PROCEEDINGS
OF THE
NATIONAL ACADEMY OF SCIENCES

Volume 17 August 15, 1931 Number 8

THE PHYSICAL BASIS OF MODERN HYDROGRAPHIC SURVEYING

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Read before the Academy April 28, 1931

Hydrographic surveying, as it is now practised in the Coast and Geodetic Survey, is so radically different from what it was a few years ago that to fully grasp the significance of the new order, one must be acquainted with the limitations and shortcomings of the old methods. To say that it is now possible to conduct major surveying operations in areas hitherto excluded because of the prohibitive cost involved, is only giving one side of the picture. It is now actually possible to survey such areas with an accuracy of detail sufficient to meet the needs not only of the navigator but of the scientific investigator as well. This remarkable advance, during the post-war period has come about principally through the application of the physical sciences, particularly in the field of acoustics, to the problems of the hydrographic engineer.

The possibility of utilizing sound as a means of measuring ocean depths and distances, was recognized long before this period, but no *practical method* had been evolved for meeting the exacting demands of modern hydrographic surveys. The scientific investigations made during the war were quickly focused on peace-time needs by the leading maritime nations of the world, resulting in this country in the development of the sonic depth finder by the United States Navy and the fathometer by the Submarine Signal Corporation.

While other countries have developed other types of echo-sounding machines, the underlying principle of all is the same, involving the measurement of the elapsed time between the emission of a sound impulse from the vessel and the return of the echo from the bottom. One-half this interval multiplied by the velocity of sound in sea water determines the depth under the surveying vessel. In the fathometer, the revolutions of a disc driven by a constant speed motor measures the elapsed time between the outgoing and incoming signals. A graduated dial calibrated for a standard velocity translates this elapsed time into depth units. But since velocity varies with the temperature, salinity and pressure of the water, these variables must first be determined before an accurate sounding can be obtained.

In the Coast and Geodetic Survey temperatures and salinities are measured at well-distributed points over the area to be surveyed, and the mean velocities within any range of depths are ascertained from theoretical velocity tables, to within very narrow limits.

The advantages of this method of sounding over former methods, particularly in deep water, are too well established to be heralded at this late date. Suffice it to say that not only is it possible to obtain a continuous profile of the ocean floor, but a vessel can now, while steaming along at

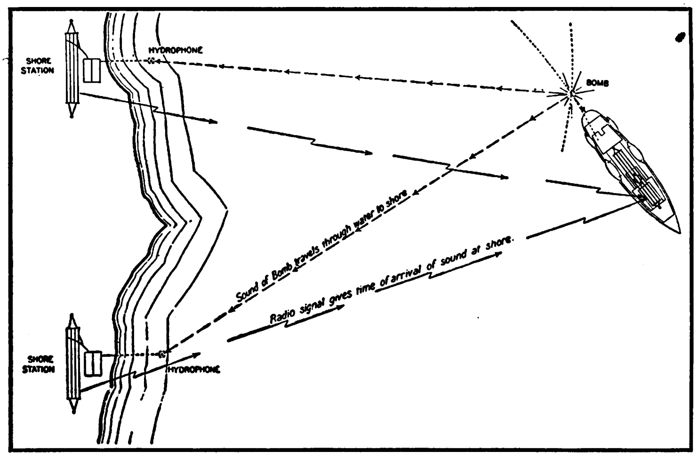

FIGURE 1
Radio acoustic position finding.

full speed, obtain a sounding of 2000 fathoms in five seconds, which formerly took from 40 to 50 minutes.

Determination of depth, however, is only one element in the prosecution of a hydrographic survey. For unless we also know the positions of these depths on the surface of the water, that is, their relation to fixed points on shore, a properly coördinated survey is impossible, and the results would be of little value as an aid to navigation or as a basis for scientific study.

Distances from shore can be determined by various means, the simplest of which is the measuring of angles between three known objects on shore or three well-located buoys offshore. This method, of course, depends for its usefulness upon the condition of the weather and upon the limitations imposed by the earth's curvature.

Beyond this limit recourse must be had to other expedients, such as "dead reckoning" and astronomic observations. Both of these methods, however, are also subject to very definite limitations; as for example, the effect of current and wind on the course and distance, the errors of the compass, the state of the weather, the condition of the sea horizon; all of which make accurate, related surveys impossible, and in areas of considerable relief often results in an improper representation of submarine features.

