Porpoise Sounds as Sonar Signals[1,2]

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THE NOTION that porpoises or dolphins—and possibly other cetaceans as well—orient themselves in the water by listening to the reflected echoes of their own noises offers challenging possibilities for research (*1, 2*). This process, known as echolocation or echo-ranging, serves as the basis of sonar, and of both sonic and supersonic depth-finding. The best example of echolocation among animals is the case of the bat, which is known to employ reflected sound to avoid colliding with objects while in flight. Griffin (*3, 4*) has shown, in fact, that the cries emitted by bats for purposes of echo-ranging extend far into the ultrasonic range.

The study of such a phenomenon in animals of the sea involves special problems of its own—particularly since scientific knowledge on this question is at present extremely meager. In order to determine whether porpoises or dolphins employ echo-ranging in water, it would certainly be necessary to establish three things: First it must be shown that these animals can hear sufficiently well and in the proper frequency range to react to the echoes of the sounds they emit; second, it must be demonstrated that the noises fall within a temporal and frequency pattern suitable for echo-ranging in water; third, it must be established that, even though they possess these mechanisms, they actually employ them to orient themselves in space and to avoid colliding with objects in their environment.

With regard to the first point, Fraser (*5*) has noted that certain porpoises will swim rapidly away from a vessel at the sound of a supersonic depth finder—a reaction which clearly implies that they can hear sounds higher than man. Whether such hearing actually exists, and the limits to which it may extend, have recently been investigated (*2*) by two of the present writers in tests upon the bottle-nose dolphin, *Tursiops truncatus* (Montagu). The results indicate that under favorable conditions this animal can regularly react to vibrations in water as high as 80,000 cycles/sec.

As a consequence of these findings, interesting questions at once arise regarding the second point. For example, if *T. truncatus* is able to respond to frequencies in water at such a high level, what kinds of sounds does he himself produce, and are they also ultrasonic? That porpoises make a variety of noises has often been observed (*6–8*), but the problem of their measurement and analysis is not an easy one. In the present paper we wish to report some beginnings in this direction and to show that the sounds emitted by these remarkable animals can conceivably be used for echo-ranging or echolocation in water.

Subjects. All the subjects were bottle-nose dolphins, or porpoises, *T. truncatus*. Three of the animals were captive specimens; others were in the free or wild state. The wild porpoises were all observed from a U. S. Navy plane personnel boat, 24 feet in length, in the Gulf of Mexico, near the laboratory of the Oceanographic Institute of Florida State University. Two of the captive animals were young but mature females, which were studied at the Lerner Marine Laboratory at Bimini, B. W. I., a field station of the American Museum of Natural History. They were kept together in a wire enclosure in the open bay (*ca.* 30′ × 50′), through which sea water flowed freely. The depth of the water at low tide was 7–8 feet, and at high tide 10–11 feet. The third captive animal was confined alone in an excavated canal or pool (*ca.* 40′ × 60′) at the Daytona Sea Zoo at Daytona Beach, Florida. It was probably also a female.

Apparatus. The sounds were picked up through a specially constructed hydrophone, or underwater microphone, capable of receiving vibrations up to and beyond 200,000 cycles/sec (200 kc). The hydrophone consisted of thick Rochelle salt blocks potted in clear plastic bonded to a brass cylinder containing a two-stage preamplifier. The signal from the preamplifier was fed into the medium-gain input stage of a high-fidelity power amplifier. Many of the sounds, after being received in this manner, were then recorded by means of an Ampex Model 307 high-speed tape recorder of the type ordinarily used in telemetering. The Ampex recorder has a rated recording range to 100,000 cycles/sec (tape speed, 60 in./sec) but will go considerably higher than this (although at reduced sensitivity). The response of the amplifier-recorder system as a whole was down approximately 3 db at 80,000 cycles/sec, and 5 or 6 db at 100,000 cycles/sec.

