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SONAR OF PENGUINS AND FUR SEALS

By

Thomas C. Poulter

*Biological Sonar Laboratory, Stanford Research Institute
Menlo Park, California 94025*

INTRODUCTION

Numerous separate studies in the field of biological sonar have dealt with such subjects as "the evidence that penguins and fur seals use sonar," "active and passive sonar," and "cavitation clicks as a sound source in marine mammal sonar." Because of the many factors in common in these independent studies, the results obtained and their analysis have been combined in the discussion which follows.

PENGUIN BEHAVIOR INDICATING USE OF SONAR

To demonstrate the facility with which penguins locate and pick up their food, a group of about 15 Humboldt penguins, *Spheniscus humboldti*, were fed in near darkness at the San Francisco Zoo during the 1963 evening open house for the members of the San Francisco Zoological Society. These penguins were in a large pool containing about three feet of cloudy water. The caretaker approached the edge of the pool with a bucket of small white bait fish, and the penguins gathered in a group along the side of the pool where they were accustomed to being fed. He threw a large handful of fish into the center of the pool and all of the penguins went rapidly from point to point picking up the fish. Then, as if the penguins had received a signal that no more fish remained, they all suddenly returned to the edge of the pool to await another handful. When it was thrown in, they returned immediately to the center of the pool and began rapidly picking up the fish. After picking up each handful of fish, the penguins would start back almost simultaneously to the edge of the pool.

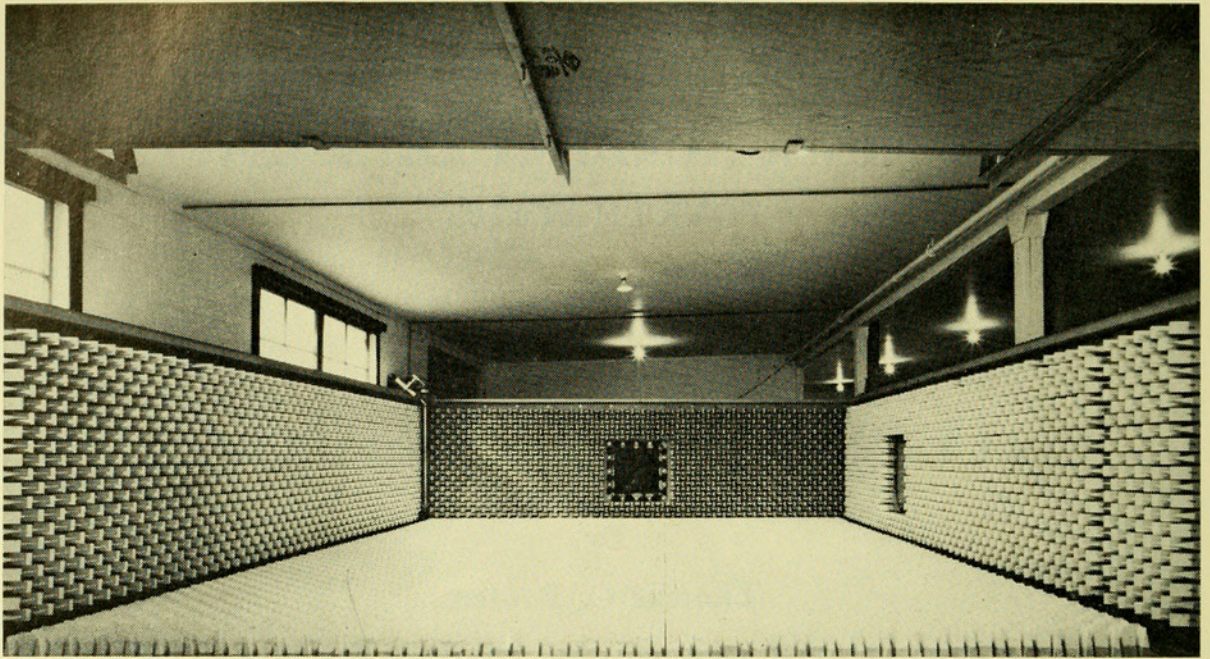


FIGURE 1. Empty anechoic tank showing construction of interior surface.

From the ease and rapidity with which they retrieved the fish, it was apparent that the penguins either had unusually acute vision under near-darkness conditions and in cloudy water or they used some means other than vision to locate the fish. On the hypothesis that their fast and accurate retrieval of the fish in the extremely poor light was due to the use of an active sonar, four of the penguins were taken to the Biological Sonar Laboratory of Stanford Research Institute (SRI) where more definitive experiments could be conducted in total darkness in SRI's anechoic research tank. This tank is 15 feet long, 10 feet wide, and 4 feet deep. It is located in a light-tight laboratory and has a reverberation decay rate of 4.450 db/second for frequencies down to 300 Hz. So far as the author is aware, after discussions with Navy research personnel and members of other bioacoustics research laboratories, the anechoic characteristics of SRI's research tank are superior to any other tank thus far constructed, particularly at such low frequencies (see fig. 1).

The four penguins were released on a four-foot-wide platform along one side of the anechoic tank and allowed to familiarize themselves with their new surroundings, with the lights on, for two hours. During this period, they spent much of the time going back and forth between the platform and the tank, diving into the tank, and walking up a ramp in one corner of the tank.

When the penguins were all on the platform alongside the tank (fig. 2) two fish were held up so that they could be seen. All four penguins immediately started to walk toward the fish. The two fish were then thrown into the opposite corner of the tank and the penguins immediately dived into the tank. Be-

