RECENT ACOUSTIC WORK
OF THE U.S. COAST AND GEODETIC SURVEY.

by

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U. S. Coast and Geodetic Survey).

In radio acoustic ranging, with which we all are acquainted, the foundation of the accuracy depends upon a knowledge of the velocity of sound in sea water. The horizontal velocity of sound has been found to be a function of so many factors that in attempting to correlate them all, a vast amount of study is necessary, and many theoretical refinements may not be necessary in practical work. The following is an attempt to describe some of the recent experiments conducted by the Coast and Geodetic Survey, to set down some of the principles and theories which have direct bearing on increased accuracy in R. A. R. work, and to list references which may be of value to any who wish to read further.

We have been reminded many times of the various attempts to measure the velocity of sound in water, of which those of COLLADON and STURM (1), Lake Geneva 1827, THRELFALL and ADAIR (2), Australia 1899, are notable. Since the world war, and especially since 1919 there have been numerous experiments made to measure accurately the velocity of sound in sea water by the use of explosives and sensitive hydrophones. It is noteworthy that all of these attempts have been made in shoal water. With the exception of the experiments of HECK and SERVICE, which resulted in a compilation of the first accurate tables for the velocity of sound (3), all experiments which have been studied by the writer have been made in shoal water, 30 fathoms or less (4). Another set of tables, differing slightly from those of HECK and SERVICE, was published by the British Admiralty in 1923 (5). These two sets of tables have been used in practically all hydrographic work since their publication.

It was obvious soon after the work of radio acoustic ranging was started by the U. S. Coast and Geodetic Survey that the apparent horizontal velocity of the sound was different from the theoretical velocity for the mean conditions of temperature and salinity, and various hypotheses were formulated to explain the difference and to establish a satisfactory working basis. In 1925, Lieutenant Jerry H. SERVICE of the U. S. Coast and Geodetic Survey, recognized that there were other factors to be considered in the application of these theoretical velocities to actual work, and applied the theory of multiple reflections to account for the apparent idiosyncrasies of this elusive quantity. This was, and is, the only plausible explanation for the travel of compressional waves in a medium between two reflecting surfaces, bounded by two media of very different elastic and inertia constants, where the velocity varies with the thickness in the medium under consideration, in this case the sea; and Lieutenant SERVICE applied this theory to explain the phenomena he encountered in his experience with hydro-acoustics.

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(1) Ann. d. Chim. et Phys., 36, *pp.* 113 *and* 225, 1827.

(2) Proceedings of the Royal Society, *London, Vol.* 46, 1899.

(3) *U. S. Coast and Geodetic Survey, Special Publication No.* 108, 1924.

Field Engineers Bulletin *No.* 5, *p.* 45, *The Start of the Acoustic Work of the Coast and Geodetic Survey, N. H. Heck.*

(4) Proc. Roy. Soc., 103, *p.* 284, 1923. *British Admiralty experiments made by A. B. Wood, H. E. Browne, and C. Cochrane.*

Annales Hydrographiques, 1919-20.

Field Engineers Bulletin, *No.* 7, U.S.C. & G.S., *June* 1934, *p.* 115, *The Velocity of Sound in Sea Water, T. B. Reed.*

(5) Tables of the Velocity of Sound in Pure Water and Sea Water for use in Echo Sounding and Sound Ranging, *Hydrographic Department, Admiralty, London.*

If the sound actually travelled by successive reflections between the bottom and the surface of the ocean, it was easy to see that it would not be possible to use one velocity for any given condition of temperature and salinity, as hoped at the outset. Rather, it would be necessary to change the apparent velocity with the changing depths and horizontal distances, as well as with the changing conditions of temperature, pressure, and salinity. Shortly after the publication of the velocity tables referred to, some of the work in shoal water off the Pacific Coast seemed to indicate that the apparent horizontal velocity approximated the theoretical velocity for the bottom temperature and salinity, and it appeared that the sound in some manner reached and travelled along the bottom, and at the favorable time came up to the surface to actuate the hydrophone. If such a relation between the theoretical velocity for bottom conditions and the apparent velocity existed, it might provide a working formula for use in the shoal waters of the continental shelves of our coasts. A number of experiments were made to investigate this relation, and a careful study of all available data was made by Mr. A. L. SHALOWITZ, Cartographic Engineer, U.S.C. & G.S. His work is described in detail in a special report and is summarized in a paper given before the National Academy of Sciences (1).

For several reasons it is well to quote his conclusion:

"AVERAGE DIFFERENCES (in meters per second) BETWEEN EXPERIMENTAL VELOCITIES AND THEORETICAL VELOCITIES FOR ASSUMED PATHS.

	Surface	*Mean*	*Bottom*
From all observations (51)	— 12.3	— 3.2	+ 1.0
From best observations (42)	— 13.7	— 4.6	+ 0.01
From observations in localities of high temperature gradient (17)...	— 18.7	— 6.7	+ 0.15

"This remarkably close agreement between measured velocities and theoretical velocities based on bottom temperatures would seem to indicate that the peak of the energy reaching the hydrophone has come not by way of the shorter straight line path where the velocity is greater, but by way of the more circuitous path of the bottom layers of water where the velocity is actually less. How is this seeming contradiction to be explained ? It has been suggested that it is primarily a question of temperature ; that a given amount of energy will travel farther in cold water than in warm water, and though the velocity of sound is greater near the surface, the energy is used up quicker and over long distances fails to reach the hydrophone. Hence the only record we get is of the energy that has come by way of the colder bottom layers.

"While there is considerable evidence to be found in support of this theory, both in the present study and in our experiences with horizontal transmission on the south Atlantic Coast, I believe it is too early to formulate a definite theory regarding the behavior of the sound wave. It will be time enough to consider these possibilities when we have supplemented our present data with experimental work carried out along certain lines which the investigation has shown is urgently needed.

"For the present, the important thing is that a practical working relation has been established between experimental and theoretical velocities that has enabled us to adopt a definite policy for the work on Georges Bank. In addition, the study has shown that any assumption that the effective sound wave travels along the surface or close to the surface is wholly untenable. Other than that, the investigation should be considered in the nature of a preliminary finding and as laying the foundation for a thorough and comprehensive study, both in the field and in the office, of the whole subject of sound transmission in all its ramifications." In spite of Mr. SHALOWITZ's warning, this fortunate empirical relation has been referred to erroneously by many as a "bottom velocity theory".

Numerous attempts were made to confirm this relation in both shoal and deep water, the most accurate of which was the taut wire determination made by the U.S.C. & G.S. ships *Oceanographer* and *Lydonia* in May, 1933, off the coast of Maryland, in

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(1) Proc. Nat. Acad. Sciences, *Vol.* 17, *No.* 8, *pp.* 445-455, *Aug.* 1931.