Methods of frequency analysis. Three general methods were used to determine the frequencies of the sounds emitted. None of these can be considered pre-

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[3] The writers wish to take this opportunity to thank C. M. Breder, Jr., of the American Museum of Natural History in New York City, for permission to use the excellent facilities of the Lerner Marine Laboratory, a field station of the Museum at Bimini, in the Bahama Islands, B. W. I. We also wish to thank Perry A. Sperber and Mrs. M. R. Sperber, of the Daytona Sea Zoo, for generous cooperation and aid. The acoustical analysis was greatly facilitated by the cooperation of the U. S. Air Force Guided Missile Center at Cocoa, Fla., and the U. S. Navy Mine Countermeasures Station at Panama City, Fla.

cise, but they do show the presence or absence of vibrations within different frequency bands and they also indicate the relative intensities of the waves that are present.

1. In the first of these methods the porpoise sounds, after being received by the hydrophone and amplified, were sent through band-pass or high-pass filters and observed on the screen of a cathode-ray oscilloscope. One such filter was an SKL variable electronic Model 302. The SKL filter is adjustable, permitting the passing of any desired frequency band from 0 to 200 kc. When the lower frequencies were filtered out, the presence of the higher frequencies could be seen directly on the oscilloscope screen at the same time that the noises were being produced. A loudspeaker permitted the simultaneous hearing of the audible component of the sounds. Another type of filter, employed particularly in studies of the wild porpoises in the Gulf, was a high-pass, high-Q filter which cut out all frequencies below 100 kc.

2. The second method was a variation of the first, yet it afforded the opportunity for more careful and deliberate work. In this case ultrasonic tape recordings obtained from the captive animals were played back on the Ampex recorder in the laboratory. The signals from the recorder were then sent through the SKL filter and were observed on an oscilloscope as in method one. This procedure permitted repeated playbacks of the same sounds under favorable laboratory conditions, with the consequent opportunity of checking and rechecking the results obtained.

3. The third and most elaborate of the techniques for determining the frequencies within the total sound complex made use of (*a*) a Panoramic Ultrasonic Analyzer, Model SB-7, and (*b*) the Fairchild Sound Measuring and Analyzing System of the U. S. Navy Mines Countermeasures Station, at Panama City, Florida.

a) The Panoramic Ultrasonic Analyzer is a scanning heterodyne receiver which automatically measures the frequency and amplitude of both sonic and ultrasonic signals. Using a stabilized sweeping system, "... the instrument tunes repetitively 6 times per sec through a 200 kc range in any part of a 10 kc to 300 kc band. As signals are tuned through, they appear on a cathode-ray tube as sharp vertical pips located horizontally in order of frequency. The heights of the pips indicate the relative magnitudes of their corresponding signals. A continuous over-all graphic presentation of the spectrum is obtained on a long persistence cathode-ray tube screen."[4] The signals from the tape of the Ampex recorder were fed directly into this device. A speaker was also in the circuit, so that the audible components of the sounds could be heard simultaneously with the occurrence of their pips upon the cathode-ray screen.

b) The Fairchild Sound Measuring and Analyzing System used in the frequency analysis is a special octave band-pass analyzing system manufactured by the Fairchild Instrument Company. The input signals are broken down into the octave bands by individual band-pass amplifiers having a maximum gain of 86 db. The filters are flat to ±1.0 db over one half of each octave band. At the cutoff points of the octave, the level is down 6 db from the center level, and the cutoff rate outside the octave band is 45 db/octave. The signals from Ampex tape recordings, after passing through the octave-band amplifiers of the Fairchild system, were read from a Dumont Model 304 oscilloscope and from a Ballentine a-c meter Model 310.

[4] Statement from manufacturer.

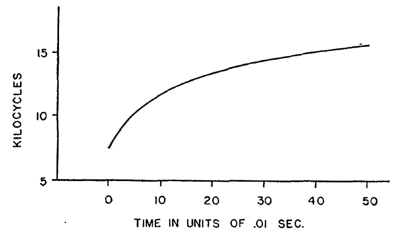

FIG. 1. Schematic diagram of one form of the porpoise whistle, showing frequency plotted against time.