It was these recognized difficulties, together with the natural evolution of hydrographic methods, that prompted the Coast and Geodetic Survey to undertake the development of an acoustic method for locating the position of a survey ship; and in 1923, in collaboration with the Sound Laboratory of the Bureau of Standards, to develop what is known today as the "Radio Acoustic Method of Position Finding."

Briefly stated, the method consists in exploding a small charge of T.N.T. near the surveying vessel, the time of explosion being recorded on a chronograph aboard the vessel. The sound wave being spherical is propagated in all directions from the center of disturbance and after the lapse of a certain interval reaches the hydrophones located at predetermined stations near shore or at suitable points offshore. Here it is transformed into an electrical impulse, which operates an automatic key at the shore station and a radio signal is sent back to the ship where a second mark is made on the same chronograph. Since all the electrical operations are automatic and instantaneous, the distance between the two marks represents the time taken for the sound wave to travel from the vessel to the hydrophone. If then the horizontal velocity of sound through the water is known, a measure of the distance to the vessel is afforded.

Because such methods can be used by day or night and under all weather conditions, it is of particular importance economically. And when used in conjunction with echo soundings, greater accuracy in the work is not only assured, but an area can now be surveyed with a degree of detail commensurate with the needs of the area, and yet at a cost far below that of former methods. To illustrate: it took a vessel 87 hours in 1922 to survey an area that in 1929 took but 44 hours, and yet five times the number of soundings were taken.

Is it surprising then that during the last few years such rapid strides have been made in completing much needed surveys along the Pacific coast?

And one needs but to examine a modern survey of a deep water area to realize what these new methods have meant in the way of delineation of important underwater configurations.

A striking example of the value of such methods was brought home to the Bureau last summer when the important but difficult survey of Georges Bank was undertaken. This bank is of vital concern to a vast fishing industry and of outstanding importance to transatlantic shipping, lying close to the principal westbound steamer lane between Europe and the

United States. It covers an area twice the size of the State of Massachusetts and its eastern edge is almost 200 miles from the nearest point of land on the New England coast. Because frequent fogs and thick weather in this locality necessitate a vessel's recourse to soundings for fixing its posi-

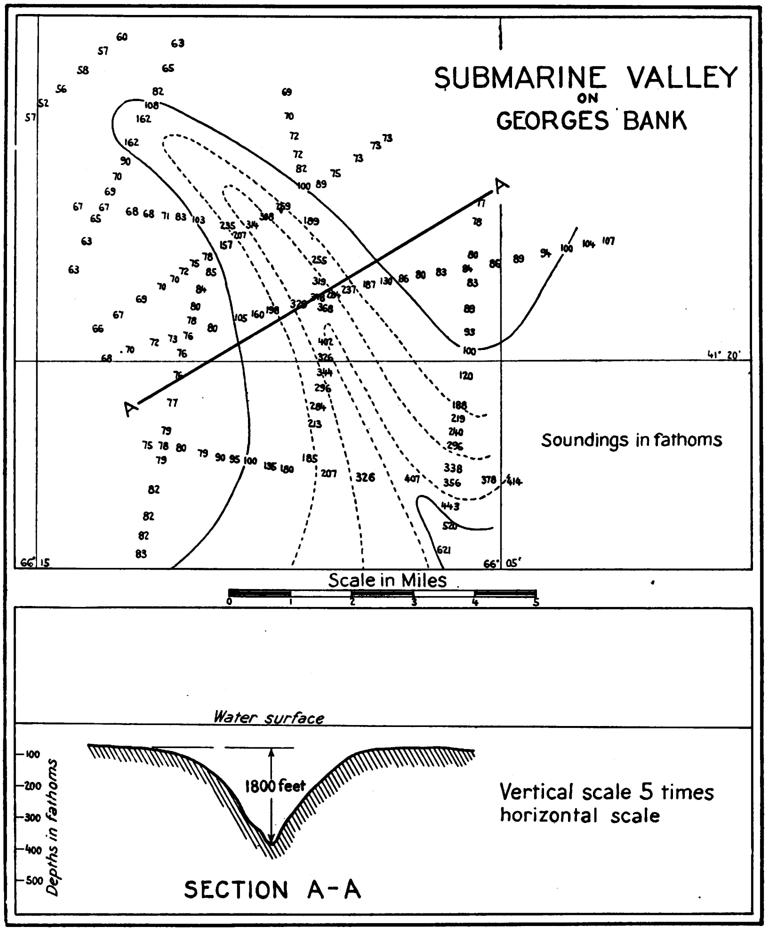

FIGURE 2
Submarine valley on Georges Bank (from unadjusted field sheet).

tion, the need for a detailed, coördinated and reliable survey of the area had long been recognized.