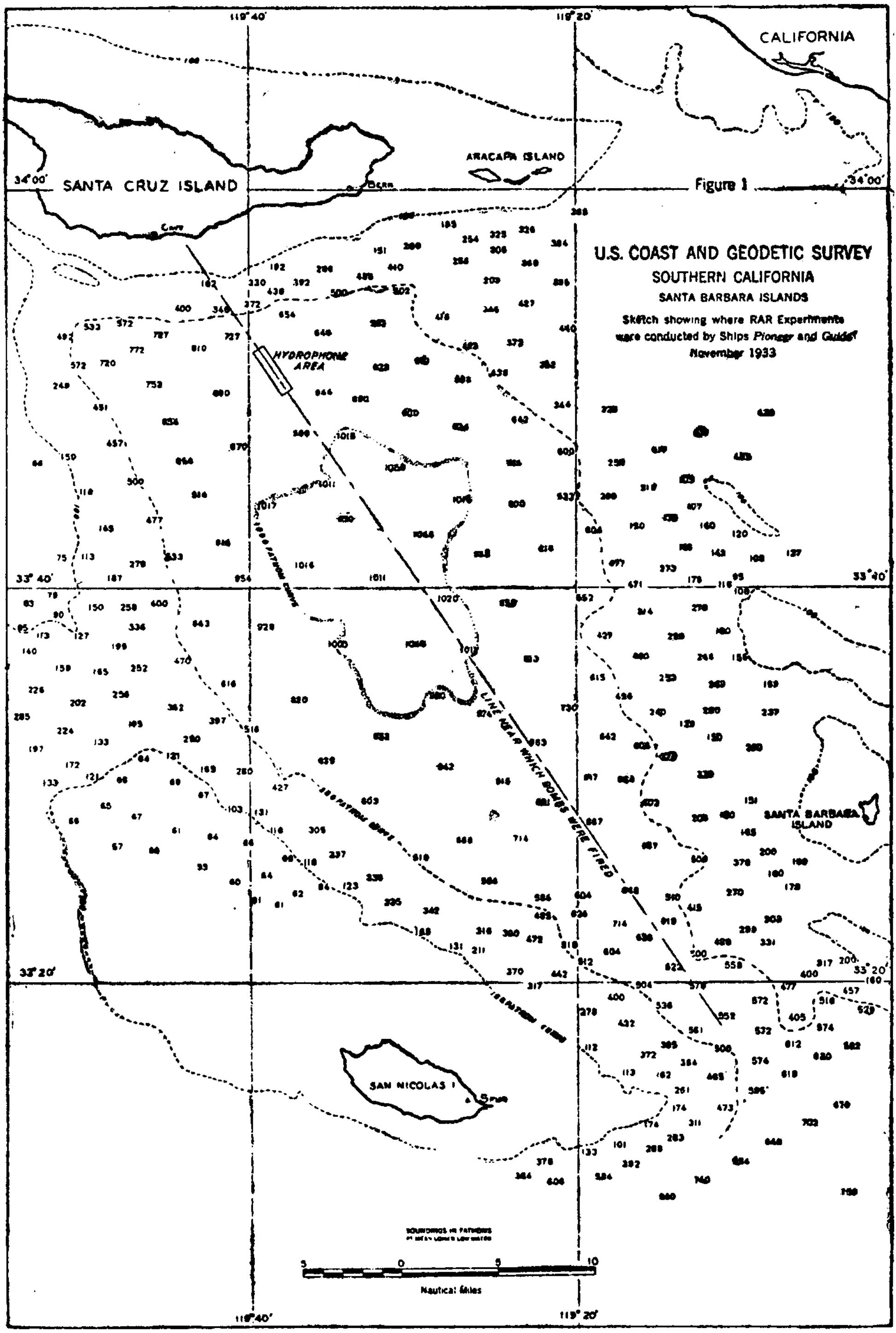
CALIFORNIA
SANTA CRUZ ISLAND
ANACAPA ISLAND
Figure 1
U.S. COAST AND GEODETIC SURVEY
SOUTHERN CALIFORNIA
SANTA BARBARA ISLANDS
Sketch showing where RAR Experiments were conducted by Ships Pioneer and Guide November 1933
HYDROPHONE AREA
LINE NEAR WHICH BOMBS WERE FIRED
1000 FATHOM CURVE
100 FATHOM CURVE
SANTA BARBARA ISLAND
SAN NICOLAS I
SOUNDINGS IN FATHOMS
Nautical Miles
5
0
5
10
119° 40'
119° 20'
34° 00'
33° 40'
33° 20'

Fig. 1.

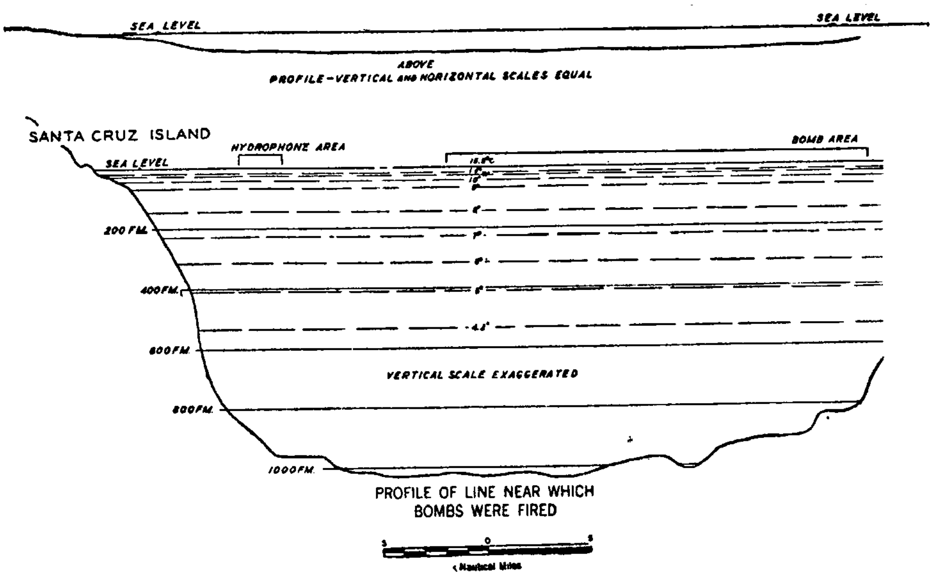

Fig. 2.

a depth of approximately 30 fathoms (1). The experiments in deep water off the Pacific Coast, up to this time, had given varied and some confusing results. In November, 1933, the first conclusive evidence that the sound waves behaved in conformity with the well known physical laws of geometrical optics was obtained by the Ship *Pioneer* under command of Lieutenant-Commander O. W. SWAINSON, U.S.C. & G.S., assisted by the Ship *Guide* in command of Lieutenant-Commander F. L. PEACOCK, U.S.C. & G.S. The details of these experiments and the data acquired are contained in Lieutenant-Commander SWAINSON's Special Report which has been published separately. A digest of this report follows, but for those who wish to study the results more carefully, the original report should be obtained.

These two vessels carried out a carefully planned program. Bombs were fired electrically by the *Guide* at various depths from sub-surface to 600 fathoms. The instant of detonation as well as the instant of explosion was transmitted to the *Pioneer* automatically by radio, and the arriving subaqueous impulses were recorded on a chronograph as actually done in radio acoustic work, and on an oscillograph from hydrophones at various depths between 30 and 850 fathoms. The *Guide* remained in one location, in deep water, while the *Pioneer* steamed away and took up stations at various distances approximately between 15 and 58 kilometers. The site selected for these experiments is ideal. It is a large submarine basin between the Santa Barbara Islands, over 1000 fathoms in depth, and due to the formation it should be free from submarine currents. (Incidentally, the temperature curve shows this basin effect, as is found in the Sulu Sea, Red Sea, and the Mediterranean. It will be noted that this curve follows the characteristic form down to 4.2° C., then is vertical below that temperature, which occurs at approximately 550 fathoms depth, the maximum depth of the rim of the basin. See Figures 1 and 2). Observers at triangulation stations on the islands located the two ships at the instant of firing the bombs as well as at the instant of reception, using triangulation methods and radio communication. The program was arranged, and tests were made to eliminate effects of lag in the apparatus. Difficulties were encountered in firing bombs at depths, and the weather turned adverse, so that only 10 bombs were actually fired at great depths and two accurate distances between the ships determined. There were obtained, however, 140 oscillograms with synchronized chronograph records, and these have furnished a wealth of information. Dr. Karl DYK, Seismologist, has analyzed these records and the resulting curves of his analysis are shown here. He has made two assumptions:

1. That the first arriving impulse registered on the oscillogram had travelled by reflected paths from bomb to hydrophone. Figure 3.

