar and are submerged about 20 cm (8 inches) below the surface of the water. The distance between the spheres is 120 cm (4 ft).

Between successive trials the spheres were interchanged at random, thus presenting the animal in every run with a new situation. As the bar was part of a rotating TV-antenna mastmounted upside down the changing of position was easily executed. The spheres were always moved between trials whether or not they actually changed their ultimate position.

At the end of the experiment 960 trials were carried out with a 90% success rate.

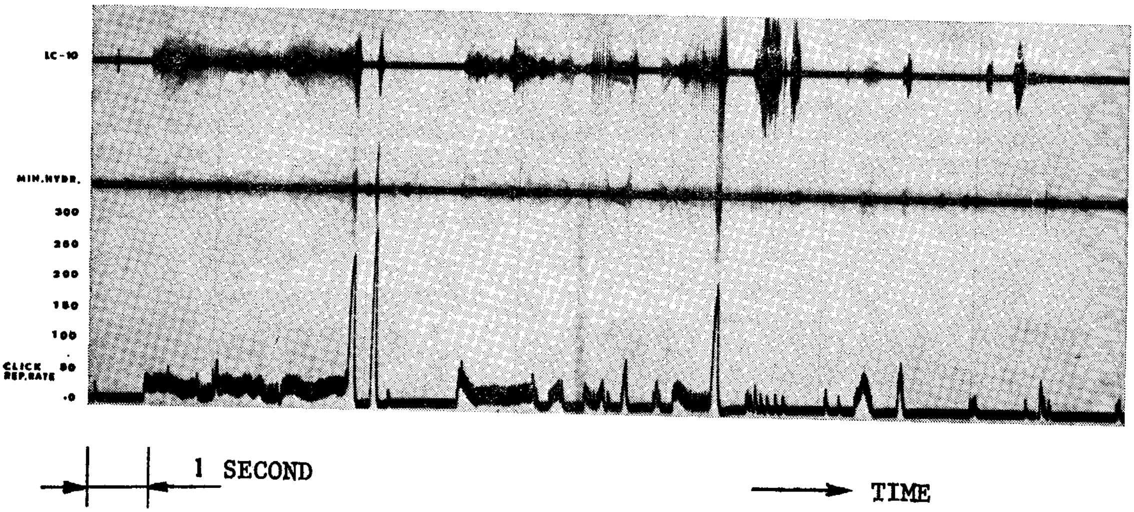

Plate 3. UV-registered dolphin signals during discrimination between a hollow and a solid sphere.

Conclusions and discussion

In plate 3 several tracks are shown registered on a UV-recorder. Starting from the top one can be observe :

- signals as picked up by the hydrophone LC 10 immersed in the Dolfinariium tank in the vicinity of the spheres. These signals do not only contain the sonar pulses but also the whistles produced by the dolphin during the performance run and after completing her task, this time to attract our attention.
- echo locating signals as used by the dolphin and picked up by a hydrophone placed with a suction cup on the rostrum.
- the click repetition rate of the sonar pulses of the dolphin during the discrimination task.

Summarizing, it can be said that the dolphin is capable of sophisticated discrimination and that the information obtained in the situation described — the echo locating trial herein — in our opinion originates for the most part from the significant differences in times of arrival of the secondary echoes of the two structurally different spheres.

As the spheres were presented simultaneously, it is apparent that a comparison of echoes is not such a severe task as in the case of a successive presentation of the spheres. A ratio of times of arrival of 0.7 does not seem to be a problem for the dolphin in this task.

It is further noted that when "looking" at the spheres, the dolphin interrogates them sequentially by scanning movements and employs a maximum repetition rate of about 300 to 500 pulses per second. The next stage of research will involve a analysis of the secondary echoes in the immediate vicinity of the hearing organ of the dolphin. In addition, the influence of target diameter and target strength for spheres of other materials will be investigated. A number of different dolphins with respect to age and sex will be incorporated in the trials.

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References

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

DIERCKS, K. J., R. T. TROCHTA, C. F. GREENLAW and W. E. EVANS 1971. Recording and analysis of dolphin echolocating signals. J. Acoust. Soc. Am. 45 : p. 1729.

DUBROVSKII, N. A., P. S. KRASNOV and A. A. TITOV, 1971. Discrimination of solid elastic spheres by an echolocating porpoise *(Tursiops truncatus),* in Seventh International Congress on Acoustics, Budapest 1971, paper 25 H3 : pp. 533-537.

EVANS, W. E. and B. A. POWELL, 1967. Discrimination of different metallic plates by an echolocating Delphinid. In Animal Sonar Systems, Biology and Bionics, R. G. Busnel, Ed. (Jouy-en-Josas, France, 1967) 1 : pp. 409-447.

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

NICHOLAS, J. L., 1967. Discussion in Norris c.s., 1967, p. 445.

NORRIS, K. S., W. E. EVANS, and R. N. TURNER, 1967. Echolocating in an Atlantic bottle-nosed porpoise during discrimination. In Animal Sonar Systems, Biology and Bionics, R. G. Busnel, Ed. (Jouy-en-Josas, France, 1967) Vol. 1 : pp. 409-447.

RYNJA, H. A. J., 1974. Sensitivity of small hydrophones. Acoustica 30 : pp. 20-30.

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