The findings discussed here will deal only with the temporal and frequency characteristics of the noises made and will ignore any absolute measures of intensity. The reasons for this limitation are (*a*) that the receiving system as a whole was an uncalibrated system so far as intensities are concerned. (*b*) Yet, even had it been calibrated, there was no way to keep the distance between the porpoises and the hydrophone constant. Since the intensity of sound varies inversely with the square of the distance from the source, a receiving system calibrated for intensities would therefore have been of little value in any case.

The system was carefully checked for its frequency responses, however, by sending pure tones from an oscillator through an underwater transducer, at 20–200,000 cycles/sec. The frequencies sent out by the transducer were then picked up by the hydrophone and amplifying equipment and were observed on the screen of a cathode-ray oscilloscope. The same frequencies were also sent directly to the oscilloscope, by-passing the underwater gear entirely. A comparison of the wave forms transmitted by these two methods showed that no distortions in frequency were introduced by the underwater system.

The porpoise whistle. Of the various noises produced by the bottle-nose dolphins observed in these studies, two were found to occur almost continuously. The first of these was a birdlike whistle, approximately .5 sec in duration. The whistle appeared in several "melodies," or pitch patterns, the most common of which resembled the cheep or whistle of a canary. This generally began in the neighborhood of 7000 cycles/sec and ended at about 15,000 cycles/sec. The pitch range was therefore slightly over an octave. Although harmonics are certainly present, we have not been able to bring them out well. The whistle overtones are apparently weak and, so far as we can determine, do not extend beyond 20 kc. This is something of a paradox, since the whistle is of course very high to human ears, and might consequently be expected to possess a strong component of ultrasonic vibrations. However, since the whistle does occur in several forms, there may be varieties of it, not yet examined, that contain harmonics beyond 20 kc. It is likely, moreover, that the whistles given by different individuals will vary considerably. A schematic representation, showing one form of the porpoise whistle, with frequency plotted against time, is given in Fig. 1.

If the bottle-nose dolphin employs reflected sound to orient itself in space, the whistle could conceivably be used for this purpose. Under such circumstances it would constitute a kind of frequency-modulated sonar. The continuously changing pitch would reflect a continuously changing echo, which at any given instant would differ from the frequency being produced. With such a method it is not necessary that the sounds be emitted in short, intermittent bursts as they are in a pulse-modulated system.

Underwater "clicks." The second and by far the more common of the underwater sounds produced by the bottle-nose dolphin is a series of rapid "clicks" or "clacks," variously described as the "rusty-hinge" sound or the "creaking-door" sound. These sounds are also reminiscent of the pecking of a woodpecker, except that their rate of occurrence is usually faster, although it can also be slower than that of the woodpecker. One is similarly reminded of the Bronx cheer made by blowing air through tightly pressed human lips. The rate at which the individual clicks occur may vary from as slow as 5/sec to 100/sec, or higher. In the latter instance the total sound takes on the general quality of a groan or a bark. Within a single group of clicks lasting several seconds, the number of clicks per second can change from fast to slow, or vice versa. When these sounds occur at approximately 15/sec or slower, they lose any tonal quality they may have possessed, and are then heard as a succession of discrete individual units. In such cases each click becomes a sharp, staccato report, like that produced by striking a heavy wooden table with a small hammer.

Since the groan or barklike effect of a train of such clicks is ordinarily low in pitch, the average listener is not likely to suspect them of containing ultrasonic frequencies. Yet the methods of analysis previously described disclose them to be heavily weighted with such frequencies. The dominant frequencies, so far as intensity is concerned, are in the sonic range, but other vibrations far above the limits of audibility are present. With respect to the wide band of vibrations represented, the clicks somewhat resemble "white noise." Analysis of our Ampex recordings has shown a tapering off of intensities from 20 kc to about 120 kc, with the occasional occurrence of vibrations extending to 170 kc or higher.

The tapering effect beyond 100 kc is undoubtedly a function of the Ampex recorder, at least in part, since this instrument is known to fall off rapidly above 100 kc and is not even rated by the manufacturer for values higher than this level. At the same time, it may be due in some degree to the nature of the sounds themselves. So far as our observations have been able to go, it would appear that the different clicks each possess somewhere near the same complex of frequencies. Certainly we have been able to detect no significant variations in pitch from one click to the next. It must be concluded, therefore, that the click or clack emitted by the bottle-nose dolphin contains frequencies that extend to 120 kc or above.