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(1) *Loc. cit.*

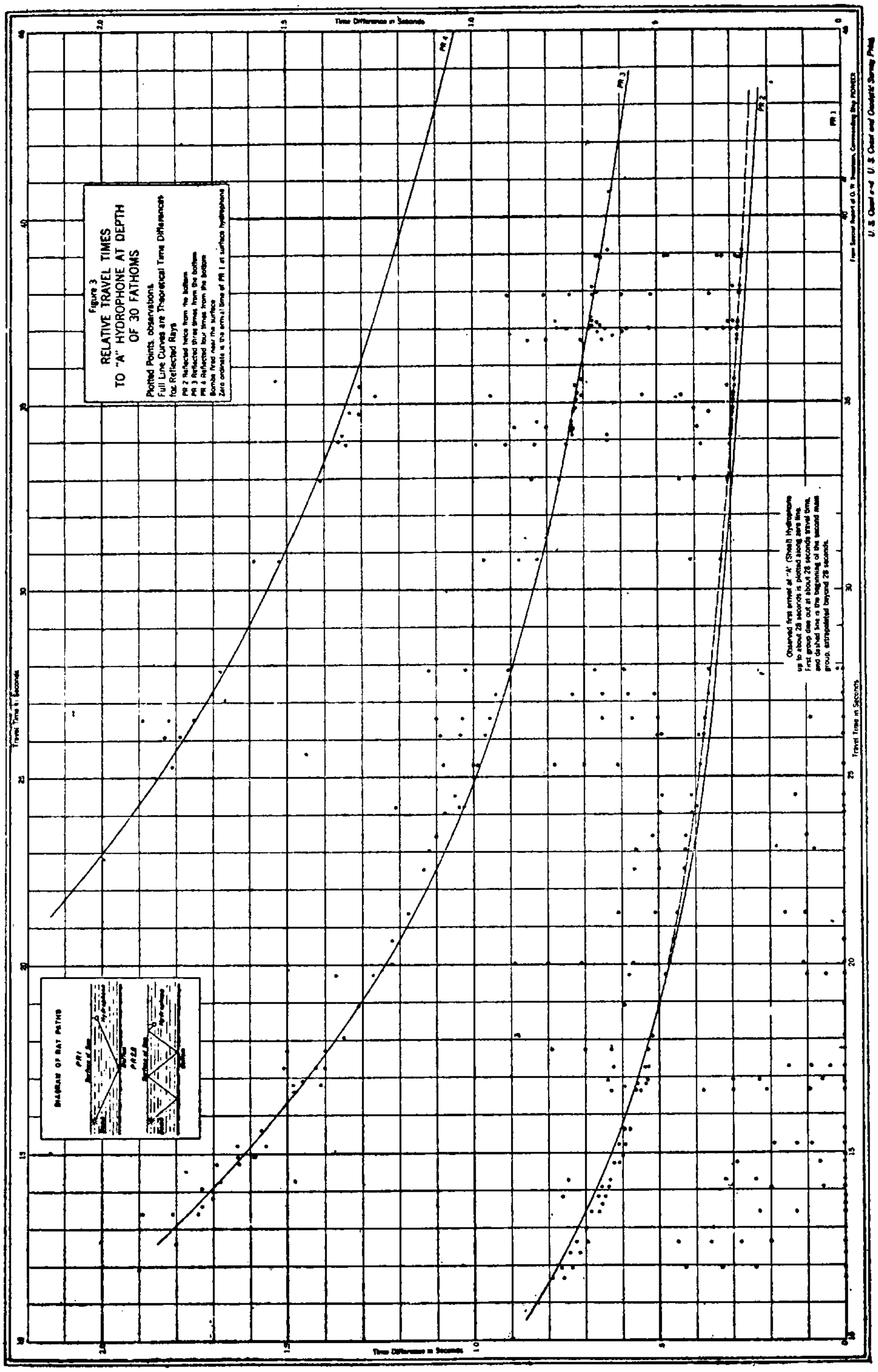
Figure 3
RELATIVE TRAVEL TIMES
TO "A" HYDROPHONE AT DEPTH
OF 30 FATHOMS
Plotted Points, observations
Full Line Curves are Theoretical Time Differences for Reflected Rays
PR 2 Reflected twice from the bottom
PR 3 Reflected three times from the bottom
PR 4 Reflected four times from the bottom
Bombs fired near the surface
Zero ordinate is the arrival time of PR 1 at surface hydrophone
Observed first arrival at "A" (Shoal) Hydrophone up to about 28 seconds is plotted along zero line. First group dies out at about 28 seconds travel time, and dashed line is the beginning of the second main group, extrapolated beyond 28 seconds.
DIAGRAM OF RAY PATHS
PR 1
PR 2 & 3
Surface of Sea
Hydrophone
Bottom
Time Difference in Seconds
Travel Time in Seconds
PR 1
PR 2
PR 3
PR 4
2.0
1.5
1.0
.5
0
10
15
20
25
30
35
40
45
From Second Report of O. W. Swainson, Commanding Ship PIONEER
U. S. Coast and Geodetic Survey Print

Fig. 3.