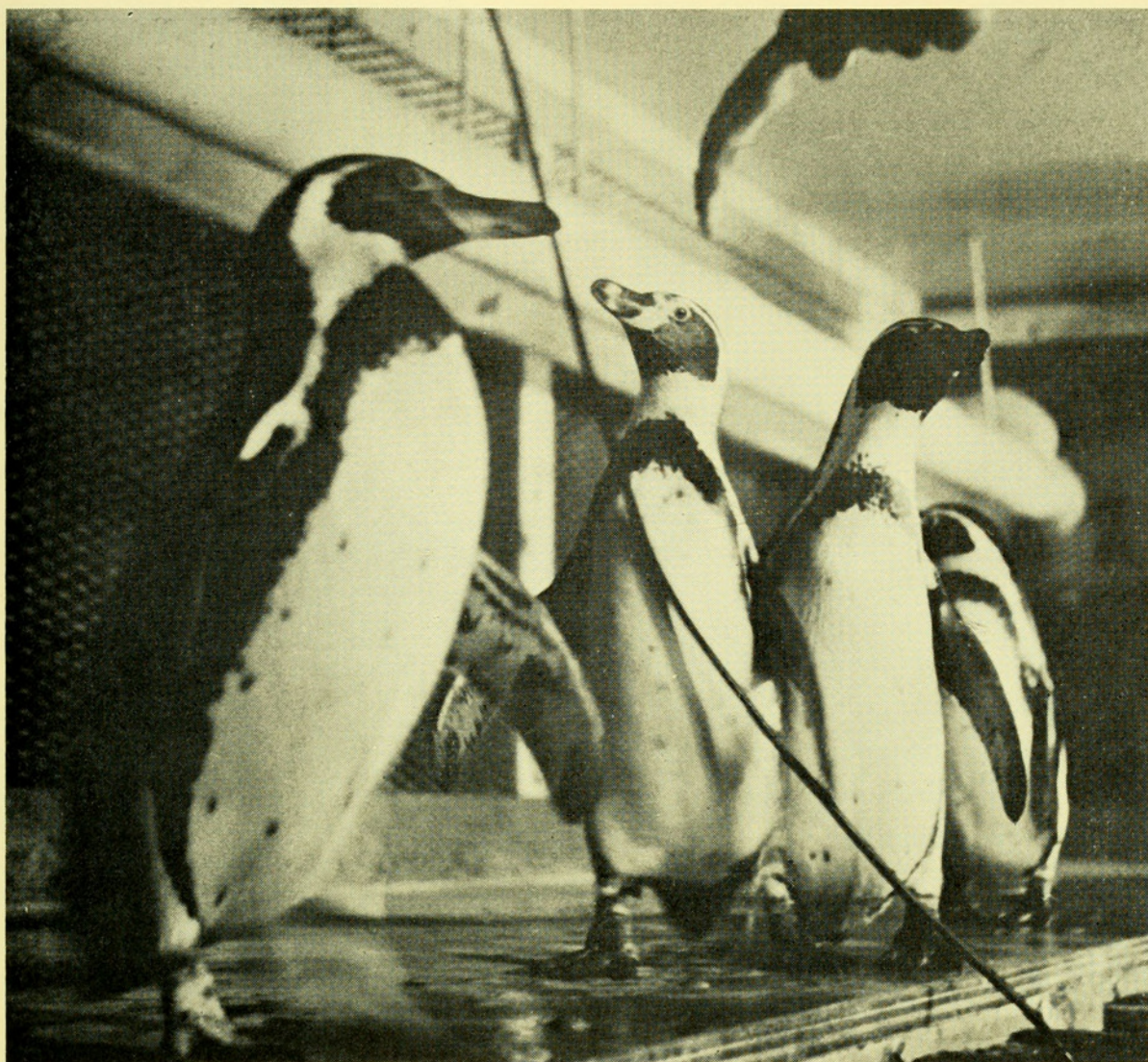


FIGURE 2. Penguins on ramp along one side of anechoic tank.

fore they hit the water, the lights were turned off and a handful of about 15 to 20 fish was immediately thrown over a wide area of the tank. After 30 seconds the penguins were heard coming up the ramp, and the lights were turned on. All fish had been picked up and eaten. Two penguins were on the ramp when the lights were turned on; they immediately returned to the water and all four penguins searched the tank for several minutes, suggesting their greater confidence in locating food in light rather than darkness. They then came over to the side of the tank and were each rewarded with a number of fish by hand.

Thirty minutes later when all four penguins were again on the platform, two more fish were held up. As soon as the penguins started toward the fish, the fish were thrown at random into the water; as the penguins again dived into the water, the lights were turned off. This time, another handful of fish was thrown into the tank a few at a time in rapid succession to widely scattered points in the

tank, over a period of about 5 to 10 seconds. Fifteen seconds after the last fish was thrown into the water, the penguins were heard coming up the ramp. The lights were then turned on, and all fish had been picked up and eaten.

Although the penguins had eaten their normal quota of fish for the day, the above experiments were repeated 30 minutes later with the same results. During all of the tests, the tank was monitored on a loudspeaker with a hydrophone in the water, and recordings were made on magnetic tape. In view of the performance of the penguins and without any evidence to the contrary, we consider these experiments to provide adequate proof that penguins use some type of sonar in locating their food.

FUR SEAL BEHAVIOR INDICATING USE OF SONAR

Up to the time that these experiments were undertaken, the animals were fed individually in order to make sure that each animal got its proper share of food.

Four northern fur seals, *Callorhinus ursinus*, which ranged in age from one hour to four days when captured were raised by hand and completely isolated from any other pinnipeds over the first two years.

When these four fur seals were 14 months old, an extensive series of experiments were started which extended over a period of three months to determine the ability of these animals to pick up either dead or live fish in daylight and in total darkness.

The recording experiments with the fur seals were made in the large anechoic sea lion research tank which is 80 feet long by 18 feet wide and 5 feet deep. The anechoic characteristics of this tank are essentially identical with those of the small tank.

The 6 by 8 foot tank used for the feeding studies was fitted with a light-tight lid which had a small trapdoor near its center so that the fish could be rapidly introduced in total darkness (fig. 3).

The dead fish used in the feeding experiments were herring which were purchased frozen and were thawed before feeding. The live fish were mudsuckers, *Gillichthys mirabilis*, and were on the average about 20 percent as large as the herring. A normal feeding for the four fur seals was about 44 herring or about 200 mudsuckers per day, therefore making it possible to conduct several different feeding experiments (from 10 to 50 dead or live fish were used in each test) during a day.

The scoring was based on the average number of seconds required per seal for retrieving and eating the fish. For the feedings in darkness, an approximate time was determined for the four seals to pick up and eat the number of fish that would be involved in the test and the light-tight lid on the tank was raised after the predetermined number of seconds had elapsed. The number of fish that remained was subtracted from the number introduced and the calculations

