A FAMILY OF SCIENTISTS

IN HONOR AND MEMORY of one of our own the Washington Academy of Sciences takes pride in presenting a reprint of a paper by Harvey C. Hayes, a member of the WAS more than half a century ago. The paper is reprinted by the kind permission of the Franklin Institute and first appeared in *The Journal of The Franklin Institute* Vol. 197, No. 3, pp. 323-354 (March, 1924). Dr. Hayes's step grandson, James C. Cole, also an acoustic scientist, is currently an officer of the Washington Academy of Sciences, and we are grateful to him for providing much of the information below.

Dr. Harvey C. Hayes was a pioneer in the investigation of underwater acoustics and was the first recipient of the "Pioneer in Underwater Acoustics" award from the Acoustical Society of America. He was also awarded the Levy gold metal and the John Scott medal, both from the Franklin Institute, and the Cullum geographical metal engraved with the inscription "Harvey C. Hayes — He supplied science with a new instrument for mapping the ocean floor and thereby opened a new chapter in Marine Physiography 1925." Dr. Hayes served on the executive council of the Acoustical Society of America from 1935-1938 and in1960 was elected as one of only 17 Honorary Fellows, as of 2007.

Dr. Hayes began his career with the Navy during World War I, working at the Navy Experimental Station located at Fort Trumbull, New London, Connecticut. After the war, he continued his efforts at the Navy Experimental Station in Annapolis, Maryland. Dr. Hayes became the first superintendent of the Naval Research Laboratory's Sound Division when the laboratory opened in1923 and served in that position for 24 years, retiring in1947 after serving the Navy for a total of 30 years.

Dr. Hayes' research included a broad range of acoustics research topics. In addition to the sonic depth finder and the development of operational sonars for the Navy, he also explored diverse areas such as lamination defects in metal plates, electrodynamic sound projectors, sound radiation from ships propellers, acoustically transparent materials for sonar domes, microphones and accelerometers.

"Dr. Hayes is recognized as the first person to accumulate any substantial amount of data at sea and was later responsible for one of the two operational sonar equipments used by the Navy at the outbreak of World War II."[1]. Hayes' sea data collection is described by Gary Weir from the U.S. Navy Historical Center [2], "To the universal acclaim of the scientific community, Hayes had then used his invention (the sonic depth finder (SDF) [3]) to make the first complete bottom profile of any ocean, during the June 1922 transatlantic crossing of the destroyer *Stewart (DD224)* from Newport, Rhode Island, to Gibraltar. With Hayes on board, the *Stewart*, … made 900 soundings of the ocean to depths beyond three thousand feet. The news of this accomplishment went through the scientific community like a bolt of lightning. … The Navy's new instrument gave scientists their first look at the configuration of the ocean floor in all its irregularity. Sound now at last began to reveal what years of work with rope and wire soundings lines had only suggested. Civilian science quickly concluded that the number and range of naval vessels as well as the revolutionary potential of the SDF made the U.S. Navy an indispensable partner in the exploration of the ocean."

Included here is a tribute to Dr. Hayes on the occasion of the dedication of the Harvey C. Hayes Room of Quarter A at the Naval Research Laboratory, May 21, 1999.

> "…the enemy has rendered the U-boat ineffective, not by superior tactics or strategy, but through superiority in the field of science, which finds its expression in the modern battle weapon — detection." Admiral Karl Doenitz.

"These are among the highest words of tribute to the genius and inventiveness of the Navy's acoustic pioneers spearheaded by Dr. Harvey Cornelius Hayes, after whom the USNS Hayes [4] is named, in a recovered report by Karl Doenitz, Grand Admiral of the German Navy during World War II."[5]

Currently Patent Office searches prior to 1975 cannot be searched by inventor; for the interested reader we list the patent numbers of 73 patents awarded to Harvey C. Hayes. Copies of these patents can be obtained at http://www.uspto.gov/ or http://www.pat2pdf.org/.

Patents Issued to Harvey C. Hayes (1923- 1944)

1,470,733	1,632,331	1,743,071	1,900,015	2,015,674
2,434,926	1,483,547	1,632,332	1,749,284	1,910,434
2,064,911	2,447,333	1,512,222	1,636,510	1,749,285
1,923,088	2,098,240	2,459,162	1,525,182	1,649,113
1,751,035	1,951,358	2,105,479	2,472,107	1,530,176
1,671,719	1,755,583	1,966,446	2,041,710	2,474,842
1,532,108	1,681,982	1,757,938	1,972,889	2,292,376
2,517,565	1,551,105	1,692,119	1,784,439	1,974,422
2,374,637	2,527,217	1,557,161	1,704,084	1,787,536
1,980,993	2,405,575	2,559,618	1,565,361	1,709,573
1,792,013	1,985,251	2,406,767	2,561,368	1,577,254
1,729,383	1,814,444	1,995,305	2,411,541	3,319,735
1,584,451	1,729,579	1,847,243	2,000,948	2,424,030
3,715,982	1,593,972	1,729,595	1,860,740	2,005,741
2,428,799	1,624,946	1,742,704	1,892,147	2,008,713
2,433,845				

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[1] J. Schultz, “Family donates collection highlighting distinguished scientific career of Dr. Harvey C. Hayes”, Labstracts, U.S. Government Printing Office 19285-361-1053, June7, 1999.
[2] G. Weir, “Surviving the Peace: The Advent of American Naval Oceanography, 1914-1924,”Naval War College Review, V. L, No. 4, Autumn 1997.
[3] H.C. Hayes, “The sonic depth finder”, Proceed. Amer. Philosophical Society, V. LXIII, No. 1, pp. 134-150, 1924
[4] USNS Hayes (T-AGOR-16), commissioned July 2, 1970.
[5] NRL Brochure for the occasion of the dedication of the Harvey C. Hayes Room of Quarters A at the Naval Research Laboratory, May 21, 1999.

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MEASURING OCEAN DEPTHS BY ACOUSTICAL METHODS[1]

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The possibility of measuring ocean depths by acoustical methods has been recognized for a number of years and numerous methods and devices developed and designed for this purpose are listed in the patent office. Most of these devices attempt to determine the depth in terms of the time required for a sound signal to travel to the sea-bottom and reflect back again -to the surface.

One of the first patents pertaining to this art was granted to A. F. Eells, of Boston, Massachusetts, wherein he was allowed two broad claims covering the method of determining depths by measuring the time intervening between the transmitting of a sound signal near the sea-surface and the return of its echo from the sea-bottom. Since then numerous patents have been. taken out covering specific apparatus designed for measuring this time interval, but none of these devices has proved to be practical for the reason that they have failed in most cases to measure the time interval in question with sufficient reliability and accuracy, and in many cases have proved to be too delicate to withstand the adverse conditions often met with on sea-going vessels and too complicated to be operated by a ship's personnel. A brief description of some of these devices follows: Fig. 1 shows the principle of operation of a sounding device invented by Reginald A. Fessenden.[2] Numeral 1 represents a disc made of insulating material that is rotated at a uniform speed by motor (2). The disc carries a conducting segment (3) that closes the electrical circuit through a submarine sound transmitter (4) when it passes beneath brushes (5), thereby sending out a sound signal. This segment also closes the circuit through a telephone receiver (6) when it passes across the brushes (7). If the echo of the signal meets the microphone or other type of sound receiver represented by numeral 8 at the instant segment (3) short-circuits brushes (7), it will be heard in the telephone receiver (6) and the time of

[1] Presented at the Stated Meeting of the Institute held Wednesday, March 21, 1923. Reprinted by permission from The Franklin Institute, *The Journal of The Franklin Institute*. Vol. 197, No. 3, pp. 323-354 (March, 1924).

[2] For a more complete description of the Fessenden depth-sounding apparatus, see U. S. Patent No. 1,217,585.

sound transmit from the transmitter to the receiver by wav of reflection from the sea-bottom will be equal to the time required for segment (3) to travel the angular distance subtended between the two pairs of brushes and indicated by the pointer (9) on the scale (10). This condition is brought about by rotating brushes (7) about the insulating disc (1) by means of the handle (11).