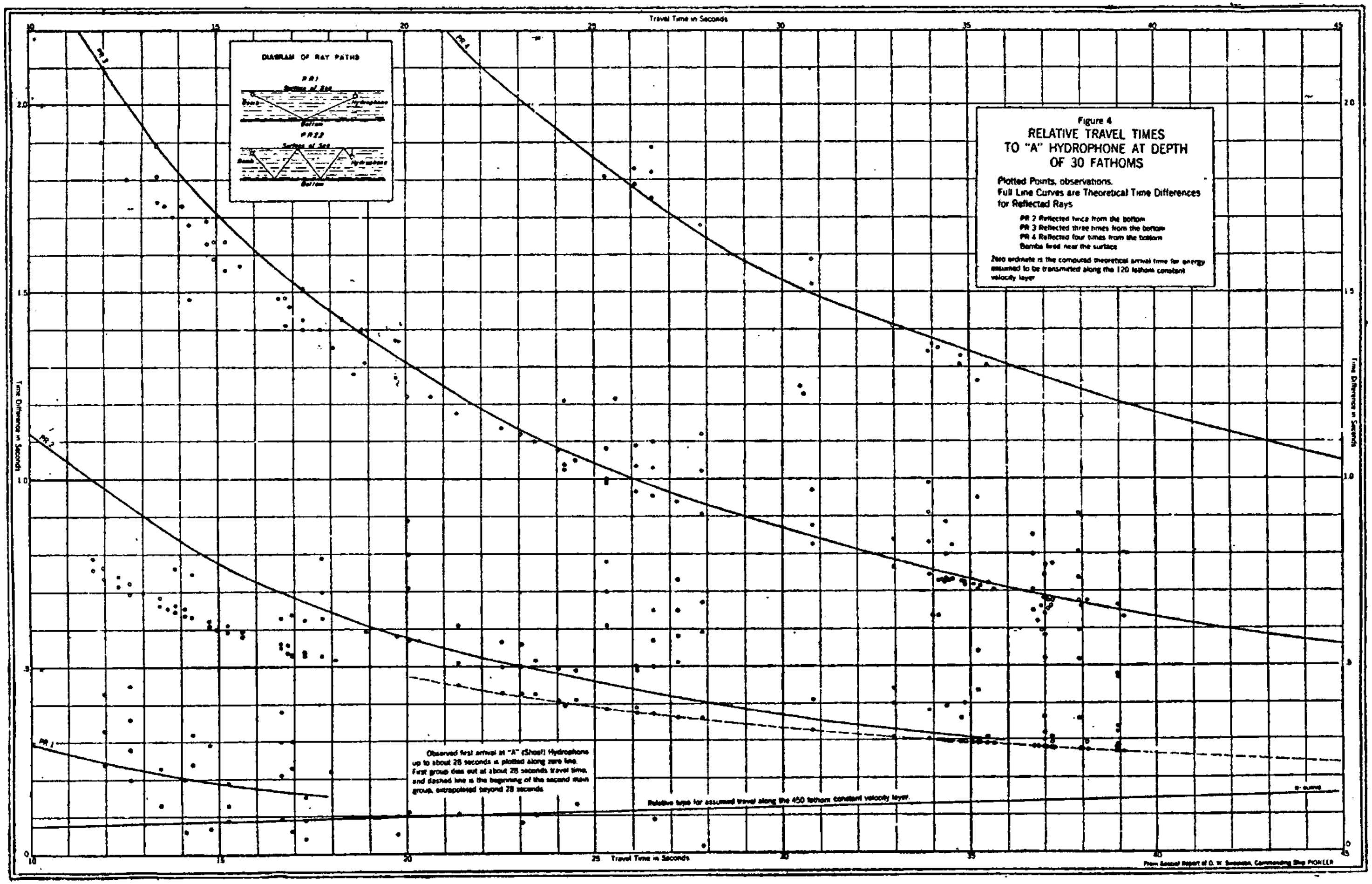
Travel Time in Seconds
10
15
20
25
30
35
40
45
Time Difference in Seconds
0
.5
1.0
1.5
2.0
PR 1
PR 2
PR 3
PR 4
DIAGRAM OF RAY PATHS
PR 1
Surface of Sea
Bomb
Hydrophone
Bottom
PR 2 2
Surface of Sea
Bomb
Hydrophone
Bottom
Figure 4
RELATIVE TRAVEL TIMES
TO "A" HYDROPHONE AT DEPTH
OF 30 FATHOMS
Plotted Points, observations.
Full Line Curves are Theoretical Time Differences
for Reflected Rays
PR 2 Reflected twice from the bottom
PR 3 Reflected three times from the bottom
PR 4 Reflected four times from the bottom
Bombs fired near the surface
Zero ordinate is the computed theoretical arrival time for energy assumed to be transmitted along the 120 fathom constant velocity layer
Observed first arrival at "A" (Shoal) Hydrophone up to about 28 seconds is plotted along zero line. First group dies out at about 28 seconds travel time, and dashed line is the beginning of the second main group, extrapolated beyond 28 seconds.
Relative time for assumed travel along the 450 fathom constant velocity layer.
B-curve
From Annual Report of O. W. Swainson, Commanding Ship PIONEER

Fig. 4.

2. That the first arriving impulse registered on the oscillogram had travelled by diffraction paths down to the constant velocity layer at approximately 150 fathoms, and thence along it to the vicinity of the hydrophone. Figure 4.

The figures are self-explanatory. The full lines are the theoretical or computed paths obtained by using the profile of the bottom and simplified formulae for computing the travel distances by reflection of the wave in the water shell; and the plotted points are actual observations taken from the oscillogram records. Figure 3 shows the close agreement between computed curves and the observed points, and the results seem quite conclusive in confirming the first assumption, namely, that the first arriving impulse had travelled a reflection path. Dr. DYK attributes some of the discrepancies found with the hydrophone at great depths to slight errors in the British Admiralty Tables of theoretical velocities, which tables were used in computing the curves. Although this is a possible source of the error, there are many uncertainties that can be selected which are purely of an observational nature, e. g. errors of depth which will multiply the travel distance errors in proportion to the number of reflections; calibration errors in the fathometer used to determine the depths over which the experiments were made, and errors in wire soundings. Since the fathometer itself depends on the velocities, although the errors in depths are not of the same order, it is apparent that the absolute velocity will be difficult to determine experimentally. Wire soundings in great depths are hardly more accurate than sonic methods; indeed, I believe that our present sonic methods of depth measurement are more dependable and more accurate than the wire methods, due to the difficulty encountered in obtaining truly vertical casts with the wire. The pertinent plates and figures of Lieutenant-Commander SWAINSON's report are reproduced here with descriptive legends.

We have additional confirmation of the results of the work of the *Pioneer* and the *Guide* in the work of the *Oceanographer* (Commander H. A. SERAN, U.S.C. & G.S., Commanding) and the *Lydonia* (Lieutenant-Commander R. L. SCHOPPE, U.S.C. & G.S., Commanding) accomplished off the coast of Maryland in the spring of 1934. These latter tests, while they do not give absolute velocities, are excellent confirmation through an entirely different method, and in a different ocean, of the results of the *Guide* and the *Pioneer* off the Pacific Coast. The data obtained by the *Oceanographer* and the *Lydonia* are shown in Figure 5. In these tests the *Oceanographer* secured the end of the taut wire apparatus to the *Lydonia*, and in an area where the depth averaged about 1450 fathoms, with uniform bottom, steamed away from the *Lydonia* firing detonators and bombs at intervals of 30 seconds. In another case, the *Lydonia* was left in deep water, approximately 800 fathoms, and the *Oceanographer* proceeded in the same manner, running inshore to shoal water. This method was used to obtain results for plotting continuous travel time curves. In both cases, the wire was buoyed with pieces of wood, two by four inches by two feet in length, which were fastened on the wire at intervals of about one-half mile. The shape of the curve assumed by the wire is doubtful, and for this reason the results cannot be used for velocity determinations. However, the results, which in this case were recorded only on a chronograph, show the possibilities that might occur in radio acoustic work, and in both tests there is unmistakable evidence of returns from the first reflection, as well as from diffracted energy. In the all deep water test, the reflected wave apparently predominated, while in the deep to shoal test, the diffracted energy seemed to register throughout the run. This is significant in showing that we have as yet no sure method of predicting which may predominate.

These recent experiments all have been carried out in deep water, and the results are quite gratifying. Before attempting to explain why the theoretical bottom velocities agree so closely with the apparent velocity in shoal water, it might be well at this time to review some of the fundamental concepts of wave motion in an elastic medium. No originality is claimed for this discussion. These principles are simply set down here in brief form for the benefit of those, who possibly like myself have found the need to review the elements of physics to which one is exposed early in education, but which principles may have been dimmed by the press of other work. They will be found in any elementary text book on physics (1).

We know from the fundamental laws of refraction that in the case of a longitudinal wave, or disturbance, traveling in a medium in which the elastic and inertia constants vary with the thickness, or in this case with the depth, the ray will be bent or refracted according to the changing velocity due to the changing constants of the medium.