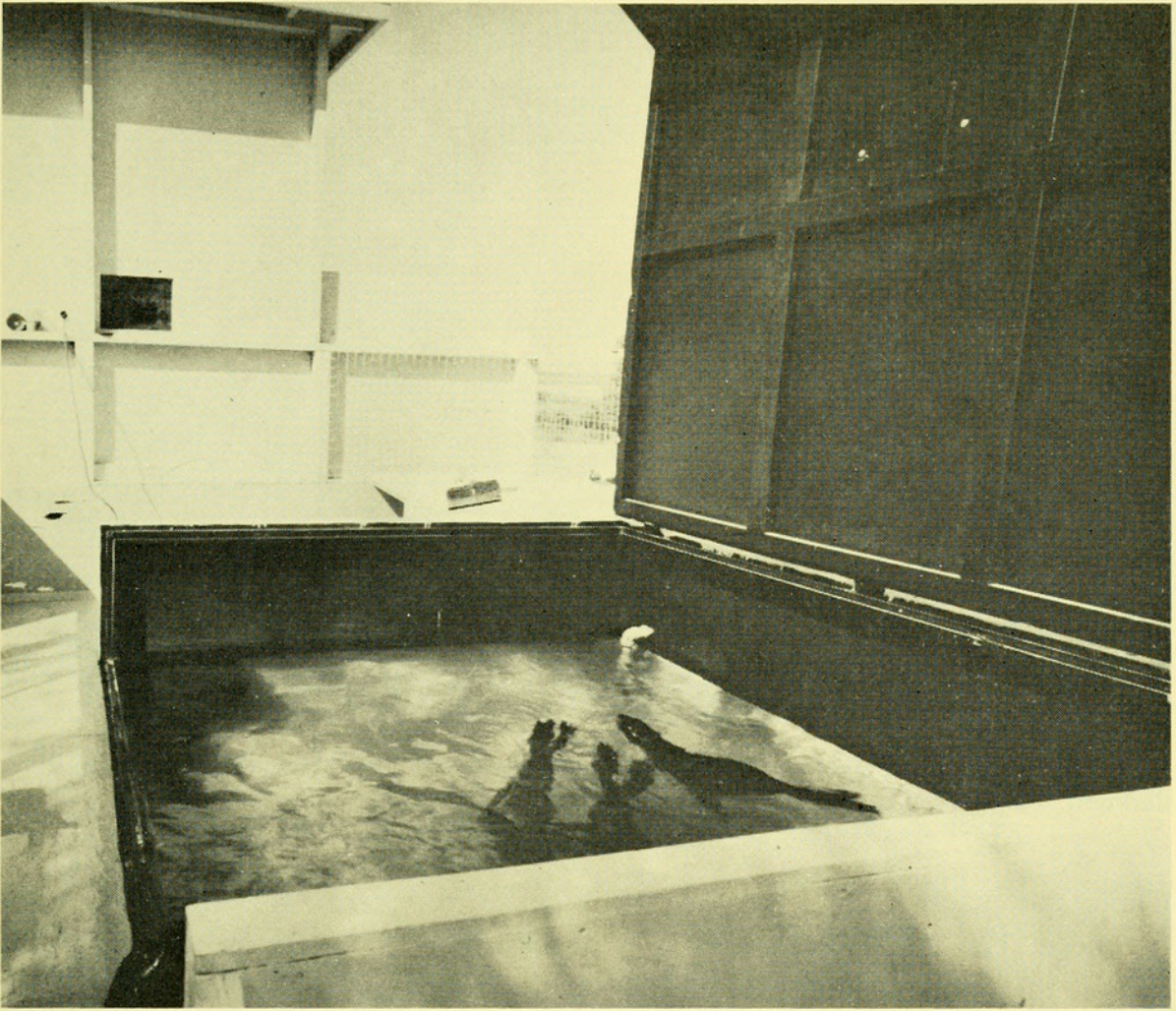


FIGURE 3. Feeding tank with light-tight lid in raised position.

made on that basis. Feeding in darkness was a completely new experience for the seals; the average time initially required for them to retrieve and eat live fish was about 15 seconds/fish/seal, but this decreased rapidly to 5.78 seconds/fish/seal.

Since the average number of dead fish used in these experiments was 44 after deducting the number that was left when the tank lid was raised and in order to eliminate any discrepancy due to the concentration of fish in the tank, 44 dead fish were used as the starting number for the daylight tests. The average retrieval and eating time in daylight was 5.28 seconds/fish/seal. (Considering the related variables, it is doubtful that the 0.5 second difference is meaningful.)

In planning the tests for the live fish in total darkness, the question arose as to whether the fish had a built-in avoidance system to escape from the seals in the dark which was comparable to their vision in daylight. To determine this, 12 mudsuckers were taken to the X-Ray Department of the Palo Alto Medical

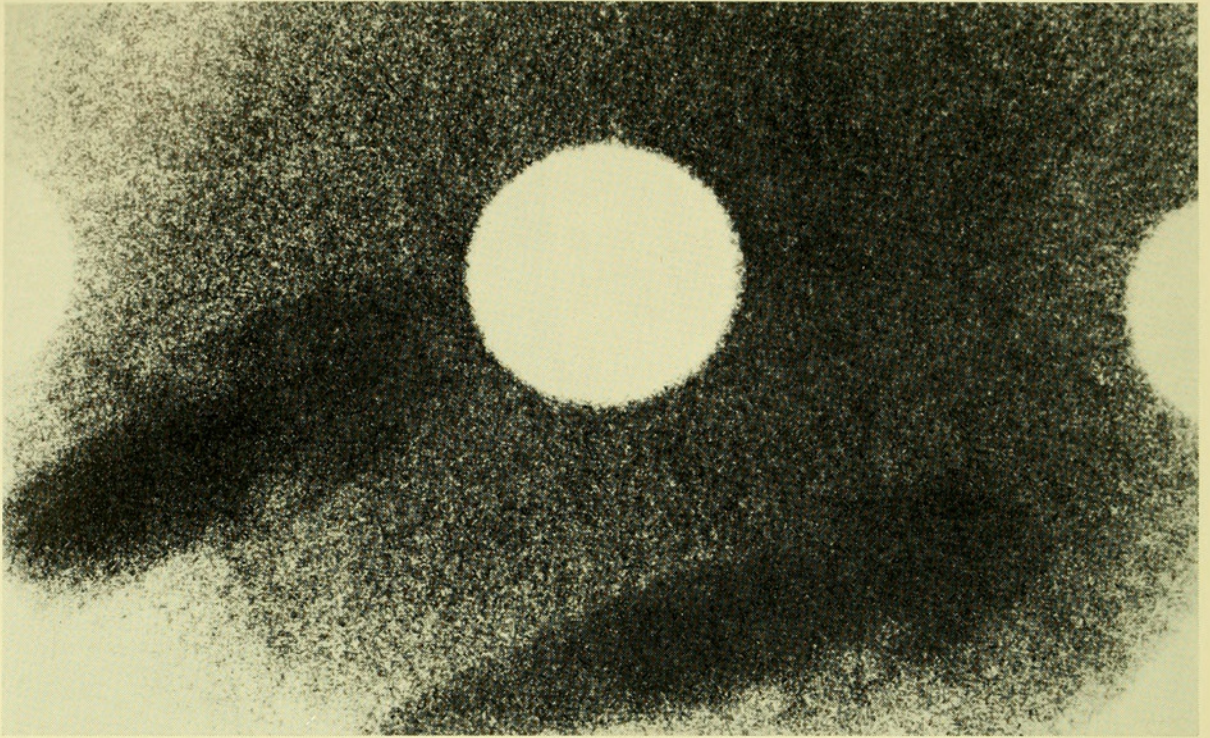


FIGURE 4. X-ray moving pictures show that mudsuckers collide with obstacles in total darkness.

Clinic and placed in a 3-inch-deep tray under the X-ray fluoroscope in total darkness. The fish were essentially as transparent to X-rays as was the water so that they were completely invisible on the fluoroscope. The clear water was then replaced with a barium sulphate (BaSO_4) slurry which reduced the visibility range of the fish to nearly zero.

We were then able to see on the fluoroscope the hole that the fish made in the slurry, and moving pictures were made of the fish in the tray as they went back and forth between barriers arranged in a row across the center of the tray. Very clear pictures of the fish were obtained, even to the extent of the detailed structure of their gills (see fig. 4). An examination of the moving pictures clearly showed that the mudsuckers had no avoidance system, as they made no attempt to avoid the obstacles.

As a substitute for the condition of total darkness, a slurry of barium sulphate was also put in the seal tank of such a density that their range of vision was reduced to about two inches or the distance from a seal's eyes to the tip of its nose. When the seals and selected large mudsuckers were first put into this milky liquid, it was such a completely strange environment for the seals that for the first 10 minutes they swam around with their heads at the surface of the water or they dove in and out of the water. Then one by one the seals realized that there were fish in the water and would disappear below the surface for many seconds at a time.