The acoustic methods of surveying have made such results attainable and the undertaking practicable. Already the survey of this bank has developed the existence of an uncharted submarine valley, two miles wide, eight miles long and 1800 feet deep lying directly in the transatlantic steamer lane and ideally oriented for vessels reshaping their course for Nantucket Shoals Light Vessel. If this submarine feature should prove unique, its value as an aid to navigation cannot be overestimated, and standing alone will have more than justified the entire cost of the project.

It is expected that when all the work on this bank is completed, a wealth of information will be unfolded, of interest alike to the geologist, physiographer, oceanographer, hydrographer and mariner.

But while the acoustic method of surveying has overcome many difficulties and increased our accomplishments, it has also brought many new problems. While most of these have been solved, sometimes by adopting practical expedients, as in the case of slope corrections for echo soundings (see Special Publication 165, Coast and Geodetic Survey) many more remain to be dealt with. Of considerable importance at the present time is the determination of the path followed by the sound wave in horizontal transmission in sea water.

It will be recalled that the velocity of sound in sea water varies with the temperature, salinity and pressure of the water. When dealing with echo soundings, where the sound penetrates all the layers from surface to bottom, the problem resolves itself into determining the mean velocity for the entire column of water through which the sound wave passes. Theoretical velocity tables have been computed based on Newton's fundamental equation,

$$\text{Velocity} = \sqrt{\frac{\text{Elasticity of the Medium}}{\text{Density of the Medium}}}$$

giving the velocity for various conditions of temperature, salinity and pressure and if the existing conditions are known the actual velocity of the sound can readily be determined.

In Radio Acoustic Position work, however, the problem of determining the mean velocity of the sound wave between vessel and shore is quite different. Here we are concerned not with vertical transmission but with horizontal transmission. And because the velocity varies between surface and bottom, unless we know the path followed by the sound wave, we cannot determine the velocity to be used for computing the position of the vessel.

Figure 3 represents a cross-section of an area off the Oregon coast from the shore to the 50-fathom depth curve. The variations in temperature between surface and bottom for this section are shown in the insert. The velocities indicated are mean theoretical velocities, computed from the temperature, salinity and pressure data for the three assumed paths of the sound wave from bomb to hydrophone. It will be seen that the difference between the surface velocity and the bottom velocity is about 22 meters per second which at a distance of 60 nautical miles might introduce an error in position of approximately 1600 meters if we made a wrong assumption as to the path of the wave. So it is quite evident that the problem is of more than mere academic concern.

It is of course possible to determine a velocity experimentally, when in close proximity to shore signals, by locating the position of the vessel by the ordinary methods of observing angles and simultaneously measuring the time for the sound impulse to reach the hydrophone. By scaling the distance on the survey sheet from the vessel to the hydrophone and dividing by the time interval we obtain the mean velocity of the sound wave be-