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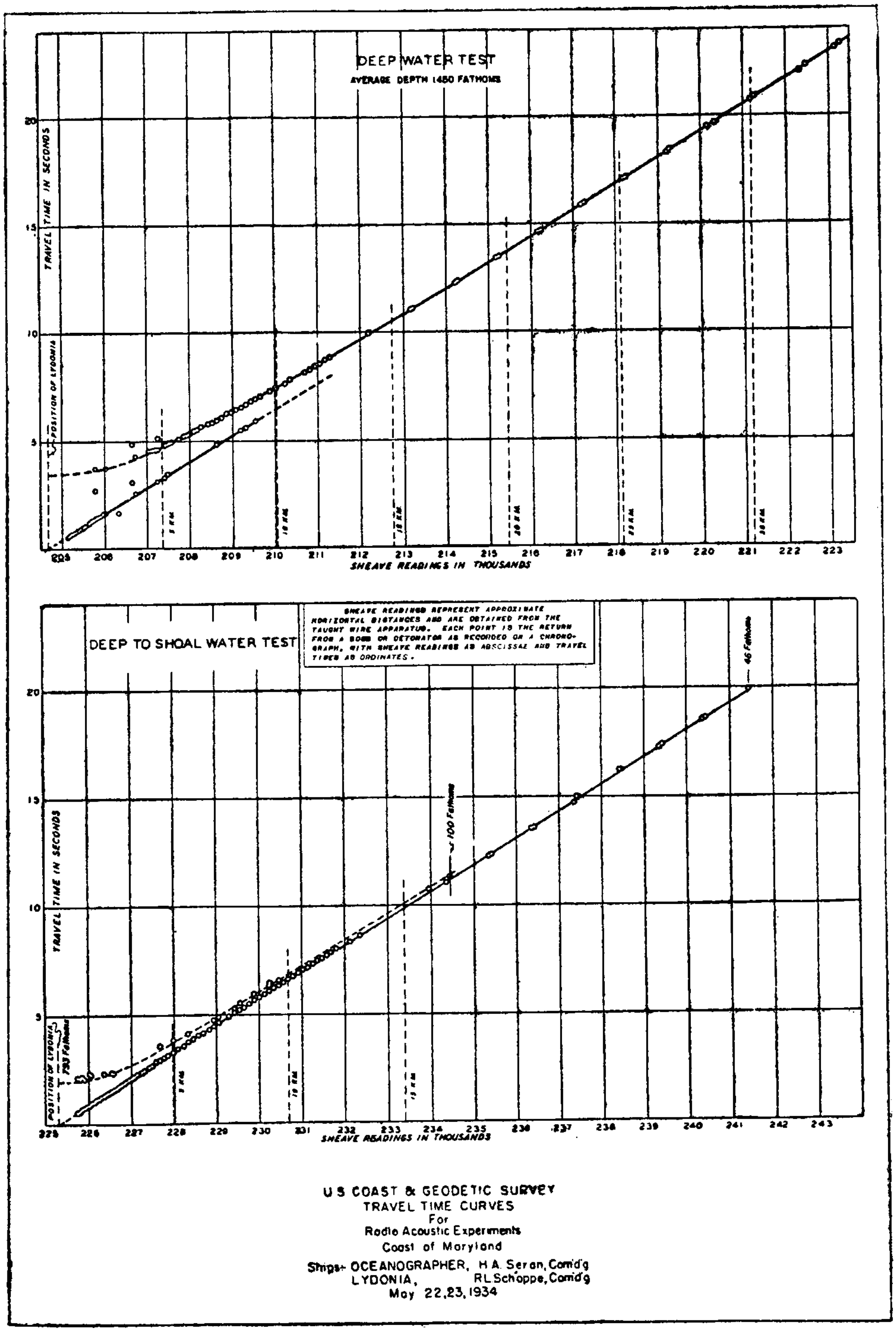
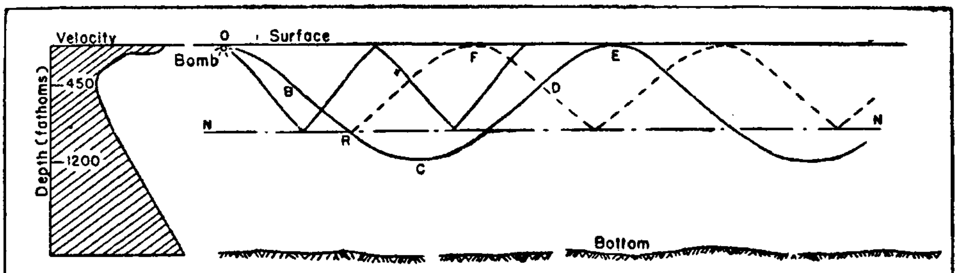
(1) Physics for Colleges, *Shelden, Kent, Paton, and Miller.*



SHEAVE READINGS REPRESENT APPROXIMATE HORIZONTAL DISTANCES AND ARE OBTAINED FROM THE TAUGHT WIRE APPARATUS. EACH POINT IS THE RETURN FROM A BOMB OR DETONATOR AS RECORDED ON A CHRONOGRAPH, WITH SHEAVE READINGS AS ABSCISSAE AND TRAVEL TIMES AS ORDINATES.

U S COAST & GEODETIC SURVEY
TRAVEL TIME CURVES
For
Radio Acoustic Experiments
Coast of Maryland
Ships- OCEANOGRAPHER, H.A. Seran, Comd'g
LYDONIA, R.L.Schoppe, Comd'g
May 22,23, 1934

Fig. 5.

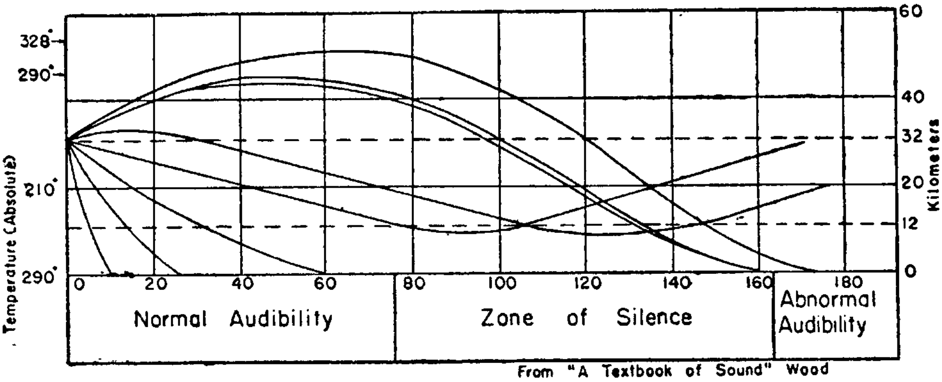


The Propagation of Sound in Deep Sea Water

Fig, 6.

So, if we consider a source of wave motion at point *O*, Figure 6, at the surface of the sea for instance, the spherical compressional wave will start outward in all directions. As we are primarily interested in that energy which remains in the water, the sources will be assumed to lie just below the surface, and we will consider only the energy which remains in the water. The rays of the wave which start vertically downward will of course suffer no refraction. Let us trace the limiting ray, the one which starts parallel to the surface. It will be curved downward while the velocity in the medium is decreasing, or, in the case of the sea, to the point *B*, at approximately 450 fathoms depth where a constant velocity layer is found. As the velocity below this point is increasing with the depth, the ray will be refracted upward, and with sufficiently deep water will eventually reach a point where it is again parallel to the surface at *C*. From the point *C*, the path will be an image of the path between *O* and *C*, for the ray will continue to be refracted upward until it again reaches the constant velocity layer at 450 fathoms (point *D*), and from *D* to *E* it will be refracted downward until it reaches the surface at *E* where it is again parallel and tangent to the surface. Since the horizontal ray of the wave, for a source at the surface, will be the limiting ray of the wave under consideration, it has been referred to as the limiting or tangent ray. The path of this tangent ray is the upper boundary of the parent wave, and is the boundary of the energy traveling on least time paths from point *O* to any point in the medium to the right of the curve *O*, *B*, *C*. For example, in Figure 6, neglecting diffraction, energy would arrive at point *D* first by way of the path *O*, *B*, *C*, *D*, and not by a straight line directly from *O* to *D* because the original ray was taken as horizontal. This limiting or tangent ray of course does not constitute a definite boundary, and there is some energy radiated from the parent wave at all points along the tangent ray, or the edge of the wave. Such a spreading of waves from the edge of a wave front is called diffraction. Although the diffracted energy should be weak in comparison with the energy in the parent wave, it is generally strong enough in our problem to complicate matters considerably, as has been noted previously. If the bottom of the sea is at less depth than the depth for complete refraction, reflection will occur. Consider a case, Figure 6, where the bottom is assumed horizontal at *N*, *N*. In this case the ray will be reflected at point *R*, and that section of the ray from *R* to *F* will be an image of that from *O* to *R*. When reflection occurs at the bottom, the waves that have been reflected only once from the bottom should not be observed at the surface beyond the point *F* where the tangent ray returns to the surface because this ray is again refracted downward and the path beyond point *F* is a duplication of this first route. Any energy, except diffracted energy, observed at the surface between points *O* and *F* would have arrived by reflection from the bottom. This is what appears on the oscillograms in the experiments of the *Pioneer*. See Oscillograms Numbers 147 to 152, lower trace, The first reflection, PR1, becomes very faint on number 149 and disappears completely on number 150 at about 28 seconds travel time. On the same oscillograms, PR2, the second reflection, maintains its amplitude through this distance. Dr. Dyk has computed a theoretical path for the tangent ray, Figure 8, which shows that for the depth in which the experiments were made, the distance to the point where the tangent ray should return to the surface is approximately 28 kilometers. Actually, the difference between a straight line and the theoretical curved path is negligible, so for purposes of computing the travel distances, straight line paths can be assumed without appreciable error.