As the seals became accustomed to the clouded water, the time that it took them to pick up the fish reduced rapidly. With this arrangement we could put a large 3-inch-square mesh screen at one side of the tank and, at a predetermined time, sweep the seals out of the tank, drain the tank, and determine the number of fish left. For the first run the time was 92.3 seconds/fish/seal. The second run it went down to 48, the third run to 18.4, the fourth run to 8.0, and then it rapidly leveled off at 6.4 seconds/fish/seal. The corresponding value for live fish in daylight was 6.46. The 0.06 greater time in daylight is not considered significant; in fact a small difference in favor of darkness might be expected since the fish cannot detect the presence of the seal in darkness and hence cannot make an escape maneuver in advance of actual contact.

The increase of 1 second/fish/seal for live fish over that for dead fish is probably due to two factors: first, the necessity to catch the live fish; second, in the process of turning the fish around to swallow it head first, they would frequently escape and have to be recaptured. Some additional tests were run by closing the lid of the tank, thus superimposing total darkness on the barium sulphate slurry, but this did not change the minimum pick-up time of 6.4 seconds/fish/seal.

EFFECT OF CONCENTRATION OF FISH ON RETRIEVAL RATE

To demonstrate the effect of concentration of fish in the tank on the seal's retrieval rate, the four seals were put in the feeding tank and 50 live fish were introduced in daylight. While four people were counting the number of fish picked up by the four seals, one person counting for each seal, a fifth person attempted to add fish at such a rate as to maintain the number of fish in the tank at 50. From these counts, it was determined that an average of 4.18 seconds/fish/seal was required, as compared with 6.43 where no additional fish were added. The rate for the individual animals, however, was in the same ratio as determined previously.

EFFECT OF FISH SIZE ON RETRIEVAL RATE

Mudsuckers are of a fourfold range in size. Selected large mudsuckers were used in the above tests; however, if mudsuckers of different sizes were used in darkness or in the BaSO₄ slurry, the largest mudsuckers were always picked up first by the seals, whereas in daylight this tendency was not so pronounced.

In an attempt to determine the effect that the size of the fish had on the seal's retrieval rate, experiments were run in darkness in which 18 fish were used covering the full size range, with about 50 percent both above and below the median. During these tests the lid was raised at a time when we estimated about half of the fish had been picked up. The seals were then allowed to eat the remainder in daylight with the following results: 12.6 seconds/fish/seal in

darkness, and 16.95 seconds/fish/seal in daylight. There are two factors that caused these retrieval times to be much longer than the previously determined 6.4 seconds. First, the runs started with 18 fish instead of 50 fish and hence a concentration effect. This is equally true of the daylight versus the darkness runs, as only about half of the fish were left when the daylight portion of the runs started. Superimposed on this is the fish size effect. When the lid was raised, the remaining fish would invariably be the smaller ones, indicating that the smaller fish make much poorer sonar targets than the large fish. The daylight portion of the runs had the disadvantage of a small number of small fish.

There is also a considerable range in the rates at which the different individual animals picked up the fish, and the following average rate per animal was obtained:

<i>Seal</i>	<i>Retrieval Rate</i>
Fred	6.67 seconds/fish
Dot	10.00 seconds/fish
Dash	6.31 seconds/fish
K-7	9.23 seconds/fish
	$32.21 \div 4 = 8.05$ seconds/fish/seal

This average pick-up rate of 8.05 corresponds to 6.43 seconds/fish/seal when all four animals were feeding simultaneously in the same tank. The difference in these rates represents a characteristic competitive effect. Notwithstanding the number of factors affecting the rate at which the seals retrieve the fish, we believe that all of them have been properly evaluated.

During this extensive series of tests, the four fur seals (17 months old at the end of the tests) demonstrated that they can pick up and eat live or dead fish just as fast in total darkness as in daylight. The author feels that this constitutes adequate proof that they use some sort of sonar.

PASSIVE AND ACTIVE SONAR

In the experiments with both the penguins and fur seals, recordings were made with very sensitive hydrophone and recording equipment during feeding and at times when they were not being fed. Although a few very minor cases of vocalization were recorded from both species, these were almost invariably obtained at times when they were not being fed. If they were using passive sonar (in which the target is usually the source of sound), their performance could be explained on that basis. However, we have no evidence of any signals coming from the live fish from either our recordings or moving pictures, and we know that the dead fish certainly were not generating any signals.

Active sonar is sonar in which the source of sound comes from the organism

using sonar or from some artificial source in its general vicinity. If we examine the magnetic tape recordings made during the feeding tests to hear what sounds were recorded and determine how they would fill the requirements for active sonar, we find that the best possible type of signals is present for both the penguin and fur seal, both from the standpoint of character of signal and of abundance, in the form of water cavitation clicks (Shaver, 1967).

CAVITATION CLICKS AS A SONAR SOUND SOURCE

It has been shown that regardless of how streamlined an object may be or how smooth its surface, if it is moving through water at velocities even much lower than the swimming speeds of penguins and fur seals, it will generate sufficient turbulence in the water to produce cavitation (Poulter, 1942). Cavitation, as referred to here, does not include the air-filled bubbles visible in the water nor the large irregular cavities that can be observed as an object moves rapidly through the water. What we are concerned with is very small cavities not larger than a few millimeters in diameter, which persist for only a few milliseconds and hence are not visible to the unaided eye. These cavities are formed in the water as a result of a reduction in pressure caused by centrifugal force or other forces in the turbulence. This turbulence is caused by the rapid motion of the animal through the water, even though the animal appears to be gliding along rapidly and to be otherwise motionless.

Two forces tend to cause the collapse of cavities (thus, the clicks) formed by turbulence in this manner: the hydrostatic pressure of the water and the surface tension of the water on the interior surface of the cavity. For cavities 5 mm. in diameter or larger, the hydrostatic pressure has the greater effect, but as the diameter of the cavity decreases, the surface tension effect goes up asymptotically to phenomenally high values. The vapor pressure in a water cavity that contains no gas other than water vapor is, in effect, essentially zero whenever the dimension is reduced to less than the mean free path of the molecules, which is several millimeters. When molecules of water strike a free surface of water, such as the interior surface of the cavity, most of them are captured in the surface of the liquid and therefore are removed from the interior of the cavity and are not available to build up a vapor pressure. As the collapse of the cavity progresses, the velocity at which the opposite faces of the cavity approach one another is at an ever increasing rate. Theoretically, this velocity would approach infinity for a head-on collision at the center of the cavity. This means that the onrushing water surrounding the cavity cannot know that the collision has occurred until its velocity has been reduced to below the velocity of sound in water (Flynn, 1956; Rayleigh, 1917; Gilmore, 1952, 1956; Fitzpatrick, 1959; Benjamin, 1956; Mellen, 1956; Parkin, 1951; Plessett, 1949; Poulter, 1932, 1942; Schneider, 1949).