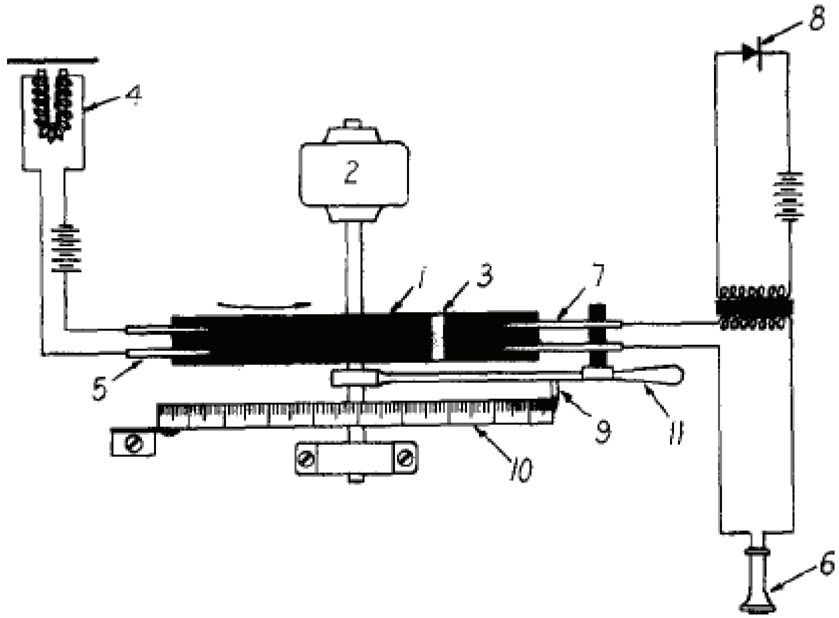
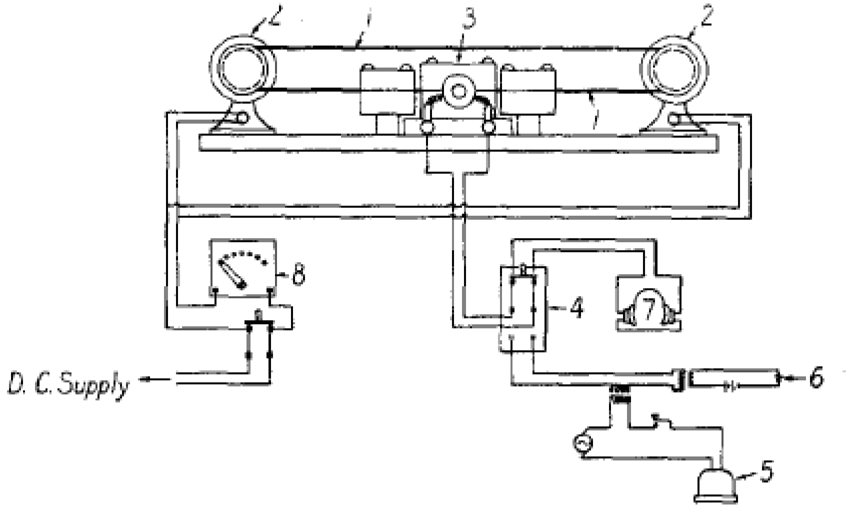


Figure 1

In practice the disc must be rotated at considerable speed or the angle swept out by the segment while the sound travels to the sea-bottom and back will be too small to measure with sufficient accuracy. This results in sending out sound signals in rapid succession and the return of echoes from the sea-bottom in still more rapid succession for the reason that a sound signal usually echoes back and forth between, the surface and sea-bottom several times before its energy is absorbed. Under such conditions sound can be heard in the telephone for numerous settings of the brushes (7) and the relation between the depth and the scale reading becomes indefinite.

Another device for measuring this time interval makes use of an electromagnetic recorder. This device, illustrated in principle in Fig. 2, attempts to determine the short-time intervals involved in taking shallow soundings by recording the transmitted signal and its returning echo on the magnetic tape (1), while it is driven rapidly by means of variable speed motors (2), and then measuring the time interval between the two records when the tape is run at a much slower speed. This measured time interval multiplied by the ratio of the reduced speed to the recording speed gives the time interval between signal and echo. In the figure, numeral 3 represents the recording and reproducing magnets. These also serve for erasing the record. Numeral 4 represents a double- throw double-pole switch by means of which magnets (3) can be inductively connected with transmitter (5) and receiver (6) for recording the signal and its echo, or with the telephone head set (7) for hearing the reproduced record. The rheostat for controlling the speed of the motors is indicated by numeral 8.

FIG. 2.



This method, while excellent from the standpoint of theory, has not proved to be practical for the following reasons:

(a) The magnetic tape does not record the signals unless their intensity is above a certain threshold value, which is comparatively high, and the echoes cannot be kept above this value over regions where the coefficient of reflection of the sea-bottom is low or over regions where the depth is great.
(b) The local disturbing noises always present on shipboard are comparatively intense and their record ofttimes distorts the record of the signals and echoes to such an extent that they cannot be readily recognized, and as a result the time interval cannot be accurately measured.

(c) It is difficult to determine accurately the ratio between the reproducing and recording speeds of the motor.
(d) The time interval, as measured at the retarded speed, cannot be determined with a high degree of accuracy for the reason that the record of both the signal and the echo then becomes less sharply defined; and although this method of determining the short interval between signal and echo results in some gain in accuracy, the gain is not proportional to the ratio between the recording and reproducing speeds.
(e) Finally the method is too slow to give soundings on short notice, as is ofttimes desirable when a ship is in dangerous waters.

Samuel Spitz, of Oakland, California, has attempted to measure ocean depths with apparatus that first records the signal and its echo on a magnetic tape and then amplifies the reproduced record. He utilizes this increased electrical output to operate a complicated system of relays and magnetic clutches and claims to accurately record by means of a pointer and dial the depth corresponding to the time interval between signal and echo as recorded on the tape. His method and apparatus, as disclosed in, U. S. Patent 1,409,794, would appear to have the inherent weaknesses of the “magnetic tape method” plus the difficulties and uncertainties that are always present to a greater or less degree in complicated relay systems. But even if the relays should function perfectly, it would seem that the local disturbing noises, caused by propellers, auxiliary machinery and slapping of waves, which (no matter how selective the receiving system may be) are recorded on the magnetic tape to some extent, would ofttimes trigger off the automatic recording apparatus and give erroneous records of depth that might be misleading. A depth-sounding device is worse than useless unless it can be absolutely depended upon, to give reliable sounding data at all times.

Alexander Behm, of Kiel, Germany, started work on the problem of measuring ocean depths by means of sound waves about twelve years ago. His first efforts were devoted to methods that involved measuring the time interval between signal and echo. Recognizing the inherent difficulties in making such measurements, he turned his attention to the possibility of making depth determinations by measuring the intensity of the echo. His method of doing this can be understood in connection with Fig. 3 wherein numeral 1 represents a submarine sound transmitter designed to produce a fairly pure sound of constant intensity and pitch. The sound passes from the transmitter to the sea-bottom and a portion reflects back to the receiver, represented by numeral 2, where by acting upon a resonant chamber it causes a tuning fork to vibrate. He measures the intensity of the echo in terms of the amplitude of vibration of a small bead carried by one prong of the fork and observes the amplitude of its motion by means of a microscope. And since the intensity of the echo and the amplitude of vibration of the fork are each a function of the depth, he calibrates the microscope scale directly in terms of depth.

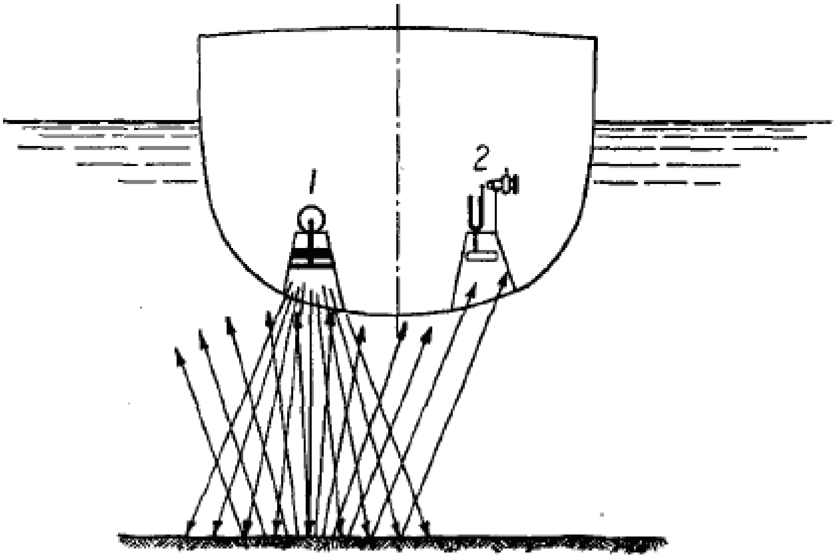


Figure 3

While this method avoids the difficulties encountered in measuring short time intervals, it introduces others that are equally hard to overcome and one that cannot be overcome. It is very difficult to generate a sound having constant intensity and pitch under various operating conditions, and it is equally difficult to keep a receiver accurately tuned to this pitch and of unvarying sensitivity. It is probable that Doctor Behm has gone far toward overcoming these two difficulties, but we fail to see how he can make allowance for the variations of the coefficient of reflection of the sea-bottom where, according to our observations, this factor may change as much as 25 per cent over comparatively short distances.