It is interesting in reviewing the foregoing theory of wave travel in deep water to compare a similar instance in the air where the same theory was applied by a number of physicists. A large ammunition dump exploded at Oldebroek, Holland, in January 1923, and the sound was heard at various distances between 100 and 500 miles, but was not detected between 60 and 100 miles of the explosion. Records of such explosions at long distances show no trace of the audible frequencies which would be the noise of the explosion, but show a pulsation in pressure of about 1 cycle per second (1). In the case of a meteor which exploded at a height determined to be between 30 and 40 kilometers (20 to 25 miles) a sound similar to thunder was heard up to 60 or 70 kilometers, and was inaudible between 60 and 160 kilometers, after which it was again audible over another zone. F.J.W. Whipple explained this occurrence by a hypothesis similar to the theory used in the under water transmission of sound. His diagram is reproduced here (2) (Fig. 7).



From "A Textbook of Sound" Wood

Fig. 7.

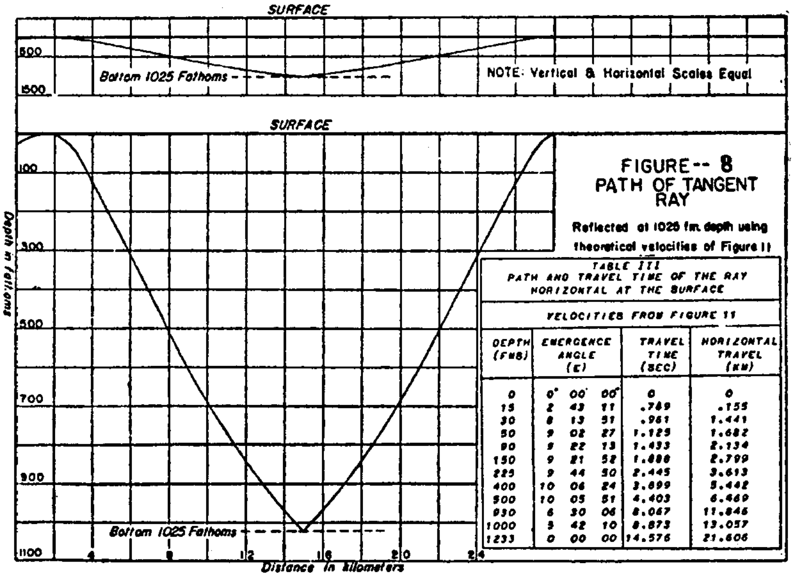


TABLE III
PATH AND TRAVEL TIME OF THE RAY HORIZONTAL AT THE SURFACE

VELOCITIES FROM FIGURE 11

DEPTH (FMS)	EMERGENCE ANGLE (E)	TRAVEL TIME (SEC)	HORIZONTAL TRAVEL (KM)
0	0° 00′ 00″	0	0
15	2 43 11	.749	.155
30	8 13 51	.961	1.441
50	9 02 27	1.125	1.682
90	9 22 13	1.433	2.134
150	9 21 52	1.888	2.799
225	9 44 50	2.445	3.613
400	10 06 24	3.699	5.442
500	10 05 51	4.403	6.469
930	6 30 06	8.067	11.846
1000	5 42 10	8.873	13.057
1233	0 00 00	14.576	21.606

Fig. 8.

Wood explains this phenomenon in air as follows: "The direct wave is steadily attenuated in its passage over the earth's surface, and at an average distance of about 60 miles becomes inaudible. The sound waves reaching the outer zone of audibility appear to have travelled with an abnormally low velocity, but this is not the case.

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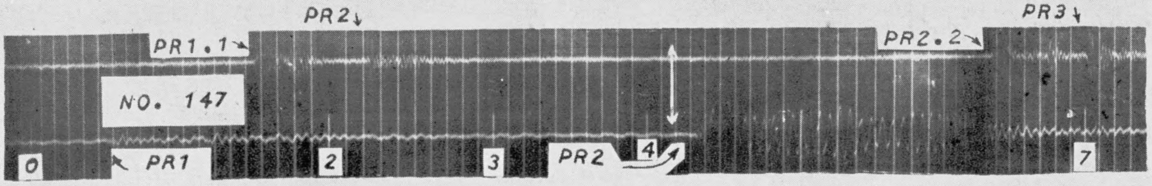
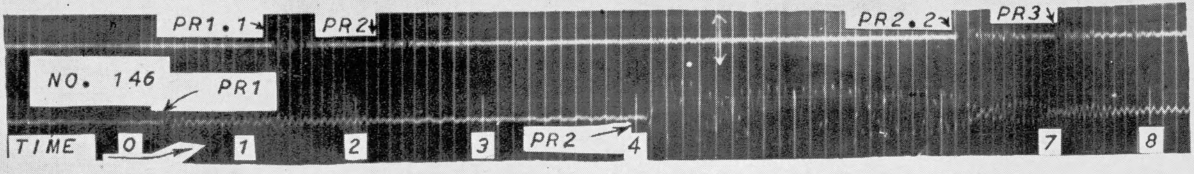
(1) A Textbook of Sound - *Wood, p.* 334.

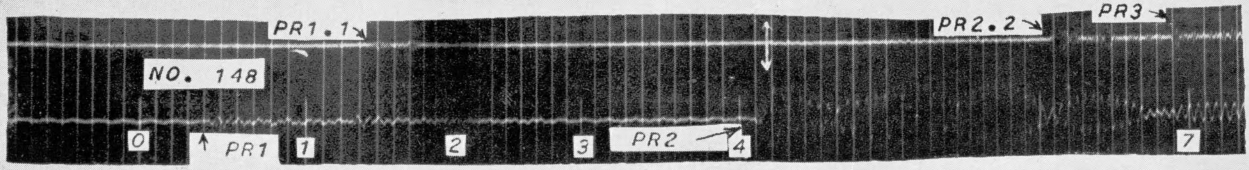
(2) A Textbook of Sound, *Wood, p.* 334, *and Monthly Notices R. A. S. p.* 89, *Oct.* 1928.



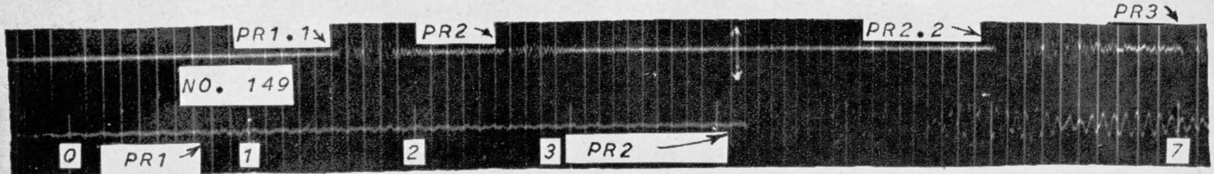
#147 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 26.10 SEC.