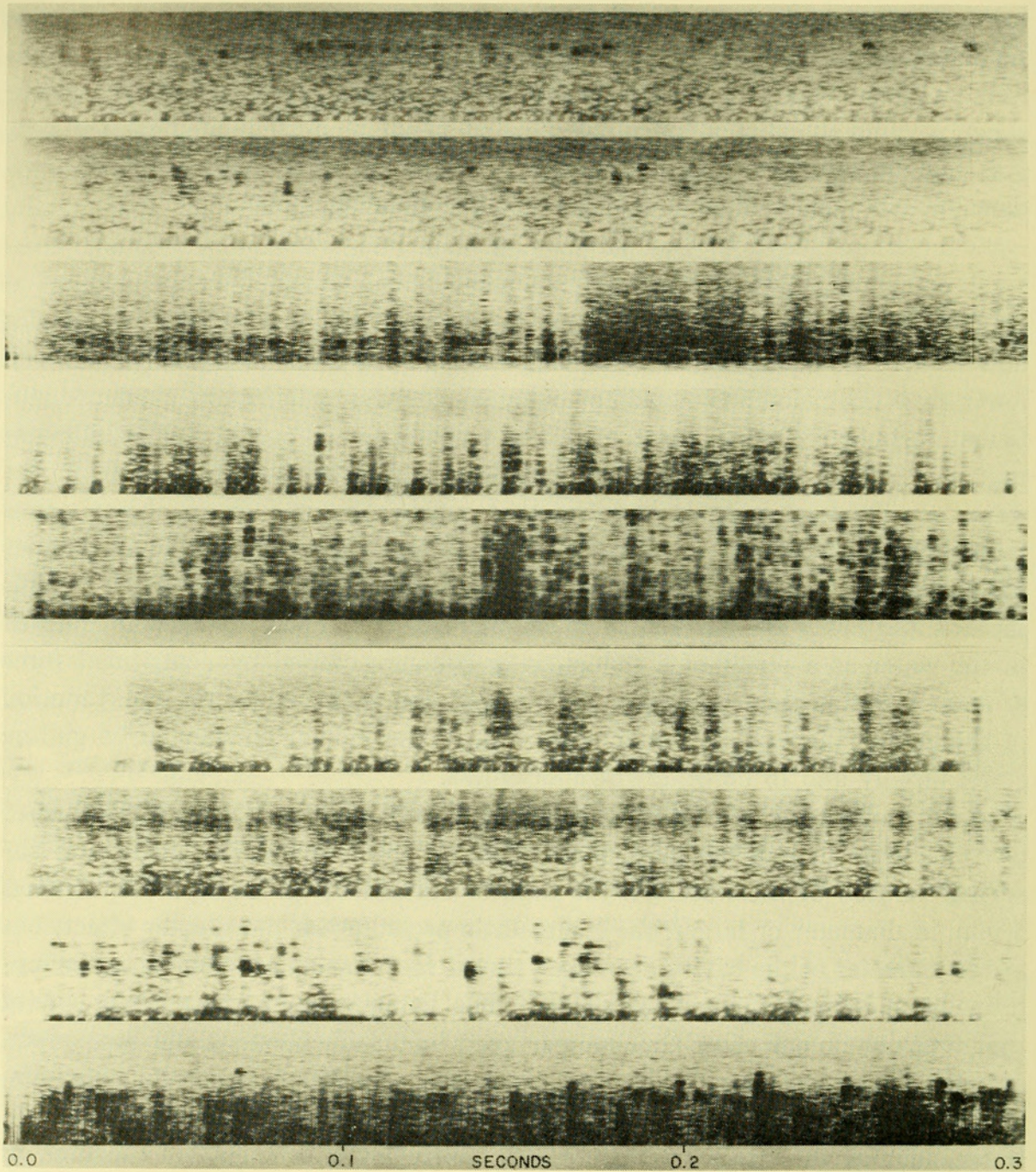


FIGURE 5. Sonograms of signals produced by: (a). Humboldt penguin gliding in water; (b). gentle motion of hand in water; (c). vocalization clicks of California sea lion; (d). fur seal catching live fish in total darkness; (e). four fur seals catching live fish in total darkness; (f). same as (b) except hand moving rapidly; (g). same as (b) except hand moving very rapidly; (h). four Humboldt penguins; (i). four Humboldt penguins swimming very rapidly.

Since these clicks are being formed in the water in close proximity to the animal's body, the sound energy travels out in all directions. As these sound pulses pass the ear of the seal or penguin, the animal registers the time that the outgoing signal starts for the target, and the returning echo gives it the elapsed

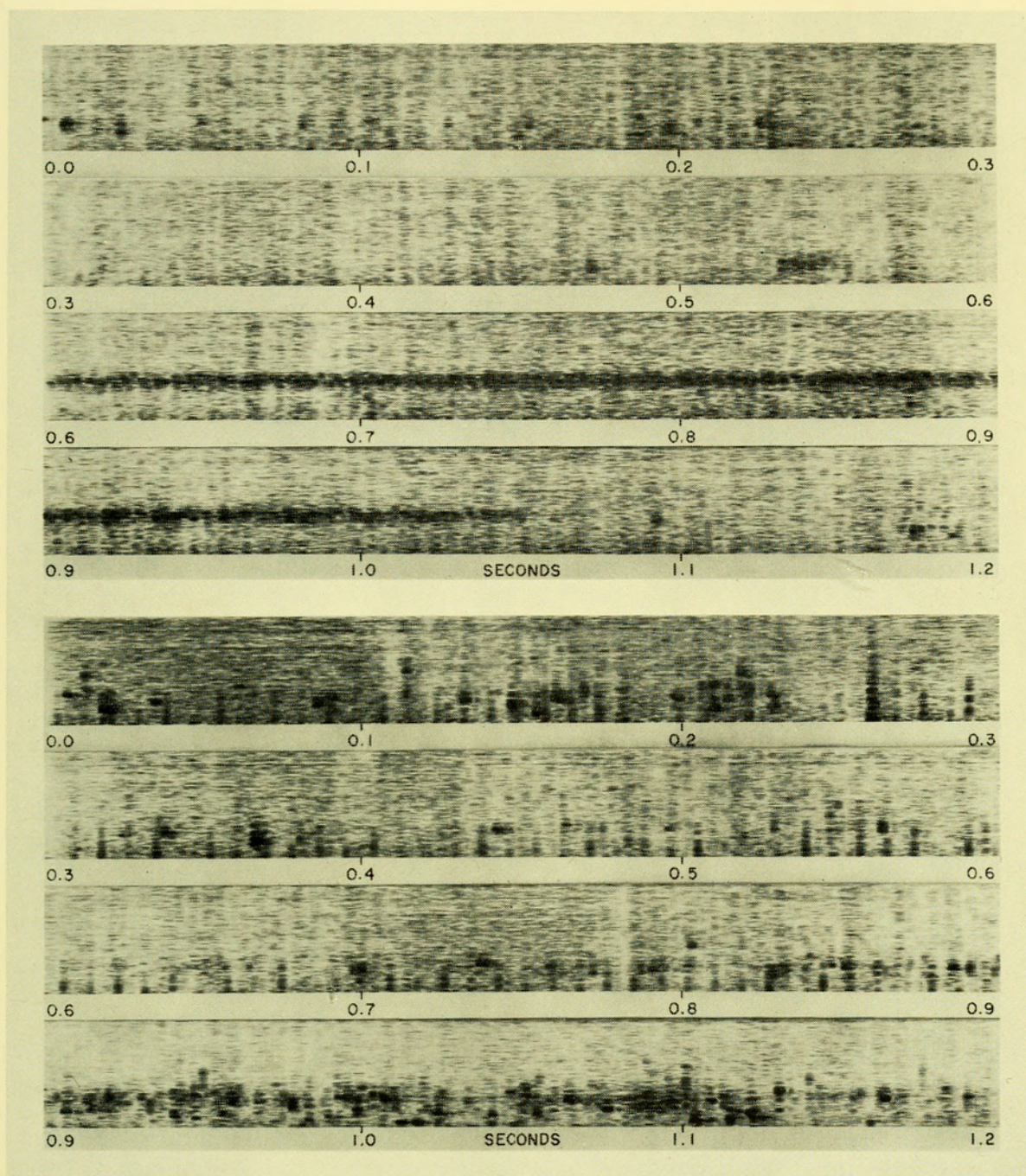


FIGURE 6. Two continuous sonagrams with four penguins feeding on fish in total darkness.

time and therefore the range information. Thus this echolocation method is just as truly active sonar as if the source of sound were within the animal's body, without the disadvantage of loudness to interfere with the animal's hearing. The random spacing of these clicks in time provides a variable sound pattern, thus enabling the animal to relate returning echoes to outgoing signals.