Fig. 2 is a photograph of the cathode-ray screen of the ultrasonic analyzer, showing the frequency components occurring between 80 and 120 kc in a series of porpoise clicks. The 80 kc marker-pulse is the low peak on the left overlapping the higher peak on the left. Only those frequencies corresponding to the position of the sweep at the moment the sound occurred are shown. The separate peaks indicate the presence of frequencies within the different clicks, which correspond to the horizontal scale. In this particular instance, 12 clicks occurred during the .5-sec photographic exposure. The heights of the pips in the photograph show the relative intensities for the different frequencies.

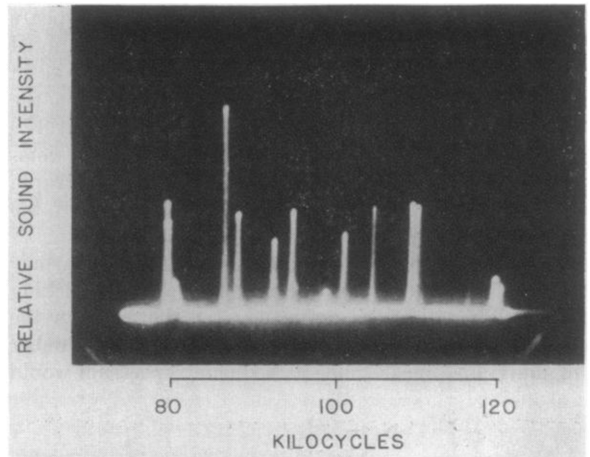

FIG. 2. Photograph of the cathode-ray screen of a panoramic ultrasonic analyzer, showing the frequency components occurring between 80 and 120 kc in a series of porpoise clicks. The separate pips represent the coincidence of the sweep of the cathode-ray tube with different clicks. The 12 clicks that occurred during the photographic exposure (.5 sec in this instance) thus contained frequencies extending at least to 120 kc.

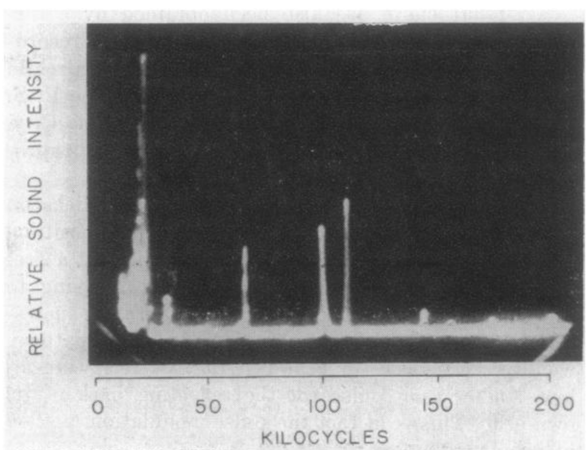

FIG. 3. Photograph of the cathode-ray tube of the panoramic analyzer when the tuning range was 10–200 kc. The strongest frequencies, so far as intensity is concerned, will be seen to lie below 25 kc, but the short pips at the right indicate the presence of frequencies at 140, 155, and 170 kc, respectively.

Fig. 3 is another photograph of the frequencies in porpoise clicks, when the tuning range of the analyzer was 10–200 kc. The 200 kc marker is the small pip on the extreme right. A marker showing 100 kc appears as the heavier of the two central pips. It will be noted that there is a massing of frequencies below 25 kc in this sample. At the same time there are pips on the right representing frequencies of 140, 155, and 170 kc, respectively. Although these are the highest components we have thus far been able to photograph, there is no reason to believe that they represent the ultimate limit.[5]

It is possible to derive an approximate frequency spectrum for the ultrasonic frequencies of the clicking sounds by noting the amplitudes of the pips on the screen of the ultrasonic analyzer for a large number of individual clicks. Such a frequency spectrum would