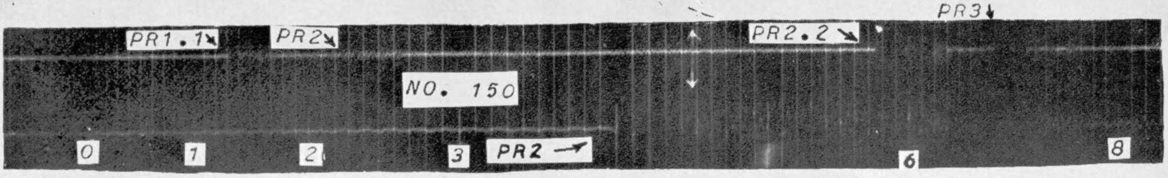
#146 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 25.7??? SEC.



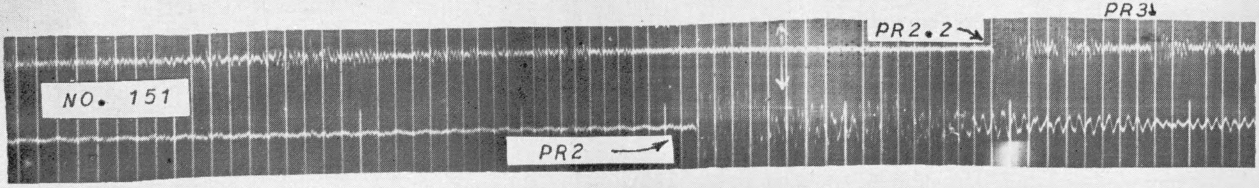
#148 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 26.55 SEC.



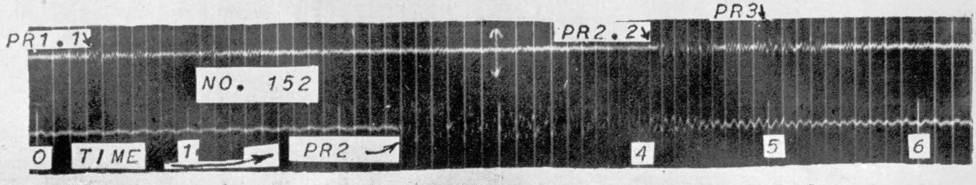
#149 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 28.20 SEC.



#150 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 29 SEC. CA.



#151 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 30 SEC. CA.



#152 DEPTH A 30 FMS. DEPTH B 850 FMS. TRAVEL TIME 31.02 SEC.

ENREGISTREMENT PAR OSCILLOGRAPHE montrant le “fading” de la première réflexion à 28 secondes environ
Impulsions reçues de bombes explosant près de la surface sur deux hydrophones “*A*” à 30 brasses d'immersion (tracé inférieur)
“*B*” à 850 » » (tracé supérieur).

*PR*1 impulsion due à une onde réfléchie une fois par le fond
*PR*1.1 » » » » » une » » » et une fois par la surface.
*PR*2 » » » » » deux » » » et une fois par la surface.
*PR*2.2 » » » » » deux » » » et deux fois par la surface.
*PR*3 » » » » » trois » » » et deux fois par la surface.

OSCILLOGRAPH showing fading out of first reflection at about 28 seconds
Impulses from near surface bombs received on two hydrophones “*A*” at a depth of 30 fathoms (lower trace).
“*B*” at a depth of 850 fathoms (upper trace).

*PR*1 is an impulse from a wave which has been reflected once from the bottom.
*PR*1.1 " " " " " " " " " " " " and once from the surface.
*PR*2 " " " " " " " " twice from the bottom and once from the surface.
*PR*2.2 " " " " " " " " twice from the bottom and twice from the surface.
*PR*3 " " " " " " " " thrice from the bottom and twice from the surface.

Actually, the sound heard in this zone has travelled by an abnormally long path, via the higher atmosphere and ultimately down to the ground again. There is some divergence of opinion as to the actual mechanism of this abnormal wave, whether it is bent downwards into the outer audible zone by refraction (due to air currents and temperature gradients) or whether it is reflected from a layer of the stratosphere 30 kilometers or more from the ground, at which level the velocity of sound increases with height. The effects doubtless arise as the result of the peculiar meteorological conditions at the time of the explosion " (1).

In our experiments with sound in water we are fortunate in that we are able to determine the physical constants of the medium with considerably more accuracy than we can in the air. The depth of the sea defines the lower reflecting surface, so there are not the unknowns in the problem that there are in the case of sound travel in the atmosphere. It is true the temperatures and salinities vary from place to place and from season to season. This seasonal change is more pronounced in shoal areas of considerable extent than in the oceans of great depths, but the effect of this seasonal change is predictable with more accuracy than is necessary for the present needs (2).

The agreement of the theoretical velocities for bottom conditions with the apparent horizontal velocity (3) is explainable by this same theory. The depth of the point *C*, Figure 6, will, of course, vary with the variations in velocity, but it is at approximately 1200 fathoms in the region of the *Pioneer's* experiment. If the depth is of the order of 30 fathoms, it can be seen that the tangent ray will fix the minimum number of reflections possible, and at such shoal depths the angle of emergence at *F* will be very small, about 6 degrees or less. This is an ideal condition for reflection of energy; i. e., there will be very little loss of energy at the bottom, if the bottom is uniform and smooth, and practically total reflection at the surface. The bottom velocity in shoal depths is generally less than at the surface, and as a wave travels by these numerous reflections, hence by a longer route than the true horizontal distance, it has an apparent velocity that is lower than the average velocity as obtained from temperatures and salinities. It so happens that the velocity gradient in shoal depths is related to the distances by reflection in such a manner that within limits the bottom velocity is close to the apparent horizontal velocity.

As an example of the number of reflections that would occur in a case where the depth is approximately 30 fathoms, the runs made by the *Oceanographer* and the *Lydonia* in 1933 are taken. (The term "apparent horizontal velocity" is used throughout the article to describe the velocity obtained by dividing the horizontal distance between bomb and hydrophone by the elapsed time between the explosion of the bomb and the reception by the hydrophone).

Averaging the returns used from the *Lydonia* (4) gives a mean distance of 24,131 meters as the horizontal distance, and a mean travel time of 16.34 seconds. The average theoretical velocity for the mean depth of 25 fathoms (46 meters) is 1485 meters per second. From these data the distance the sound must have travelled in the water would have been 24,264 meters, or a distance of 133 meters greater than the true horizontal distance. If it travelled by reflections, there would have to be about 28 reflections from the bottom and 27 reflections from the surface to account for this difference. If this were the case, the first reflection would have been 430 meters horizontal distance from the source and the emergence angle would be about 6°. This distance seems logical, for the tangent ray, according to DYK's results, would strike the bottom at a horizontal distance of about 670 meters, and the energy which would be carried through a large number of reflections would probably be transmitted by that part of the wave which was reflected from the bottom a short distance ahead of the tangent ray. It may be argued that there is not sufficient energy to stand the losses of the large number of reflections assumed in this case, but when the amount of energy in a half pint of T.N.T. is known to be approximately 660,000 foot pounds (900,000 kw. for 0.001 sec), and the 1000-cycle oscillator for a type 312 Fathometer transmits only about 0.2 kw. into the water, it is not unreasonable to believe that so many reflections are possible and quite

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(1) *See Wood* - A Textbook of Sound, *p.* 333.