It is probable that Doctor Behm fully recognized these weaknesses in his method and apparatus for he later resumed his efforts to measure the time between signal and echo and has finally succeeded in making this measurement with a high degree of accuracy with comparatively simple and rugged apparatus. His transmitter, represented by numeral 1 of Fig. 4, consists of a tube extended through the ship's skin and the sound signal is produced by exploding a cartridge that has been slipped into position in this tube. The cartridge is fired electrically by closing a key mounted

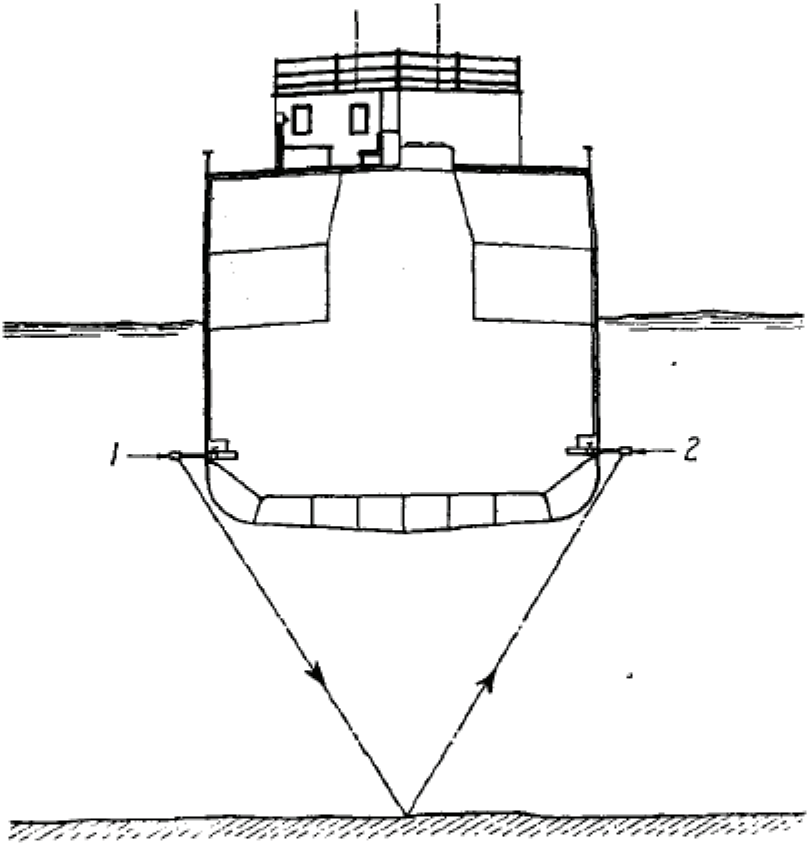


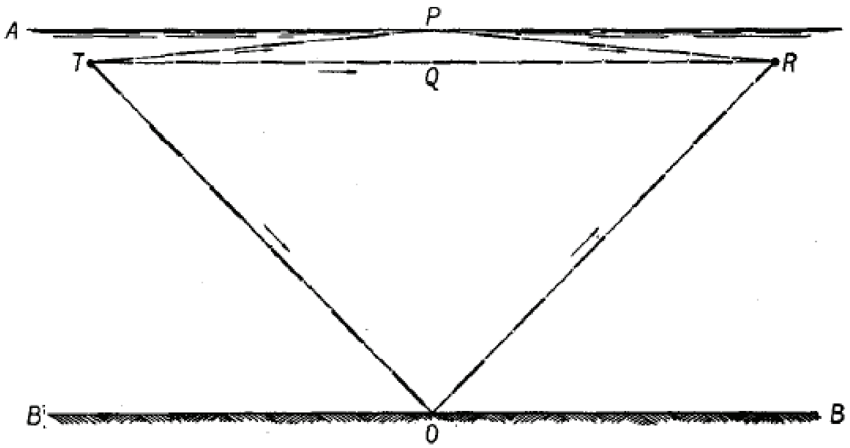
Figure 4

on or near the recording apparatus which is located in the chart house or on the bridge. The receiver is mounted in a similar tube, numeral 2, projecting from the opposite side of the ship's hull where it is shielded from the direct sound generated by the cartridge. The means for recording the time of sound transit between transmitter and receiver by way of reflection from the sea-bottom consists of an ingenious design of chronograph that is started moving when the cartridge is fired and stopped by the fluctuation in the receiver circuit when the sound wave, reflected from the sea-bottom, strikes the receiver.

This sounding device, which the inventor calls the Behm-Echolot, represents a large amount of excellent research and the exercise of considerable ingenuity. It should give reliable sounding data for depths within about eight) fathoms.

As an instrument for aiding navigation, any depth-sounding device should be able to do more than determine the depth of water occasionally. It should serve to take any number of soundings in rapid succession in order that well-defined charted contours may be identified with certainty and thus serve for determining the position of the vessel. In case of the Behm-Echolot this would not only require a very large supply of cartridges, but would prove to be expensive.

It has been found in practice that a determination of the slope of the sea-bottom is helpful in locating ' landmarks " along a charted route and that the value of a depth-sounding device, as an aid and safeguard to navigation, is greatly enhanced if it will also serve to determine the direction of sound beacons at dangerous points along shore and at harbor entrances, and also signals from other vessels. The depth-sounding devices developed in the U. S. Navy, and which will now be described, serve these purposes. The determination of depth by acoustical methods was assigned as a research problem in the Bureau of Engineering of the U. S. Navy as a result of a discovery made on the transport U. S. S. *Von Steuben* during a trip from New York to Brest in March, 1919. This vessel had been equipped with one of the submarine sound receivers that the Navy had developed at its New London Station for use in locating U-boats and it was proposed to test the value of the device as an aid and safeguard to navigation. It was found that the direction of nearby vessels and submarine bell signals could be accurately determined while leaving New York harbor and when approaching Brest, but that in mid-ocean the propeller sounds of other vessels as well as of the *Von Steuben* herself could not be heard. This fact led to the discovery that the only sounds heard in a submarine sound receiver located near the surface are the components that have been reflected from the sea-bottom. The explanation of this fact can be readily understood by referring to Fig. 5 wherein (A–A) represents the sea-surface, (B–B) the sea-bottom, and T and R a sound transmitter and a sound receiver, respectively, each submerged a distance represented by (P–Q). If the distance (P–Q) is small compared with the distance (T–R) (as is usually true in practice), then the two sound paths (T –P –R) and (T –Q –R) are practically of equal length. Sound from T reaches R by the three paths (T–P–R), (T–Q–R), and (T–O–R), but since the two paths (T–P–R) and (T–Q–R) are practically equal and since the surface-reflected ray suffers a change of phase of a half a wave-length upon reflection, the sound traversing these two paths interferes destructively at *R* and only the sound that has been reflected from the sea-bottom can be heard.



Mutual cancellation of direct and surface-reflected rays.

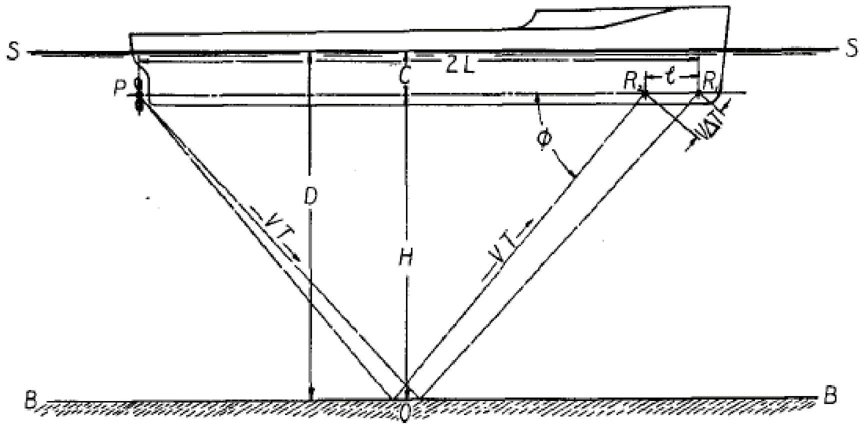
Figure 5

As soon as it was discovered that the sounds heard in our receivers had arrived by way of reflection from the sea-bottom, it appeared probable that methods could be developed for determining the depth of the water by means of submarine sound waves, providing the character of the sea-bottom in general is such as to reflect sufficient sound energy to give an audible echo. Before starting this work some preliminary tests on the efficiency of the deep-sea floor as a sound reflector were made on the destroyer U. S. S. *Wilks* which showed that clear audible echoes of signals from submarine sound oscillators could be received from depths at least as great as 2000 fathoms. Since that time good echoes have been received in depths greater than, 3000 fathoms and so far as the author knows there has been no case reported where echoes could not be heard.

It should be stated, however, that nothing definite is known regarding the coefficient of reflection of the sea-bottom other than the fact that echoes have been heard over such regions or routes as have been tested. Over certain regions it has been noted that the echoes are much less clear-cut than are the signals. This distortion is doubtless due to a gradual change in the density of the material forming the sea-bottom. But the fact that an echo is heard at all would seem to argue against the somewhat general conception that the deep-sea bottom consists of an ooze-like deposit perhaps hundreds of feet thick, the density of which increases very slowly from the top to the rock foundation beneath. From the character of the echoes one would judge that the density of the ooze does not vary much from that of water throughout its depth or else that it has settled to a dense foundation, except for a comparatively shallow region near its surface. If the first assumption is true, the sound penetrates the ooze and reflects from the underlying rock. If the second is true, the sound reflects from the solidified ooze and the comparatively thin transition layers immediately above this.

Three methods have been developed for determining ocean depths by means of sound waves, two of which serve for measuring depths less than about one hundred fathoms and one of which serves for measuring any depth greater than about forty fathoms. All three methods make use of the time required for a sound signal to travel from a transmitter to a receiver by way of reflection from the sea-bottom. It will be seen that this time interval, which is too short to be measured directly with sufficient accuracy, can be determined indirectly as a function of a much shorter time interval that can be very accurately measured. Of the two methods that serve for determining shoal depths, one has been termed the "Angle of Reflection Method" and the other the “Standing Wave Method.” The method that serves for greater depths has been called the “Echo Method.”