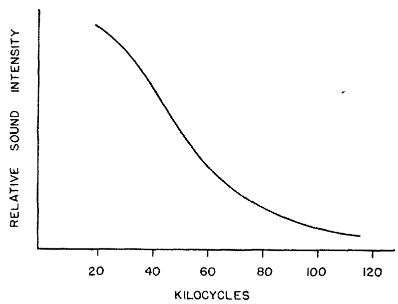

FIG. 4. Ultrasonic frequency spectrum derived from high-speed tape recordings of the typical porpoise click. Essentially the same graph was obtained by two independent methods of acoustical analysis.

indicate relative rather than absolute sound intensities, since these intensities are not only a function of the input signal but are also a function of the recording system. The spectrum derived in this way for frequencies higher than 20,000 cycles/sec is given in Fig. 4.

A similar curve has also been obtained by a different method of analysis. In this case Ampex recordings of dolphin sounds were run through a Fairchild Sound Measuring and Analyzing System, at the U. S. Navy Mine Countermeasures Station at Panama City. The graph obtained is again essentially that reproduced in Fig. 4.

Clicks as echo-ranging signals. Since the clicks do not vary systematically in frequency composition, they would be unsuitable for echo-ranging by a frequency-modulation method such as that applying to the whistle. But, on the other hand, a rapid succession of short impulses, of constant frequency pattern, would be excellent for echo-ranging, if time were allowed after each pulse for the reflecting back of its own echo. This is in fact the pulse-modulation method of echo-ranging.

So far as timing and duration are concerned, the clacks produced by the bottle-nose dolphin satisfy fully the requirements necessary for echo-ranging in water by the pulse-modulation method. The duration of the shortest of these sounds has been found to be about 1 msec (.001 sec). Others are considerably longer. At a water temperature of 82.5° F, and a salinity approximately that of the water at Bimini, for example, sound in sea water travels 5063 ft/sec. In .001 sec it would therefore travel a distance of 5.06 feet. This means that the initial vibrations of a single click .001 sec in length would be reflected back to the point of emission at the termination of that click, from an object as close as 2.53 feet. The speed with which a porpoise could react to this reflected signal would, of course, depend upon additional factors, such as, for example, its reaction time. But since the clicks are emitted in rapid succession, it is unlikely that the presence of any object would be sensed all at once. The approach to the object would be shown by a gradual change in the timing of the echo through many hundreds of successive impulses.

Most of the dolphins to which we have listened, or from which we have obtained recordings, have been found to be making such noises whenever the hydrophone was placed in the water. The sounds have been picked up when the animals were swimming slowly as well as when they were swimming fast, and sometimes when they were standing on their tails in the water, or were otherwise almost motionless. Such continuous sound production would be essential if the porpoises were regularly using these noises to locate objects in their environment.

Advantages of ultrasonic frequencies. Moreover, the wide band of frequencies represented in these noises offers special advantages for echo-ranging in water because of the factors of (*a*) masking and (*b*) resolution.

a) Under ordinary circumstances a porpoise may react to the sonic frequencies he produces, but in many instances these frequencies would be masked or obscured by the background water noise, which is mostly at lower frequency levels. Such noises as the sound of waves, the rushing of water past the animal's own body in fast swimming (like wind blowing by human ears), the sounds of ships' propellers, and the noises made by other organisms of the sea, are all, so far as is known, below 10,000 cycles/sec. When the basic porpoise frequencies are obscured or interfered with by such disturbances, the high-frequency components of the click would still filter through. It is possible in some cases that the ultrasonic frequencies alone would be all that could be heard.

b) High frequencies would also be better for echolocation because they are shorter in wavelength and consequently have a greater resolving power or directionality. They would indicate the presence, the size, and the shape of an object, by echoes, better than longer waves. A tone of 5000 cycles/sec, for example, if transmitted at a sound speed of 5000 ft/sec, produces a wave 1.0 feet in length. But if the frequency is increased to 50,000 cycles/sec, the sound speed remaining the same, the wavelength becomes 0.1 feet. The higher the vibration rate, the shorter the wavelength, and consequently the more precise the resolution as determined from the reflected echo.