(2) *See* Field Engineers Bulletin, *U.S.C. & G.S., No.* 5, p. 37, *T. B. Reed. Theoretical Velocity of Sound in Sea Water and the Practical Use in R. A. R. Hydrography.*

(3) *Loc. cit.*

(4) *See page* 119, Field Engineers Bulletin *No.* 7, *Velocity of Sound in Sea Water, T. B. Reed.*

probable. In some cases such a small amount of energy as developed by the oscillator mentioned has given as many as 13 reflections in 100 fathoms. In the latter case (soundings) the angle of incidence is 0° which is a condition for greatest loss by reflection. There are complicating conditions affecting reflection of compressional waves at varying angles of incidence on surfaces between media of different densities, as between the water and sea bottom, and water and air; due to the lack of data on these factors, we can consider the problem only qualitatively. In this particular case where the sound waves are confined between reflecting surfaces, the usual rate of decrease in intensity is reduced (1). From the literature of seismology it would appear that an angle of incidence of the order resulting in the above case, namely 84°, would be close to the optimum condition for maximum reflected energy. Another important consideration in the amount of energy transferred by reflection is the relation between the wave length and the irregularities of the reflecting surfaces. The effective frequency of a bomb is undoubtedly low, of the order of 5 to 30 cycles probably, and the wave length will consequently be long in proportion to the irregularities of the sea bottom and the sea surface, which fact also contributes to greater efficiency of reflection. It can be shown that the range of transmission in water will vary inversely as the square of the frequency, and apparently there is also less loss due to heat conduction at the lower frequencies.

Dr. Herbert Grove DORSEY, Principal Electrical Engineer, U.S.C. & G.S., makes the following comments about the frequencies of bombs under water:

" It is my belief that the frequency of the bomb which actually does the work is rather low, and I would not be surprised but what the frequency may be less than 150 cycles per second. One reason for thinking this is that you can put a condenser across the input circuit from the hydrophone and still get the bomb returns. I have had the operators on the *Hydrographer* try different amounts of capacity across the input circuits, then use the same capacity across the same kind of hydrophone during the laboratory tests for measuring the inductance, computing the higher frequencies which would easily come through the combination. By this method I have had them put as much as 4 microfarads across the input to the amplifier using the Baldwin unit in the magnetophone. This combination indicates that the frequencies are probably less than 150 cycles per second.

" I believe that the really effective part of the bomb explosion for our work is just a shove in the water. Of course, by Fourier's theorem, all frequencies must be present from zero to infinity. The higher frequencies undoubtedly are damped out very quickly and the lower frequencies get through more readily. Water noises, such as are made by the waves of the beach, ship noises, etc., are probably between 100 and 2000 cycles per second. If the lower frequencies are effective, and specially if they are more effective than the high frequencies, then by using a direct current amplifier we could easily cut out the higher frequencies and still allow the lower frequencies to come through and be correctly amplified. By cutting out the higher frequencies, we eliminate a large part of the water noises. We had a good example of this on the *Hydrographer* when they got out to about 100 fathoms and, in the Gulf of Mexico, they heard a peculiar noise in the water at a rather high frequency. It was so bad that they just couldn't do RAR when this noise was at its height, which seemed to be about two o'clock in the afternoon. At my suggestion, they put a condenser across the input and they began to get better results, which, of course, was very encouraging. Their standard input circuit includes two microfarads across the input transformer and while this eliminates so much of the water noise that they hang the hydrophone over the side of the launch, they still get the bomb sounds just as easily as before."

The oscillograms of the *Pioneer*'s experiments show high frequencies, of the order of 170 to 500 cycles or more, but these may be the natural frequencies of the hydrophone diaphragms as mentioned in Commander SWAINSON's report. On most of these oscillograms there appears to be some interference of frequencies which results in decided nodes and an underlying frequency was suspected. Mr. Frank NEUMANN, Seismologist, U.S.C. & G.S., has recently had considerable success in analysing seismograms by precise integration, to obtain the displacement curves from the acceleration curves given by an accelerometer having a considerably higher natural frequency than the frequency of the

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(1) A Textbook of Sound, *p.* 317, *Wood.*

seismic wave (1). Since the suspected bomb frequencies in radio acoustic ranging might be many times less than the resonant frequency of the hydrophone, Mr. NEUMANN suggested that one of these oscillograms be analysed by his method. This he did, and uncovered a frequency of about 2 per second, and one of about 20 per second, from the particular trace selected. These results are subject to considerable doubt, due to the mechanical structure of the oscillograph used, and it appears that the frequency of 2 per second may be the frequency at which Dr. McILWRAITH turned the crank on the camera of the oscillograph, resulting in small flexures of this frequency between the wires of the oscillograph and the film of the camera!

In the future, oscillograms will be made with precautions taken to permit analysis by Mr. NEUMANN's method, as it may be possible to determine valuable information from the integrated curves.

It might be mentioned that in case magnetophones are used to receive the wave, the resulting curve is probably a velocity curve rather than an acceleration curve, so that a single integration should give a displacement curve. In the case of a carbon button hydrophone, where the impulse transmitted to the amplifier depends on a change in resistance with the motion of the carbon particles, the curve given is probably an acceleration curve, and would then require two integrations to give the displacement.

Another important point in practical radio acoustic ranging is the fact that sources of small intensity and large area are likely to be more efficient than sources of great intensity and small area, because of the serious attenuation of waves of large amplitude. This may partly explain why occasionally it has been possible to record a wave from an ordinary detonator when a larger charge of T.N.T. would not get through.

The two recent tests, the one on the Pacific Coast for which we have oscillograms, and the one on the Atlantic Coast showing the travel time curves to be returns from reflected waves, are sufficient evidence to plan additional experiments for the purpose of finding a practicable method to increase the accuracy of RAR methods and to eliminate some of the small errors in the present methods.

The practical problems of correlating these investigations with actual work are:

1. To determine some method for fixing the apparent velocity to be used in a given area.
2. To determine theoretical velocities more accurately.
3. To find, if possible, more economical and efficient methods for radio acoustic ranging.

Our present chronographic record does not permit determining which wave is being recorded, so that it becomes necessary first to fix in some manner this fact. There is also diffraction to be considered, and this is an important factor, especially over short distances. The use of accurate logs combined with profiles of the bottom between the bomb and the hydrophone might indicate when the apparent velocity should be changed. It is of first importance that we be able to recognize in deep water which reflection is recorded, and I believe additional tests should be made with the purpose of acquiring more information on this point. Although it is desirable to increase our knowledge of the theoretical velocities, it is not necessary that the absolute velocity be known in order to increase the accuracy of RAR methods, provided a way can be found to predict the apparent velocity more accurately and to recognize the various reflections when they arrive. With this in mind I believe that a test should be made simulating actual conditions by obtaining oscillograms of the returns received on a hydrophone in shoal water from a series of bombs fired from a ship which steams directly off shore from the magnetophone, into deep water, obtaining a true profile of the bottom as the run is made. By firing the bombs at frequent intervals, similar to the way they were fired in the test described in Commander SERAN's report, and obtaining simultaneous chronograph and oscillograph records of each return, it may be possible to devise a way to identify which impulse is recorded by the chronograph; a way to correct the various returns to give the true horizontal distances, and possibly to revise our instrumental

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(1) Analysis of Strong Motion Seismograph Records of the Western Nevada Earthquake of January 30, 1934, with Description of a Method of Analysing Seismograms by Precise Integration.

equipment. In the test suggested, the ship should, of course, obtain visual positions during the entire run, as well as temperature and salinity data. In a travel time curve thus obtained, the apparent horizontal velocity is given by the slope of the curve, and this relation might be used to advantage.

The Ships *Pioneer* and *Guide* completed additional acoustic experiments in December 1934, and the results will be available when the study of the records has been completed.

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