In all cases the sonagrams in figures 5, 6, 7, and 8 are run with a linear scale and a narrow filter setting on the Sonagraph with the sound recorder being op-

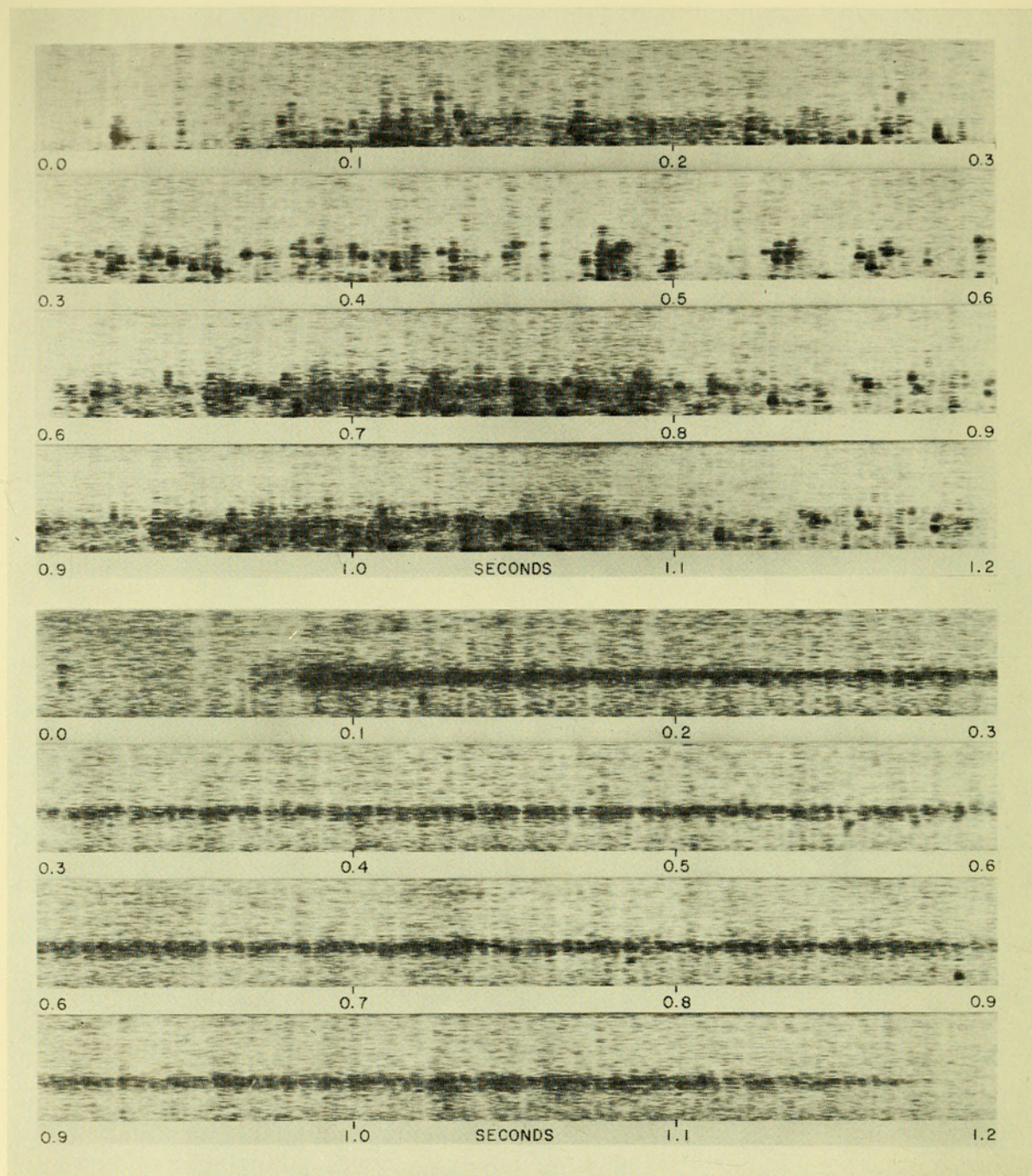


FIGURE 7. Two continuous sonagrams with four penguins feeding on fish in total darkness.

erated at $\frac{1}{8}$ actual recording speed. The frequency range therefore goes from 640 Hz. at the bottom to 64 kHz. at the top and the length of the individual sonagrams represents an elapsed time of 0.3 second.

Sonagram (a) shows a comparatively small number of cavitation clicks with the major energy of each concentrated in a narrow frequency range. These were generated by a Humboldt penguin gliding smoothly through the water in the anechoic tank. Even though there are only 20 clicks showing in this sona-