The angle of reflection method can be understood by referring to Fig. 6, wherein (B–B) represents the sea-bottom (supposed for convenience to be horizontal), and (S–S) represents the surface. The propeller (P) of the vessel represents a sound source and R_1 and R_2 represent two sound receivers mounted within the peak-tank or within a blister-like enclosed space on the outside of the ship's skin. These receivers are spaced a distance (1) on a horizontal line passing through the propeller. The distance between P and the mid-point between the two receivers is $2L$. The path of the sound waves from propeller to receivers will be (P–O–R). If the sea-bottom is horizontal, the triangle (P–O–R) is isosceles, having the side (P–O) equal to the side (O–R). If $2T$ represents the time of sound transit from P to R, and V represents the velocity of sound in sea-water, then,



Sounding by angle of reflection method.

Figure 6

(1) $H^2 = (V{\bullet}T)^2 - L^2$

(2) and $\dfrac{V{\bullet}T}{L} = \dfrac{\ell}{V{\bullet}\Delta T}$ (corresponding sides of similar triangles)

(3) wherefore $V{\bullet}T = \dfrac{\ell{\bullet}L}{V{\bullet}\Delta T}$,

Substituting the value of ($V.T$) in equation (1) gives

(4) $H^2 = \dfrac{\ell^2 L^2}{V^2{\bullet}(\Delta{\bullet}T)^2} - L^2 = L^2\left\{\dfrac{\ell^2 - V^2{\bullet}(\Delta T)^2}{V^2{\bullet}(\Delta T)^2}\right\}$

(5) wherefore $H = L{\bullet}\dfrac{\sqrt{\ell^2 - V^2{\bullet}(\Delta T)^2}}{V{\bullet}\Delta T}$

where ΔT is the difference in the time of arrival at the two receivers of corresponding increments of the propeller sounds. The total depth (D) is given by the equation:

(6) $D = C + H = C + L{\bullet}\dfrac{\sqrt{\ell^2 - V^2\Delta T^2}}{V{\bullet}\Delta T}$.

All the factors on the right-hand side of equation (6) are constant and known except ΔT. The distance the receivers and propellers are submerged is C, half the distance from the propellers (or whatever source of sound is used) is L, the spacing of the two receivers is ℓ, and V is the velocity of sound in sea-water which may be regarded as constant. The determination of depth therefore depends upon the determination of ΔT. This time factor, though much smaller than the time interval between signal and echo, can be determined with a high degree of accuracy by making use of the so-called binaural sense.

It has been proved experimentally that the direction of sounds is largely determined by the difference in the time of arrival of corresponding portions of the sound waves at the two ears. If the sound strikes the right ear first one unconsciously judges the source to be located at his right, if it strikes the left ear first he judges the source to be located to his left. If the sound strikes both ears simultaneously it appears to be neither to the right nor left and is said to be binaurally centred. The sense of direction of sounds, which is dependent upon the difference in the time of arrival at the two ears, has come to be called the "binaural sense." When one judges the direction of a sound to be neither to his right nor left, or in other words, when he judges it to be binaurally centred, he unconsciously estimates that the sound waves strike the two ears simultaneously; and the high development of the binaural sense is such that he estimates correctly to within about one two-hundred-thousandth of a second.

Of the two receivers shown in Fig. 6, suppose the output from one is brought to one ear of the operator, and that from the other receiver is led to the other ear, respectively. If the time of energy transit to the ear from each receiver is the same, the difference in the time of arrival of the sound at the two ears will be ΔT, the time difference in arrival at the two receivers, and, through the operation of the binaural sense, the sound will appear to come from the side of the operator because one ear is stimulated earlier than the other. Moreover, the sound will appear to be located on the side of the observer carrying the ear that receives the earlier stimulation. If now the energy-conducting path leading from each receiver to its respective ear be constructed so that the time of transit over the path can be varied continuously or by very small increments, it will be possible for the operator to make the sound reach his two ears simultaneously by increasing the time of transit across the path leading to the ear that is first stimulated or decreasing the time of transit between the other receiver and its respective ear or by increasing the time of transit to one ear and simultaneously decreasing the time of transit to the other ear by a proper amount. When the sound has been binaurally centred in this way the difference in the time of transit across the two paths, connecting between the two receivers and the observer's ears, respectively, is equal to the time increment (ΔT).

The process of binaurally centring a sound in this way has been called "compensation,"[3] and any device used for this purpose is called a "compensator." It is evident that the compensator can be calibrated to give the value of ΔT or any function of ΔT, and as a result can be calibrated to give the depth (D) directly. This is done in practice.

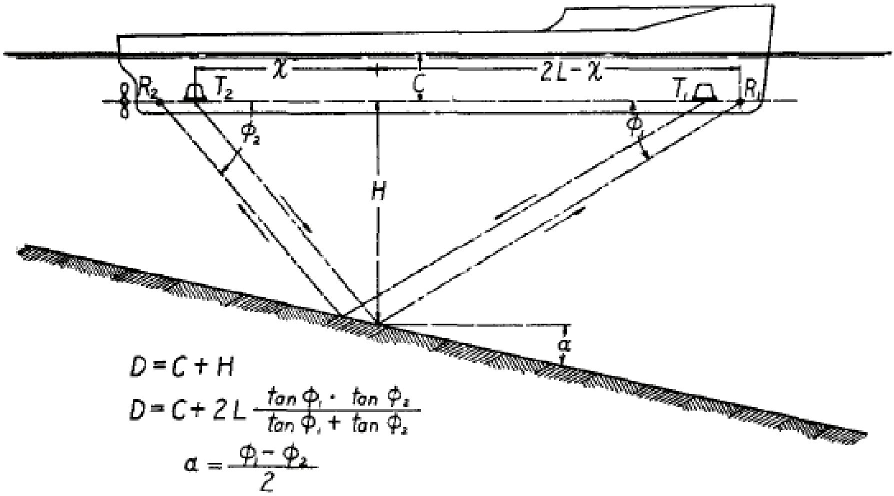
It is to be noticed that the last term of equation (6) can be written as the tangent of the angle (ϕ) that the direction (O–R) makes with the horizontal line (P–R) and that equation (6) can be written:

(7) $D = C + L \tan \phi$.

When the sounding equation is put in this form it becomes obvious that the sounding data given by the angle of reflection method become more accurate as the depth becomes less, a result much to be desired. On the other hand, it shows that the method breaks down for depths so great that the angle (p) approaches a right angle. It has been found in practice that this method gives reliable soundings to depths equal to about three times the distance between the sound source and the receivers. For most vessels this will cover depths as great as 100 fathoms and ofttimes more.

It is evident that the method, as described, becomes inaccurate when the slope of the sea-bottom varies from the horizontal for the reason that the triangle (P–O–R) will not be isosceles. In. general the method gives too great values when the vessel approaches shoaling water and too small when running into

[3] The process of binaurally centring a sound by compensation was developed by the Navy in 1917-18 at its research station in New London, Conn. For a more complete description of the process, see *Proc. Amer. Phil. Soc.*, **59**, No. 1, 1920, or the *Marine Rev.*, Oct., 1921.



Method for eliminating error due to shelving bottom.

Figure 7

increasing depths. In most regions the sea-bottom within the hundred fathom curve is fairly uniform for the reason that it has been, leveled off by the action of storm waves and the method described has been found to give fairly accurate sounding data.

By referring to Fig. 7 it will be seen that the method can be made accurate by installing a sound transmitter and receiver in each end of the vessel. The same compensator serves for both sets of receivers as does the same power outfit for driving both transmitters. The operator sounds transmitter (T_2) and with his compensator measures ϕ_1. Then by throwing a multipole switch he sounds T_1 and measures ϕ_2. It can be shown that

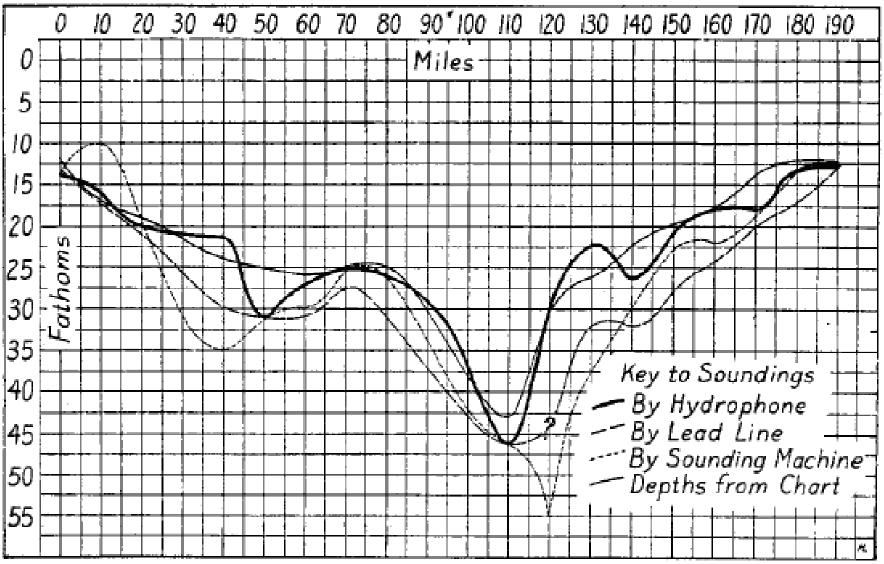
$$(8)\ D = C + 2L\frac{\tan\phi_1 \bullet \tan\phi_2}{\tan\phi_1 + \tan\phi_2},$$

and that α, the slope of the sea-bottom, is given by the equation,

$$(9)\ \alpha = \frac{\phi_1 - \phi_2}{2}.$$

While this more refined method is to be preferred for making hydrographic surveys, the simpler approximate method serves for navigational purposes as can be seen by a consideration of the curves shown in Figs. 8 and 9.