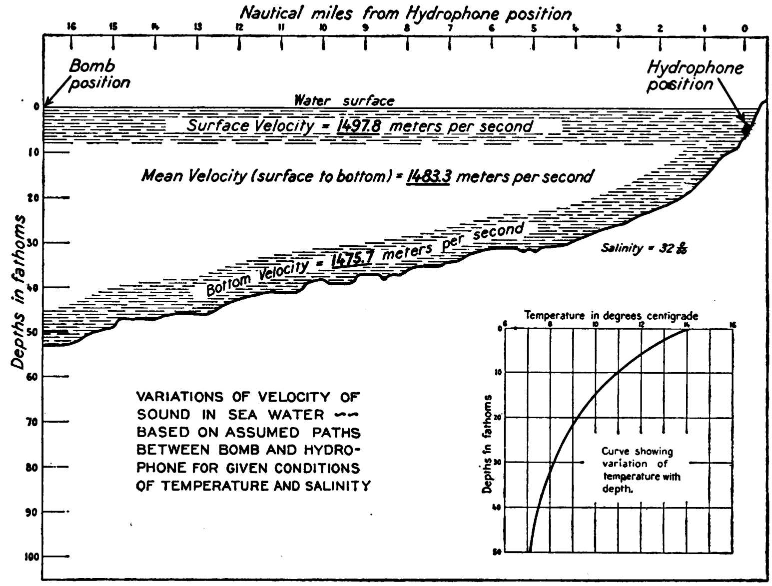

FIGURE 3
Variation of horizontal velocity of sound with assumed paths.

tween bomb and hydrophone. This velocity can then be used when working in a locality where the physical conditions of the water are approximately the same. But when the field of work is far removed from shore control some other means must be found for determining the most probable velocity of the area. This was the problem with which we were confronted when the work on Georges Bank was undertaken. In view of the vast amount of data that had been accumulated by the Coast and Geodetic Survey in its sound ranging work on the West Coast, it seemed desirable to approach the problem from the observational rather than the theoretical point of view.

A detailed study was, therefore, made of all the experimental velocity data along the Pacific coast and in Alaska, with a view to determining the relation existing between experimental values and theoretical values based on assumed paths. As the sound wave could pass through an infinite number of physical conditions between surface and bottom in its journey from bomb to hydrophone, it was decided at the outset to limit the investigation to three principal considerations:

1. The relationship of experimental velocities to theoretical *surface* velocities.
2. The relationship of experimental velocities to *mean* theoretical velocities between surface and bottom.
3. The relationship of experimental velocities to theoretical *bottom* velocities.

It should be emphasized at this point that while velocities have been

Group 33–37 J′ (H. 4636)—Coast of Oregon—September 24, 1926.

To KGAM—Test in 88 fathoms—Measured time 28 seconds

Sound passes through 74 fathoms for 0.7 distance
Sound passes through 45 fathoms for 0.15 distance
Sound passes through 32 fathoms for 0.10 distance
Sound passes through 18 fathoms for 0.05 distance

Temp. at surface = 13.1°	From serial temps. taken September 29, 1926, about five miles to westward		Salinity = 33.4
Temp. at 18 fms. = 8.6			
Temp. at 32 fms. = 7.2			
Temp. at 45 fms. = 7.0			
Temp. at 74 fms. = 6.8			

Velocity at surface = 1495.9 meters per sec.

Bottom Velocity		*Mean Velocity* (Surface to bottom)	
Velocity at 8.6° = 1480.3	Corrected for salinity and for pressure at the respective depths	Mean temp. at 18 fms. = 11.1°	From serial temps as above.
Velocity at 7.2 = 1475.4		Mean temp. at 32 fms. = 9.6	
Velocity at 7.0 = 1475.9		Mean temp. at 45 fms. = 9.0	
Velocity at 6.8 = 1475.0		Mean temp. at 74 fms. = 8.2	
Mean velocity (weighted) = 1475.4		Mean temp. bomb to hyd. = 8.6°	
		Mean depth bomb to hyd. = 31 fms.	
		Mean velocity = 1480.7	

Experimental Velocity = 1475.4 (mean of 5 good obs.)

FIGURE 4

Typical computation of theoretical velocities

measured in the past by various investigators with a high degree of accuracy and isolated comparisons made with theoretical values, never has so much data covering such a variety of conditions been available for investigative purposes.

Actually the present study covered the experiences of eight survey parties over a period of four years, and included experiments in areas extending from the cold waters of the Gulf of Alaska to the warmer waters of northern California. The comparisons cover tests made in depths varying from 20 to 250 fathoms and at distances ranging from three to 60 nautical miles from the hydrophone. The cases selected for comparison are random ones and chosen without regard to probable results. The deductions to be drawn are therefore free from any bias of specially selected observations.