[5] After the completion of this paper, an ONR report by Schevill and Lawrence (9) has reached us in which frequency components as high as 196 kc are reported in some porpoise sounds.

Listening to the echoes from clicks. Echoes from sounds made under water will bounce off from the surface of the water and from the bottom, as well as from objects located in a horizontal plane. That echoes of this sort are actually produced by porpoise clicks can be clearly demonstrated in two ways: (1) They can be seen on the screen of a cathode-ray oscilloscope. (2) They can be heard by the human ear under the proper acoustical and temporal conditions. The actual hearing of the echoes is accomplished by reducing the playback speed of the recording tape. The original tape speed of the Ampex ultrasonic recorder is 60 in./sec. Tests have been made with playback speeds of 1/8, 1/16, 1/32, and 1/64 of the recording rate. This has the effect of lowering the intensity as well as the number of cycles per second of the sounds played. For example, a bona fide frequency of 100,000 cycles/sec, reproduced at 1/64 of its original speed, becomes 1562.5 cycles/sec. The duration of the sound is correspondingly lengthened by a factor of 64.

Under such circumstances, the echo becomes clearly audible. It can be heard by most people at 1/16 of the recording speed, is very clear at 1/32, and is often a booming reverberation at 1/64 of the original rate. An inherent difficulty in measuring the duration of any single click is brought to light by this slow playback method, since a click cannot often be clearly separated from its own echo. One would have to be certain, in obtaining precise time measurements of this sort, that there was no echo at all—a difficult if not impossible prerequisite.

Although the facts recorded here do not establish conclusively that the bottle-nose dolphin actually uses echo-ranging, they offer good circumstantial evidence to that effect. *T. truncatus* certainly possesses what may be described as a "sonar system." The final proof that he employs it for echolocation must come by testing captive animals for the avoidance of objects in water after vision has been eliminated.

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News and Notes

Scientists in the News

James Bliss Austin, director of research and chief of U. S. Steel Company's Research Laboratory, Kearny, N. J., has been appointed chairman of the Committee on Chemical Warfare, U. S. Department of Defense, to succeed **Randolph T. Major,** vice president and scientific director of Merck & Co.

A. Ludlow Clayden has been appointed technical associate in Sun Oil Company's Chemical Research and Development Department. **John G. Moxey, Jr.,** succeeds him as manager of the Automotive Laboratory.

A. W. B. Cunningham, of the University of Edinburgh, has been appointed professor of pathology at the University of Texas Medical Branch, Galveston, where he will both teach and conduct research on arthritis and diseases of the joints.

Herbert N. Eaton retired on Jan. 31 as chief of the Hydraulics Section of the National Bureau of Standards, a position he has held since 1928. He had been with the bureau since 1919.

Gustav Egloff, petroleum scientist and director of research for Universal Oil Products Company, has been selected by five national engineering societies to receive the Washington Award for 1953, for leadership in petroleum research and in community services.

Nicholas Ercoli has been appointed head of the Department of Pharmacology and Chemotherapeutics, Research Division, Armour Laboratories, Chicago. Dr. Ercoli was formerly scientific director of the Istituto Sieroterapico Milanese Serafino Belfanti, University of Milan.

K. P. Ewing, entomologist of the U. S. Department of Agriculture, has been named head of the department's Division of Insects Affecting Cotton and other Fiber Plants. Mr. Ewing will succeed **R. W. Harned,** who will continue with the Bureau of Entomology and Plant Quarantine as staff assistant and consultant.

Herbert S. Gaskill, of the Indiana Medical School, Indianapolis, has been appointed professor and head of the Department of Psychiatry, University of Colorado, to succeed **Franklin G. Ebaugh,** who retired Jan. 1.

Blaine L. Glendening has been appointed principal chemist for the Kansas Public Health Laboratories, Topeka. He was formerly assistant chemist with the Kansas Agricultural Experiment Station.

Glenn C. Holm, member of the North Dakota Agricultural College Veterinary Department since 1949, has been named dean of agriculture and director of the Agricultural Experiment Station. Dr. Holm will succeed **H. L. Walster,** who will retire this spring.