The curves of Fig. 8 represent sounding data taken by the U. S. S. *Breckenridge* while en route from Charleston, South Carolina, to Key West. The course ran in part along the edge of the continental plateau, where the sea-bottom was very uneven and erratic. Two successive casts of the hand-lead made not more than a minute apart, while the vessel was not steaming over five

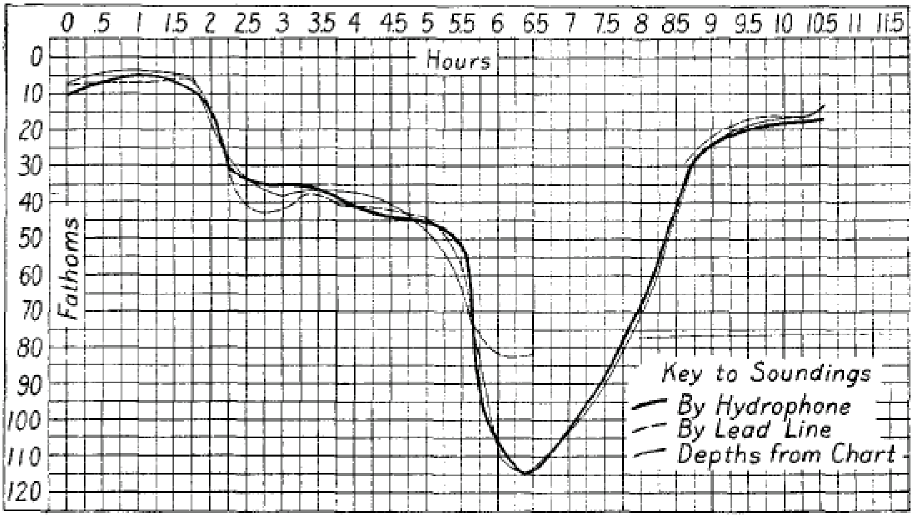


Comparative sounding data, electrical Hydrophone M V-62. *U. S. S. Breckenridge* en route from Charleston to Key West, January 14, 1920.

Figure 8

knots, ofttimes showed a discrepancy of five or six fathoms. Under such conditions it was not expected that the acoustical sounding data would be at all accurate. However, the curves seem to show that the soundings given by the hydrophone are perhaps more reliable than any of the others. It is certain that these soundings, which are represented by the full heavy line, do not depart from the charted values, which are represented by the light full line as much as do the soundings taken by the lead-line or the sounding machine. Moreover, it will be noticed that, except at the 138-mile mark, the acoustical curve passes through every point where two or more of the other curves coincide. This fact tended to make all who took part in the test believe the acoustical sounding data were, on the whole, most reliable.

The sounding data represented by the curves of Fig. 9 were taken during a run from Newport, Rhode Island, out to the hundred-fathom curve and back, and show the accuracy with which the apparatus can give soundings where the sea-bottom is somewhat regular. It will be noticed that the acoustical sounding data agree very closely with the charted depth except at the beginning and end of the run where the water was shoal. In these

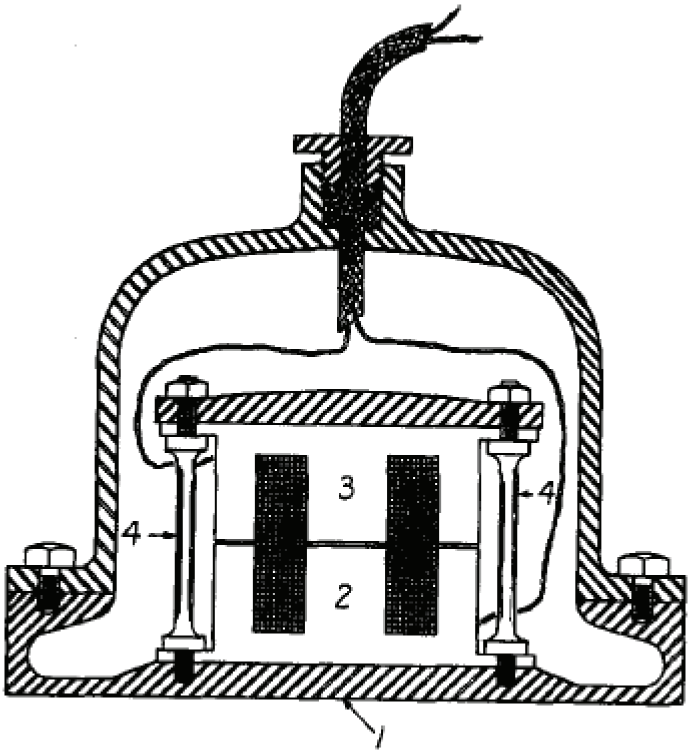


Comparative sounding data, acoustical Hydrophone M V-16B. *U. S. S. Blakeley*-150. Cruising off Montauk Point, May 27, 1920.

Figure 9

regions the agreement with the hand-line data is close. All who took part in this test believe the charted depths in the shoal region are too small for the reason that the hand-line soundings consistently gave about two fathoms greater depth; and there was a general feeling that the acoustical data represented the depth very accurately at all times.

The term "M V -Hydrophone," used in the caption of both Figs. 8 and 9, refers to the type of submarine sound receiver used for determining the time increment (ΔT). This type of receiver employs several sound receptors instead of two as described above. The receivers are equally spaced along a straight line passing through the propeller (P) and so connected through the compensator that the forward half of the receivers connects with one ear in place of a single receiver as described, and the receivers of the rear half of the line connect through the compensator to the other ear. The compensator itself is so ingeniously designed that when any sound striking the receivers is binaurally centred the responses to this sound from all the receivers arrive at the ears in phase. This results in making the intensity of the received sound considerably greater than it would be if only one receiver connected with each ear. But this is not the only advantage of this type of receiver.



Schematic diagram of a submarine sound transmitter.

Figure 10

Any sound that reaches the receivers and is not binaurally centred will have the responses from the several receivers arriving at the ears out of phase and they will partially destroy one another by destructive interference with the result that the sound heard is less intense than it would be if only one receiver connected with each ear. The M V - Hydrophone, therefore, can be focussed on any sound that the operator desires to hear, so that this particular sound gives a loud, clear response at the ears while all other sounds, and hence the local disturbing sounds, are greatly weakened.[4]

The ship's propellers form a convenient sound source for use in determining depths by the angle of reflection method, but any submarine sound transmitter of the oscillator type serves equally well. The principle of operation of such a sound transmitter can be understood by reference to Fig. 10, wherein numeral 1 indicates a rigid diaphragm in contact with the water, numeral 2 represents one-half of a powerful electromagnet rigidly attached to the diaphragm, and numeral 3 represents the other half of the electromagnet which is suspended in position by the elastic steel rods represented by numerals 4. When an alternating current is passed through the magnetizing coil, the suspended half of the magnet vibrates back and forth alternately compressing and stretching the rods by which it is suspended and exerting a powerful thrust and pull on the heavy diaphragm that may equal several tons.

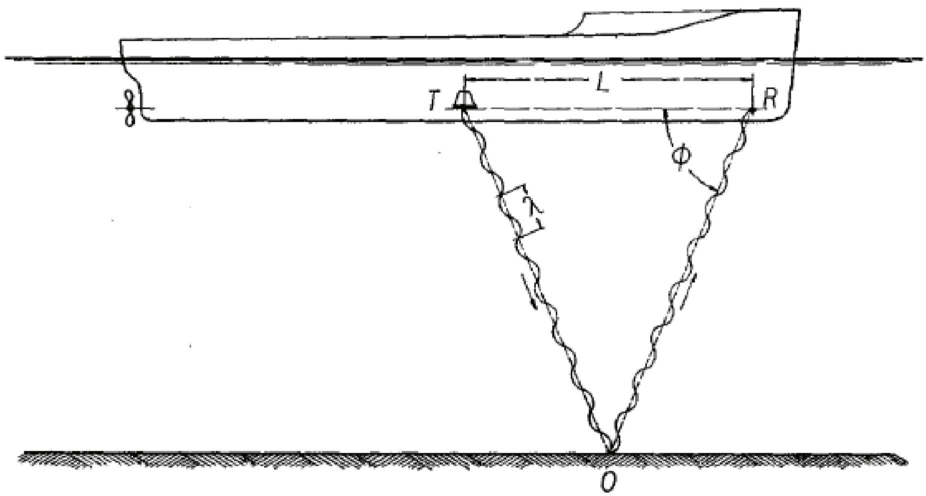


Figure 11

Because of the incompressibility of water, it becomes necessary to exert great forces on the diaphragm to produce even a slight amplitude of motion. The submarine sound oscillator can be used for sending code or any other kind of signals by placing a key in the alternating current circuit.