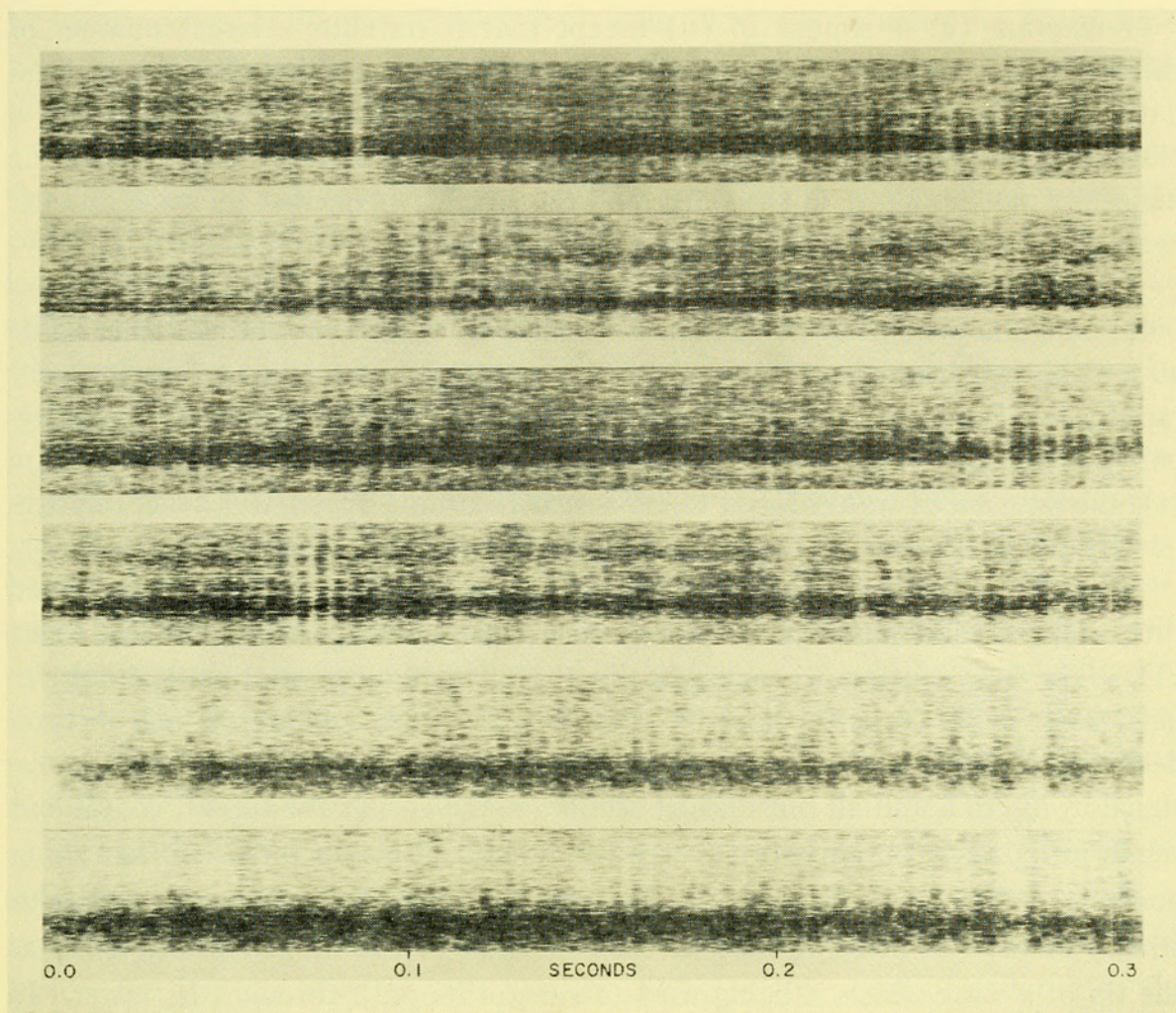


FIGURE 8. Six sonagrams of signals recorded with two or three King penguins swimming in daylight.

gram in 0.3 second, it represents a clicking rate of 66 clicks/second with some frequencies as low as 650 Hz. and others as high as 50 kHz.

Sonagram (b) shows an almost identical set of cavitation clicks occurring at about the same rate but these were generated by moving the hand gently in the water in the same anechoic tank. Sonagram (c) shows the vocalization clicks of a California sea lion, *Zalophus californianus*, again in the same anechoic tank with the same Sonagraph setting and $\frac{1}{8}$ actual tape recording speed. This signal shows a clicking rate of 160/second, and the frequency range continues up beyond the 64 kHz.

The signal for sonagram (d) was formed by one fur seal catching live fish in total darkness. It will be observed that the clicks in this case also consist of almost entirely white noise, and that they resemble quite closely the vocalization clicks of the California sea lion in all of their characteristics. However by listening to them at actual recording speed, they sound entirely different.

Sonagram (e) is similar to (d) except that it contains a larger number of clicks and this signal was generated by four fur seals catching live fish in total darkness. The signal from which sonagram (f) was made was generated in a manner identical to that from which sonagram (b) was made except that the hand was moving faster in the water and the signal represented by sonagram (g) again was identical but the hand was moving still faster.

The cavitation clicks represented by sonagram (h) were made by four Humboldt penguins swimming at moderate speed in the anechoic tank with the lights on and no fish in the tank. When the same four penguins were swimming very rapidly in the anechoic tank with the lights on and no fish in the tank, the signal was recorded from which sonagram (i) was formed. In making sonagram (i), the tape speed was reduced to $\frac{1}{16}$ actual recording speed and hence the frequency range goes up to 128 kHz. and the elapsed time down to 0.15 second.

Figures 6 and 7 each contains two continuous sonagrams covering an elapsed time of 1.2 seconds and each covering the frequency range from 640 Hz. to 64 kHz. The four continuous sonagrams in these two figures were made from signals recorded in the anechoic tank with four penguins feeding on fish in total darkness. It will be observed that most of the last half of the first continuous signal in figure 6 and all but a short section at the end of the second continuous signal in figure 7 contain a broad frequency band of higher intensity than other portions of the signal. We suspect that this is formed by an almost continuous stream of cavities being formed as some portion of the animal's body such as the tip of a wing which is being used to control its path through the water. In selected portions of the tape being recorded with the lights on while watching the penguins swimming in the tank, we got the impression that these long continuous bands (maximum of 1 second) were formed as the penguins were making a long sweeping curve but this was not definitely established.

The signals from which the six sonagrams in figure 8 were made were recorded in daylight as two or three King penguins, *Aptenodytes patagonicus* were swimming in a shallow pool with gradual sloping sides at the San Francisco Zoo.

Many recordings were made just off the Cape Crozier Adelie penguin, *Pygoscelis adeliae*, rookery in the Antarctic with Adelie penguins in the water, but there were so many signals from the leopard seal, *Hydrurga leptonyx*, that we were never able to identify any signals from their swimming except a big splash as they fell back into the water after an unsuccessful attempt to land on the ice as they jump from the water.

It is apparent that the sound energy generated by cavitation produces an excellent source of clicks for purposes of echolocation if one compares them with the clicks generated by the porpoise, *Tursiops truncatus* (Kellogg, 1961; Norris, 1961), or the California sea lion and other species specifically for echo-

location purposes (Poulter, 1966, 1963; Schevill, 1963). Cavitation clicks have been shown to have the necessary characteristics for the accurate determination of range and bearing (Shaver, 1967).

Various experimentors have employed high-speed photography to determine the existence of individual cavities roughly spherical in shape which grow and collapse as discussed above (Mueller, 1928; Knapp, 1948; Harrison, 1952; Norris, 1961; Eisenberg, 1957). The author also has observed the formation and collapse of cavities under a microscope, using a stratoscopic light where the cavities were being formed at the same point in space at a rate of 8000/second by means of a magnetostriction oscillator (Poulter, 1942).

Although pressures as high as 315,000 psi. have been postulated at the point of collapse of such cavities, the author has found through studies of the penetration of liquids into glass and various metals (Poulter, 1942, 1932) that these pressures actually exceed 225,000 psi. in ethyl alcohol and diethyl ether. However, because of the change of phase in water occurring at 108,000 psi., with an accompanying decrease in volume of 40 percent, it would be theoretically impossible for the pressure in the collapse of a cavity in water to exceed that pressure. The work that would have to be done in causing this decrease in volume is sufficient to stop the forward motion of the water.