For each experimental velocity a computation similar to the one shown in figure 4 was made. The theoretical velocities were determined in the following manner: The vertical section between vessel and hydrophone was first subdivided into zones of various depths, the number depending upon the regularity or irregularity of the bottom. Velocities were then computed for each zone from the temperature, salinity and pressure data for that zone. The mean velocity was then obtained by weighting these various velocities in accordance with the ratio that each zone bore to the entire distance. In computing the theoretical velocities, the British Admiralty tables (H.O. 282) were used exclusively, being particularly well adapted for sound ranging work. Corrections on account of the variation of the force of gravity with latitude were entirely disregarded, since the corrections for the depths involved would not exceed one-tenth meter per second.

Figure 5 gives comparisons of experimental velocities with theoretical velocities for various paths. In studying this table it should be borne in mind that although 51 comparisons only are listed, in reality many more are represented, for each experimental value may be the value of a single determination or it may be the mean of a group of determinations, frequently as many as five. Wherever it was possible to use a number of observations as a basis, as in cases where the tests were made close together and the sound passed through approximately the same depths under the same conditions of temperature and salinity, this was done, since such procedure eliminated small accidental errors in the measured velocities.

The temperature data on which the theoretical velocities were based were selected from observations taken close to the day on which the velocity tests were made and in approximately the same locality. In a number of cases the mean season curve for the various depths had to be resorted to. Since temperature is the predominating factor, at least in shoal water, in the determination of sound velocity in sea water, theoretical velocities computed from such data must of necessity be somewhat doubtful. It is nevertheless well to remember that any temperature variation from the mean will manifest itself more in the surface and mean velocities rather than in the bottom velocities, since the latter depend on depths that are usually below the region of high temperature fluctuations.

Figure 5 shows that in all the cases considered the theoretical surface velocities exceed the measured velocities by an average of 12.3 meters per second, that the mean velocities (between surface and bottom) exceed the measured velocities by an average of 3.2 meters per second, *but that the bottom velocities average only one meter per second less than the corresponding measured velocities.* It should be noted in this connection that the comparisons in Shelikof Strait are the only ones where the average difference for the group between the experimental velocity and the theoretical mean velocity is less than the average difference for the bottom velocity. No explanation for this exception could be adduced from the available data. It is, however, significant that this group is the only one that indicates the effective sound energy as passing through temperature conditions higher than the mean. In all other cases the reverse holds true. It would, therefore, appear reasonable to reject these comparisons as erratic. And the

EXPERIMENTAL VELOCITY (E)	SURFACE VELOCITY (S)	MEAN VELOCITY (M)	BOTTOM VELOCITY (B)	E − S	E − M	E − B
		Gulf of	*Alaska*			
1469.8	1490.9	1478.1	1469.2	−21.1	−8.3	+0.6
1467.4	1483.0	1477.2	1470.2	−15.6	−9.8	−2.8
1471.7	1483.0	1480.1	1473.2	−11.3	−8.4	−1.5
1471.0	1483.0	1474.8	1469.2	−12.0	−3.8	+1.8
1470.0	1484.8	1477.0	1469.5	−14.8	−7.0	+0.5
1468.9	1495.1	1476.9	1468.8	−26.2	−8.0	+0.1
1469.2	1483.7	1474.6	1469.3	−14.5	−5.4	−0.1
				Av. −16.5	Av. −7.2	Av. −0.2
		Shelikof	*Strait*			
1470.2	1477.7	1465.5	1464.9	− 7.5*	+4.7*	+5.3*
1470.1	1477.7	1465.2	1465.1	− 7.6*	+4.9*	+5.0*
1474.0	1488.5	1471.6	1466.6	−14.5*	+2.4*	+7.4*
1466.0	1488.9	1470.7	1466.4	−22.9	−4.7	−0.4
1468.2	1477.2	1466.2	1464.9	− 9.0*	+2.0*	+3.3*
1473.0	1477.2	1465.5	1464.5	− 4.2*	+7.5*	+8.5*
1467.8	1488.9	1474.7	1469.1	−21.1	−6.9	−1.3
				Av. −12.4	Av. +1.4	Av. +4.0
		Oregon and	*Washington*			
1477.8	1495.9	1487.6	1479.0	−18.1	−9.8	−1.2
1475.4	1495.9	1480.7	1475.4	−20.5	−5.3	0.0
1478.5	1497.8	1484.7	1477.3	−19.3	−6.2	+1.2
1482.1	1497.8	1486.0	1478.7	−15.7	−3.9	+3.4
1475.2	1497.8	1483.7	1476.2	−22.6	−8.5	−1.0
1475.3	1497.8	1483.3	1475.7	−22.5	−8.0	−0.4
1476.7	1497.8	1480.3	1475.4	−21.1	−3.6	+1.3
1476.1	1497.8	1480.1	1475.7	−21.7	−4.0	+0.4
1477.4	1497.8	1483.7	1476.1	−20.4	−6.3	+1.3
1476.4	1497.8	1484.7	1477.4	−21.4	−8.3	−1.0
				Av. −20.3	Av. −6.3	Av. +0.4