[4] A description of the M V -Hydrophone will be found in the *Marine Review* of October, 1921.

The "Standing Wave Method" of determining depths can be understood by referring to Fig. 11 wherein *T* represents a submarine sound transmitter and *R* represents a submarine sound receiver, the two being separated a distance (*L*). The sound transmitter is driven by an alternating current supply so designed that the frequency of the current can be controlled and varied by the operator over the range included between about 500 and 1500 cycles per second. This circuit is provided with means for giving the frequency with a high degree of accuracy at all times. The operator uses a two-telephone head set, one phone of which is inductively connected with the A. C. circuit that drives the sound transmitter. This connection is preferably made through a variocoupler. The other phone is connected with the output from the sound receiver (*R*). With the phones connected in this way, it will be seen that the sound heard in the inductively connected phone has, at all times, a definite phase relation with the sound waves leaving the transmitter and the sound generated by the other phone has a definite phase relation with the sound waves reaching the receiver. If the operator adjusts the frequency properly, he can make the sound heard in the two phones have the same phase and can recognize this condition through the fact that the sound will then be binaurally centred. If the sound leaving the transmitter has the same phase as the sound waves arriving at the receiver, then (*T–O–R*), the sound path between transmitter and receiver, represents a whole number of wave-lengths. Calling this path-length, *S*; and the time required for sound to travel a distance equal to one wave-length, ΔT; and the velocity of sound in sea-water *V*, we have the relation:

$$(1)\ S = V \bullet N \bullet \Delta t$$

where $N\Delta t$ represents the time required for the sound to travel the whole path-length. But Δt, which represents the time for one wave to pass a fixed point, is equal to one second divided by the frequency (*n*) of the sound. Expressed as an equation, this becomes:

$$(2)\ \Delta t = \frac{1}{n}$$

and by substituting this value in equation (1), we have:

$$(3)\ S = N\frac{V}{n}$$

and the path-length (S) between transmitter and receiver would be known if the number of wave-lengths (N) in the standing wave system were known.

The value of N can be found by varying the frequency of the sound until a second standing-wave system is established.

Suppose the operator adjusts the frequency so that the sound is binaurally centred. Call the frequency (n_1). This will be equal to the frequency of the A. C. current. Then suppose he slowly raises or lowers the frequency. He will notice that the sound apparently passes away from binaural centre and finally comes back across centre. Each time the sound comes back across binaural centre, he has varied the number of waves in the standing wave system by one. Suppose he varies the frequency until the number of waves in the system differs from the number in the original system by a and he determines this number by counting the number of times the sound comes to a binaural centre while he slowly changes the frequency. Call the final frequency which he carefully adjusts for a binaural balance, n_2. Then since the path-length (S) is the same in the two cases, we have:

$$(4)\ S = N\frac{V}{n_1} = (N \pm a)\frac{V}{n_2}$$

wherefore (5) $N = \pm a\dfrac{n_1}{n_2 - n_1}$,

the sign before a being such as to make N positive. Substituting this value for N in equation (4) gives:

$$(6)\ S = \frac{aV}{n_2 - n_1}$$

which gives a very simple working formula for determining S, the sound-path from the transmitter to the receiver by way of reflection from the sea-bottom.

It will be noticed that the determination of S does not furnish sufficient data for calculating the depth except when the sea-bottom is horizontal as shown in the figure. The point of reflection (o) may be anywhere on the surface of an ellipse having T and R as the two foci and the sum of the radius vectors (O–T) and (O–R) equal to S. If, however, the M V -Hydrophone is used for the receiver, the angle (ϕ) that the radius vector (O–R) makes with the principle axis (T–R) can be readily determined. This furnishes data for the complete solution of the depth and the slope of the sea-bottom.

This method has proved to be extremely accurate for measuring shallow depths. It gives greater accuracy as the depth becomes more shallow for the reason that the less the depth the greater the change of frequency that is required to change the number of waves in the standing wave system. The method breaks down at great depths for the reason that a small change in the frequency introduces so many waves into the system and so rapidly that they cannot be accurately counted and thus the factor a becomes indefinite.

From the above description, it might be thought that each sounding taken by the standing wave method requires the solution of a problem in conic sections and would therefore be slow and cumbersome in practice. Such, however, is not the case. Having determined the value of S and ϕ, the depth can be determined from a family of curves with very little effort or loss of time.

It will be noticed that the apparatus employed for utilizing the standing wave method of determining depths is practically the same as that used with the angle of reflection method. The same receiver and transmitter serves equally well for both methods, but the standing wave method requires, in addition, some means for controlling the pitch of the transmitted signal and a frequency meter for determining the pitch.

The method, as outlined, has been found to give accurate results and to be easily applied. It can be modified somewhat without impairing its efficiency. Instead of energizing one phone by inductive connection with the A. C. circuit of the transmitter, it can as well be energized by a second receiver located near the transmitter. And instead of energizing the two phones separately so that the binaural sense can be utilized for adjusting the frequency to bring about a definite phase relation between the sound leaving the transmitter and that reaching the receiver, both currents can be passed through both phones in parallel, or series, in which case the observer can adjust the frequency to give a maximum or minimum response in the phones. He will then determine a by counting the number of maxima or minima, respectively, that occur during the change of frequency from the first to the second adjustment. This arrangement can be used by an operator who is deaf in one ear.

The "Echo Method" of determining depths is very similar to the standing wave method. It consists of sending out a continuous series of short sound signals separated by equal time intervals and means for varying continuously the time interval between successive signals from about one-tenth of a second to about ten seconds, the means being such that the interval between successive signals can be accurately determined. If S represents the distance the sound travels in passing from the transmitter to the receiver by way of reflection from the sea-bottom, t represents the time of transit and V represents the velocity of sound in seawater, then we have the relation:

(1) $S = V.t$,

and it becomes necessary to determine t.

If the period between successive signals is made such that a signal returns to the receiver at the same instant that one is sent out from the transmitter, then we have the equivalent of a standing wave system, and if p represents the time interval between successive signals we have the relation:

(2) $t = N.p$,

where N is the number of signals that are in transit between the transmitter and receiver. Substituting this value for t in equation (1) gives:

(3) $S = V.N.p$.

The factor V is known and the factor p can be determined by the apparatus that is employed to automatically close and open the A. C. circuit through the transmitter. This apparatus, which serves as an automatic sending key, will be described later.

To determine N the operator will vary the frequency at which the sound signals are transmitted until the signals and echoes are heard simultaneously in the two telephone receivers, one of which is inductively connected with the A. C. transmitter circuit and the other of which is connected through the compensator of the M V-Hydrophone to the submarine sound receivers. This is the same arrangement that is employed in the standing wave method. The operator may continue varying the frequency of the signals until the coincidence between signals and echoes has arrived and passed by a times to the final adjustment. Then since the distance the sound has travelled between transmitter and receiver has remained constant, we have the two equations:

$$(4)\ S = V.N.p_1 = V.(N \pm a).p_2$$

where p_1 and p_2 represent, respectively, the time interval between successive signals in the two cases. Solving for N, we find:

$$(5)\ N = \pm a \frac{p_2}{p_1 - p_2}$$

and by substituting this value for N in equation (4), we have:

$$(6)\ S = V \bullet a \bullet \frac{p_1 p_2}{p_1 - p_2}.$$

It is obvious that the sign of N must be such as to make S positive.

Equation (6) can be simplified by replacing the p factors, which represent the time between signals, by a set of n factors, representing respectively the frequency of the signals. If this is done, equation (6) reduces to:

$$(7)\ S = \frac{V \bullet a}{n_2 - n_1},$$

which is identical with the sounding equation developed in connection with the standing wave method. The automatic transmitting key, that must serve for varying the value of p and for determining its value, might be a pendulum with arrangements for varying its period of vibration and for closing and opening the transmitter circuit. If this were done the factor p or its reciprocal $\frac{1}{n}$ would be expressed in terms of the well-known pendulum laws. But since pendulums do not work well on board ships, it is preferred to use a disc caused to revolve at constant speed, similar to the revolving plate of a graphophone, and a small friction wheel resting on this surface with means for moving it inwards or outwards along a radius of the constant speed disc. With this arrangement the speed of the friction wheel can be varied continuously from zero to a value that is dependent upon the speed of the disc and the ratio of the radius of the disc to that of the friction wheel. The closing and opening of the transmitter circuit is accomplished by contact points operated by a cam-wheel attached to the axis of the friction wheel. If this cam carries one tooth, one signal will be transmitted for each revolution of the friction wheel, while if the cam carries *C* teeth equally spaced about its circumference there will be *C* signals transmitted for every revolution of the friction wheel.