All of this takes place within less than a microsecond, and the rebound results in a rapidly expanding shock pulse in the water with an initial shock or sound pressure of 108,000 psi. The water, therefore, rebounds with such a velocity that it pulls a second but smaller cavity at the point of collapse of the first cavity. This process repeats itself several times until the rebound energy is no longer great enough to pull the water apart and form a new cavity (Knapp, 1948; Benjamin, 1956; Mellen, 1954; Jorgensen, 1958; Poulter, 1942). Under these conditions, to pull the water apart requires a much greater force than that necessary to overcome the hydrostatic pressure, because the water actually has a tensile strength of several thousand psi. Theoretically, the tensile strength of water should go as high as 60,000 psi., but actual measurements have never gone beyond about 20 percent of that value.

The author has conducted experiments with oils under a tension of 16,000 psi. and found that a column of oil $\frac{5}{8}$ -inch in diameter and five inches long elongated $\frac{3}{4}$ -inch before it broke. The number of times that the cavity will be reformed is therefore less than if it did not have to overcome this tensile strength in the water. It will also depend upon the depth that the animal is in the water, since the force that is required to part the liquid is the sum of the hydrostatic pressure and the tensile strength of the liquid. Correspondingly, the formation of the initial cavity is effected by these same quantities. During the year that the author served aboard submarines, he learned that cavitation noise in the

water from the propellers is one of the easiest means of detecting the presence of a submarine. It is therefore a general practice for a submarine to increase its depth of operation in order to reduce the cavitation by the associated increase in hydrostatic pressure of the water.

When a marine mammal trainer wants to get the attention of his subject, it is only necessary for him to move his hand rapidly back and forth in the water and produce cavitation clicks. These clicks actually contain more energy than do those made by the porpoise and California sea lion. In general, the frequency within the cavitation pulses generated by the swimming of the fur seal and the penguin may vary from less than one to more than 50 kHz., and the shock pulse may reach its full amplitude in the first half cycle or in less than 5×10^{-6} seconds (Mellen, 1954, 1956; Jorgensen, 1958; Meyer, 1957; Gute, 1956).

CONCLUSION

From the preponderance of evidence that the penguin and fur seal have a capability for locating fish in total darkness which is equivalent to their vision in daylight, and further because of the complete absence of any vocalization signals in the water when they are feeding and the presence of cavitation clicks so excellently suited for echolocation, we believe that they do use an active sonar and that the cavitation clicks in the water constitute their source of sound.

The fact that the fur seals were as young as they were when captured and were isolated from all other pinnipeds until after these tests, demonstrates that their sonar capability is an innate ability rather than something they are taught by adult animals.

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The author is deeply appreciative of the assistance of Lawrence Martinez in the conducting of these experiments.

SUMMARY

Thus one more species each of marine mammals and the diving birds have been added to the rapidly expanding list of living organisms using an active sonar system in their avoidance of obstacles and the location and retrieval of their prey.

This is the first instance other than man himself in which an active sonar system has been developed around a sound source other than some form of vocalization.

LITERATURE CITED

BENJAMIN, T. BROOKE

1956a. Unpublished communication that evidence of a shock wave has been observed at Kings College, Cambridge, by means of tiny transducers made of chips of barium titanate.

1956b. Cavitation in liquids. Doctoral dissertation, Cambridge University.

EISENBERG, P.

1957. Modern development in the mechanics of cavitation. Applied Mechanics Reviews, vol. 10, p. 85.

FITZPATRICK, H. M., AND M. STRASBERG

1959. Hydrodynamic sources of sound. David Taylor Model Basin, Department of the Navy, Report no. 1269.

FLYNN, H. G.

1956. The collapse of a transient cavity in a compressible liquid. Doctoral dissertation, Harvard University.

GILMORE, F. R.

1952. The growth and collapse of a spherical bubble in a viscous compressible liquid. California Institute of Technology, Report no. 26-4.

1956. Collapse of a spherical bubble in a compressible liquid. Speech presented at a meeting of the Division of Fluid Mechanics, American Physical Society, Pasadena, California.

GUTE, W.

1956. Zur Entstehung Der Stosswellen Bei Der Lovitotion. Acoustica, vol. 6, p. 526.

HARRISON, M.

1952. An experimental study of single-bubble cavitation noise. David Taylor Model Basin, Department of the Navy, Report no. 815.

JORGENSEN, D. W.

1958. Measurements of noise from cavitating submerged water jets. David Taylor Model Basin, Department of the Navy, Report no. 1126.

KELLOGG, W. N.

1961. Porpoises and Sonar. Chicago, University of Chicago Press.

KNAPP, R. T., AND A. HOLLANDER

1948. Laboratory investigation of the mechanism of cavitation. Transactions of the American Society of Mechanical Engineers, vol. 70, p. 419.

MELLEN, R. H.

1954. Ultrasonic spectrum of cavitation noise in water. Journal of the Acoustical Society of America, vol. 26, p. 356.

1956a. An experimental study of the collapse of a spherical cavity in water. Journal of the Acoustical Society of America, vol. 28, p. 447.

1956b. Spherical pressure wave of finite amplitude from collapsing cavities. U. S. Naval Underwater Sound Laboratory, Research Report no. 326.

MEYER, E.

1957. Some new measurements on sonically induced cavitation. Journal of the Acoustical Society of America, vol. 29, p. 4.

MUELLER, H.

1928. Über den gegenwärtigen Stand der Kavitationsforschung. Die Naturwissenschaften, 16 Jahrg., Heft 22.

NORRIS, K. S., J. H. PRESCOTT, P. ASA-DORIAN, AND P. PERKINS

1961. An experimental demonstration of echolocation behavior in the porpoise, *Tursiops truncatus*. The Biological Bulletin, vol. 120, pp. 163-176.

PARKIN, B.

1951. Scale effect in cavitating flow. California Institute of Technology, Report no. 21-7.

PLESSETT, M. S.

1949. Dynamics of cavitation bubbles. Applied Mechanics, vol. 16, p. 277.

POULTER, T. C.

1942. The mechanism of cavitation erosion. Journal of Applied Mechanics, pp. A-31-A-37.
- 1963a. Sonar signals of the sea lion. Science, vol. 139, no. 3556, pp. 753-755.
- 1963b. The sonar of the sea lion. IEEE Transactions of the Professional Technical Group on Ultrasonics Engineering, vol. UE-10, no. 3, pp. 109-111.
1966. The use of active sonar by the California sea lion, *Zalophus californianus* (Lesson). The Journal of Auditory Research, vol. 6, pp. 165-173.

POULTER, T. C., AND R. O. WILSON

1932. The permeability of glass and fused quartz to ether, alcohol and water at high pressure. Physical Review, vol. 40, no. 5, pp. 877-880.

RAYLEIGH, LORD

1917. On the pressure developed in a liquid during the collapse of a spherical cavity. Philosophical Magazine, vol. 34, p. 94.

SCHEVILL, W. E., W. A. WATKINS, AND C. RAY

1963. Underwater sounds of pinnipeds. Science, vol. 141, no. 3575, pp. 50-53.

SCHNEIDER, F. R.

1949. Some compressible effects in cavitation bubble dynamics. Ph.D. Thesis, California Institute of Technology.

SHAVER, H. N., AND T. C. POULTER

1967. Sea lion echo ranging. Journal of the Acoustical Society of America, vol. 42, no. 2, pp. 428-437.



Poulter, Thomas C. 1969. "Sonar of penguins and fur seals." *Proceedings of the California Academy of Sciences*, 4th series 36, 363–380.

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