FIGURE 5

Comparison of experimental velocities with theoretical velocities for various paths

(*Continued on next page*)

FIGURE 5 *(Concluded)*

EXPERIMENTAL VELOCITY (E)	SURFACE VELOCITY (S)	MEAN VELOCITY (M)	BOTTOM VELOCITY (B)	E − S	E − M	E − B
		Northern	*California*			
1479.9	1489.7	1482.8	1479.0	− 9.8	−2.9	+0.9
1477.2	1489.7	1481.9	1478.7	−12.5	−4.7	−1.5
1479.2	1489.7	1482.4	1479.1	−10.5	−3.2	+0.1
1477.2	1489.7	1481.6	1478.6	−12.5	−4.4	−1.4
1480.9	1489.7	1481.7	1478.5	− 8.9	−0.8	+2.4
1479.3	1489.7	1481.3	1478.5	−10.4	−2.0	+0.8
1478.9	1489.7	1481.4	1478.3	−10.8	−2.5	+0.6
1481.1	1489.7	1481.7	1478.3	− 8.6	−0.6	+2.8
1490.1	1497.3	1492.0	1489.3	− 7.2	−1.9	+0.8
1489.1	1494.5	1492.0	1491.2	− 5.4	−2.9	−2.1
1490.6	1494.5	1493.0	1491.7	− 3.9	−2.4	−1.1
1483.7	1497.3	1490.5	1486.7	−13.6	−6.8	−3.0
1488.0	1497.3	1490.5	1486.2	− 9.3	−2.5	+1.8
1489.2	1498.8	1491.7	1489.4	− 9.6	−2.5	−0.2
1485.2	1499.2	1488.1	1485.0	−14.0	−2.9	+0.2
1480.2	1489.0	1485.0	1480.2	− 8.8	−4.8	0.0
1479.7	1489.0	1484.2	1480.4	− 9.3	−4.5	−0.7
1480.9	1489.0	1483.0	1480.3	− 8.0	−2.1	+0.9
1481.0	1489.0	1483.8	1480.0	− 8.1	−2.8	+0.7
1478.2	1489.0	1483.4	1479.9	−10.8	−5.2	−1.7
1479.0	1489.0	1483.8	1480.7	−10.0	−4.8	−1.7
1493.8	1493.2	1487.4	1484.9	+ 0.6*	+6.4*	+8.9*
1487.8	1493.2	1487.9	1485.8	− 5.4	−0.1	+2.0
1490.4	1493.2	1487.4	1485.5	− 2.8*	+3.0*	+4.9*
1486.2	1493.2	1489.6	1486.7	− 7.0	−3.4	−0.5
1489.0	1492.1	1487.4	1483.1	− 3.1*	+1.6*	+5.9*
1489.0	1492.1	1488.8	1485.2	− 3.1*	+0.2*	+3.8*
				Av. − 8.3	Av. −2.2	Av. +0.9
		Grand Average		−12.3	−3.2	+1.0

result is a most extraordinary correspondence between measured velocities and theoretical bottom velocities.

Figure 6 gives the average differences between experimental and theoretical velocities computed from best observations (this excludes all thos- comparisons marked with an asterisk in Fig. 5) and from observations made in localities where the temperature gradient is high, such as exists in Alaska and off the coasts of Washington and Oregon. The latter is, after all, the critical test as far as determining the path of the effective sound energy, for where the temperature difference between surface and bottom is slight, the experimental velocity would be found to agree with almost any theory of sound wave propagation.

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.

	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

FIGURE 6

Average differences (in meters per second) between experimental velocities and theoretical velocities for assumed paths.

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.