Suppose the constant period of revolution of the disc is *P* seconds and that the radius of the friction wheel is *r*. Also suppose the distance from the centre of the disc to the point of contact between the disc and friction wheel is *R*. Then since there is no slip between the friction surfaces we have:

$$(8)\quad \frac{2\pi R}{P} = \frac{2\pi r}{p}$$

and

$$(9)\quad p = \frac{P \bullet r}{R},$$

if the cam-wheel carries one tooth, for then the period *p* between signals is the same as the period of revolution of the friction wheel. If, however, the cam-wheel carries *C* uniformly spaced teeth, then:

$$(10)\quad p = \frac{P \bullet r}{C \bullet R},$$

and

$$(11)\quad n = \frac{1}{p} = \frac{C \bullet R}{P \bullet r}.$$

Substituting this value in equation (7) gives for the sounding equation:

$$(12)\ S = \frac{a \bullet V \bullet P}{C\left(R_2 - R_1\right)},$$

where a is the number of signals in transit that have been introduced in passing from the first to the second condition for coincidence between signals and echoes, V is the velocity of sound in sea-water, P is the constant period of revolution of the disc, r on is the radius of the friction wheel, C is the number of teeth the cam that operates the contact points for closing and opening the transmitter circuit, R_1 is the distance from the centre of the disc to the point of contact with the friction wheel for the first adjustment for coincidence between signals and echoes in the two phones and R_2 is the corresponding distance for the second similar adjustment.

The accuracy with which depths can be determined by this to which the speed of the disc method depends upon the degree can be kept constant and the accuracy with which R can be the disc is driven by a tuning-fork speed-measured. In practice the disc is driven by a tuning-fork speed-controlled motor operating through a worm and gear. With this arrangement the speed of the disc is kept constant to within a tenth of a per cent. The friction wheel is moved out and in across the disc by means of a spiral thread operating in a nut, and the position of this wheel on the disc is determined by means of a micrometer scale on the end of the member carrying the spiral thread. This arrangement permits of measuring R to within .002 inch.

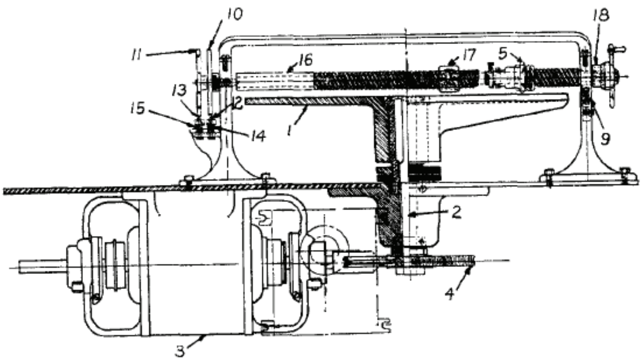
A factor that lends for accuracy in adjusting the friction wheel results from the fact that each signal echoes back and forth between the sea-bottom and surface several times. And, if the interval between signals is accurately adjusted for coincidence with any echo, the multiple echoes will all be coincident; while if the adjustment is not quite accurate, the multiple echoes will vary from coincidence two, three, or n times as much as does the first echo. This dispersive effect of the multiple echoes proves to be an aid in making an accurate adjustment for determining depth, whereas they prove to be a disturbing factor in case of Fessenden's method that has been described. It has been demonstrated in practice that the value of R can be determined to within two or three-thousandths of an inch and this results in measuring the time of sound transit to the sea-bottom and back to within one five-hundredth of a second.

The velocity of a sound in sea-water for moderate depths and average temperature is about 4800 feet per second. But the velocity (V), which can be accurately expressed as:

$$V = \frac{1}{\sqrt{\mu \bullet \rho}},$$

where μ is the adiabatic compressibility and ρ is the density, is evidently affected by both the temperature and pressure of the water and will, therefore, vary with the depth. The variation of the temperature of sea-water with the depth is not well known over most of the ocean areas, but it is well established that the temperature conditions below 1000 fathoms or even 500 fathoms do not vary greatly. Therefore, when the velocity is determined for depths beyond these values, the variation of depth, which alone is of value in determining submarine contours, can be determined to within an error represented by the distance that sound travels in sea-water in about one five-hundredth of a second or to within about ten feet. But since in determining depths the distance *S* that the sound travels in going from transmitter to receiver is divided by two, the error is also halved, and the depth variation will be determined to within about a fathom.

The variation in the velocity of sound, as it proceeds to greater depths, that is produced by increase in pressure, is in opposition to the variation produced by the change of temperature when, as usual, the temperature decreases with increasing depth. As a result the average value of 4800 feet per second for the velocity of sound gives sounding data accurate to within 1, or at most, 2 per cent. The determination of the velocity of sound in seawater under various conditions of temperature, pressure and salinity is being undertaken by the Navy and its solution will increase the absolute accuracy with which soundings can be taken by the echo method.



Practical design of sonic depth finder.

Figure 12

Fig. 12 shows the nature of a practical design of the automatic signalling key as developed at the Engineering Experiment Station, U. S. N., Annapolis, Maryland. A disc (1) twenty inches in diameter, carrying a vertical axis (2), is driven at a constant speed of one revolution. in ten seconds by means of a dynamotor (3) whose armature shaft carries a worm that engages in gear 4 which is keyed to axis 2 at its lower end. The speed of the dynamotor is kept constant to within a tenth of a per cent by means of a tuning-fork control for varying the load. The top of disc 1 is covered with canvas or other suitable material for forming a friction surface for driving friction-wheel 5. This wheel, which is two inches in diameter, engages with shaft 6 by means of a slot and spline arrangement such that member 5 can slide along member 6, but which causes both of these members to rotate in unison. The axis of shaft 6 is so mounted that it is parallel with the friction surface of the disc and intersects the axis of pinion 2 extended upward.

Shaft 6 is supported by self-aligning ball-bearings (7 and 8), the former of which is set in a groove such that it can slide a short distance up and down and thereby allow the pressure between members 1 and 5 to be adjusted by varying the tension on spring 9. It carries two cam-shaped discs near the end supported by bearing 8, one of which (10) carries a single saw-tooth-shaped depression and the other (11) carries ten such depressions uniformly spaced about its circumference. Two spring members, 12 and 13, bear against the two cam discs, respectively, and by snapping down into the depressions as the cams rotate, serve to operate the two pairs of contact points (14 and 15) in such a way as to temporarily close the alternating current circuit of a submarine sound oscillator transmitter. Arrangement is provided whereby either spring member can be made to operate against its respective cam, but which prevents both members from operating at the same time.

Member 16, which carries a spiral thread engaging in a nut in member 17, serves to move the friction wheel 5 along shaft 6 and measures the radius R of the circle that member 5 scribes on member 1 by means of a micrometer scale on cylinder 18. The smallest scale division represents one one-hundredth of an inch and readings can be estimated to tenths of a division.

The sounding equation,

$$S = 2D = \frac{a \bullet V \bullet P \bullet r}{C\left(R_2 - R_1\right)},$$

when applied to this design of key has the following values for the several constants:

V = 4800 feet per second.
P = 10 seconds.
r = 1 inch.
C = 1 or 10, depending upon which cam is used.

Inserting these values, we have for D the depth:

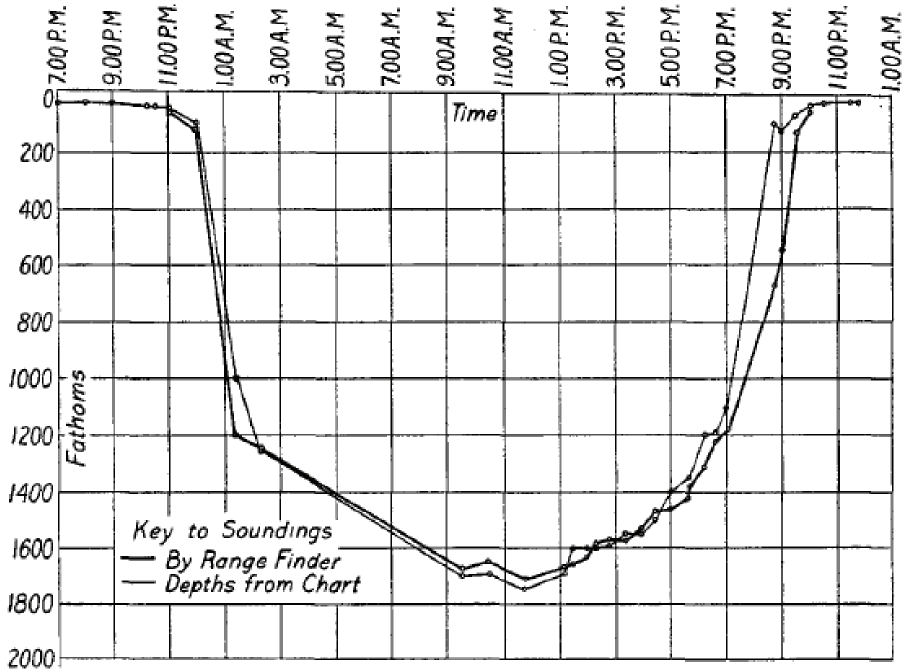
$$D = \frac{48000 \bullet a}{2C\left(R_2 - R_1\right)} \text{ feet}$$

or

$$D = \frac{4000 \bullet a}{C\left(R_2 - R_1\right)} \text{ fathoms,}$$

where, as before stated, a is the change in the number of signals in transit, brought about by varying the adjustment of the friction wheel through the radial distance (R_2 -R_1), and C is one or ten, depending on which cam-wheel is employed.

When both C and (R_2 -R_1) are given their greatest value, 10 in each case, it will be noticed that the device is then adjusted for measuring its most shallow depth, which is 40 fathoms. With this adjustment the time interval between successive signals is



Comparative sounding data. Sonic range finder, type 2. *U. S. S. Ohio* en route from New York to Annapolis, February 13-15.

Figure 13

one-tenth of a second and the value of *a* is one. Under such conditions each signal echoes back to the receiver at the instant the next successive signal is transmitted and the determination will be very accurate for the reason that the value ($R_2 - R_1$) will be large (ten inches) and any small error in determining this value will only introduce a small percentage error. But suppose a depth of 4000 fathoms were being measured. Then in order that an echo should reflect to the receiver at the same time the next successive signal is transmitted the time interval between successive signals would need to be ten seconds and the value of ($R_2 - R_1$) would be only one inch. Under such conditions the slight error made in measuring ($R_2 - R_1$) would result in ten times as much percentage error as in case of the shallow measurement. If, however, we send the signals ten times as fast, *i.e.*, once per second, then there would be ten echoes in transit and a would become ten and the value of ($R_2 - R_1$) would now become ten inches, the same as in case of the shallow depth measurement, with the same resulting error in our 4000-fathom sounding that was made in determining the shallow sounding. By choosing a proper value for a, the value of the measured factor ($R_2 - R_1$) can always be made large, and this results in reducing the experimental error.

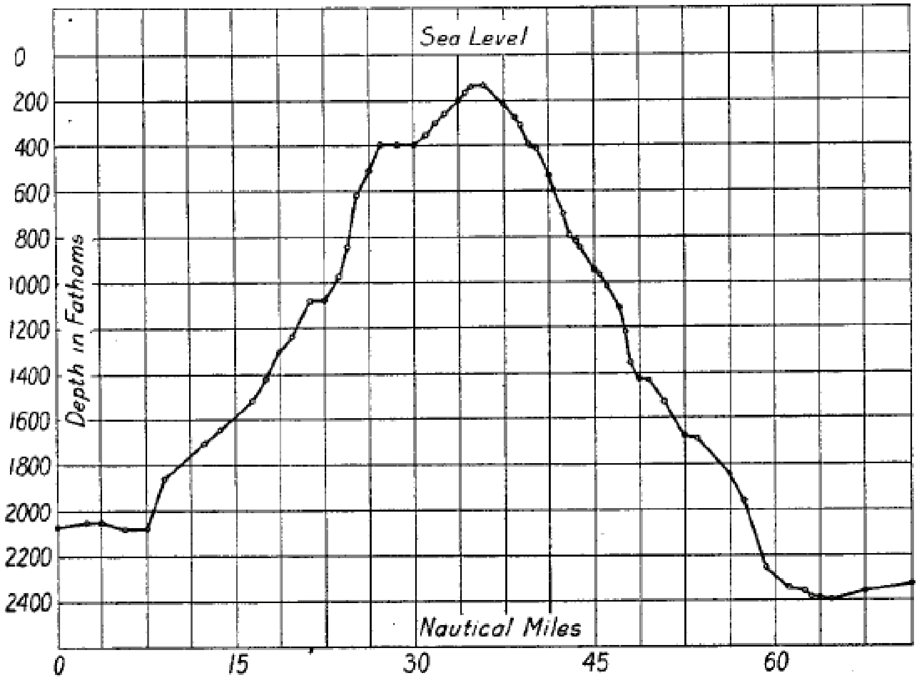
Some idea of the accuracy with which deep-sea soundings are determined by the "echo method" can be gained by referring to Fig. 13, wherein the heavy line curve gives the depth as determined by this method and the light line curve gives the corresponding charted depth over a course bearing southwest from the Ambrose Channel Light Ship to latitude 37 north and thence west to Cape Charles Light Ship. The charted depths in some instances represent interpellations between somewhat widely separated soundings on the chart. Nevertheless, the data included between 2: 00 A.M. and 6: 00 P.M. are over a fairly uniform sea-bottom and the charted values probably represent the true depth with considerable accuracy.

A line of soundings taken by the author on board the U. S. S. destroyer *Stewart* while she steamed from Newport, Rhode Island, to Gibraltar, Spain, at a steady speed of I5 knots, has demonstrated the ruggedness, ease and rapidity of operation, accuracy and dependability of the acoustical depth-sounding apparatus that has been described. The apparatus at no time failed to function properly and required no repairs or adjustments during the entire trip. The average time required to make a sounding was about one minute. Throughout the course soundings were taken at least every twenty minutes, and in regions where the depth varied somewhat rapidly they were taken at times as often as every minute.

These soundings determine the profile across the Atlantic along a great circle route from Newport to the Azores and from thence across the Josephine and Gettysburg Banks to Gibraltar.

This profile cannot be reproduced in its entirety, but some idea of the accuracy with which it represents the variations in depth can be gained by considering Fig. 14, which refers to the Gettysburg Bank along a section defined by the course of the *Stewart*. At the time this Bank was discovered by the U. S. S. *Gettysburg*, soundings showed the bottom to consist of sand and rounded pebbles. The profile of Fig. 14 gives evidence of old shore

FIG. 14.



Contour of the Gorringe or Gettysburg Bank. Soundings taken by *U. S. S. Stewar* June 28, 1922.

terraces at a depth of 400 fathoms, and it therefore appears probable that this region has been above sea-level at some remote age. During the months of October and November, 1922, the U. S. S. destroyers *Hull* and *Corey*, using the echo method, made a survey of the ocean floor along the California coast from San Francisco to Pt. Descanso from the hundred-fathom curve out to a depth of 2000 fathoms. The area covered was approximately 35,000 square miles and the work was accomplished in thirty-eight days. Over 5000 soundings were taken while the ships steamed steadily at twelve knots. There is no doubt but that these soundings, as assembled in chart form by the Hydrographic Bureau of the U. S. Navy, represent the contour of the sea-bottom with considerable accuracy even though the survey was made at the rate of about 1000 square miles per day. This survey has demonstrated beyond a doubt that the ocean beds can now be charted with a high degree of accuracy and that the survey work can be done with a speed and an economy of expense and effort that has heretofore been believed impossible.

The data represented by this chart furnish subject-matter for an extended paper and, therefore, cannot be covered at this time. It may be stated, however, that this region has been surveyed for the reason that seismographic records for the past ten years show that numerous earthquakes have had their origin within this area. It is proposed to re-survey this area after such records have shown that one or more earthquakes have had their origin herein. It is hoped that a comparison of the two charts will give some definite information regarding the movement of the earth's crust resulting from such disturbances. A comparison of the present chart with the older charted values shows discrepancies of hundreds and even thousands of fathoms in, some localities. It is uncertain whether these marked variations are due to errors made in the earlier surveys or to movements of the earth's crust resulting from the numerous earthquakes that have originated within this region since that time. It seems certain that repeated surveys of this and other unstable regions of the sea floor will furnish much valuable data relating to the movement of the earth's surface.

The application of the methods and apparatus for taking depth soundings that have been described are more numerous and valuable than one might at first suppose, as has become evident to the author through the many letters of inquiry that he has received.

Their value as an aid and safeguard to navigation has been repeatedly proved on various vessels of the U. S. Navy. And their value does not cease when a vessel steams into ocean depths for such survey work as has already been done shows that the deep-sea mountains and valleys will furnish numerous “landmarks” for determining the progress of a vessel, as soon as the main trade routes have been carefully charted. Moreover, the M V -hydrophone receiver, besides determining the direction of sound signals used for sounding purposes, will equally well determine the direction of such signals transmitted from other moving vessels or from light vessels placed at harbor entrances or at dangerous points along shore. In this way it serves to prevent collisions during conditions of low-visibility and to direct vessels safely into harbor or away from dangerous rocks and shoals. If all ships were equipped with the sound apparatus that has been described and would sound their submarine sound transmitter during fog, the navigator could then know the bearing of every vessel within, a radius of at least ten miles, in addition to knowing the depth of water underneath his own vessel. With such information at his disposal, the grounding of, or collision between, vessels could be absolutely avoided.

These sound devices will serve to make a cheap, quick and accurate survey of rivers and harbor entrances through which a channel is to be dredged, thereby furnishing accurate data for computing the amount of material that must be moved. They will also serve to determine the capacity of reservoirs with a minimum of effort and expense.

A study, during the flood period, of the beds of such rivers as the Yangste, the Mississippi and others that are wont to overflow and cause great loss of both lives and property, would doubtless furnish much valuable information for controlling such streams. The velocity of the water is usually so great that soundings cannot be made with the hand-lead, but by means of the "standing wave method" the beds of such rivers can be surveyed with great accuracy. Such surveys made at numerous sections of the stream should show over what portion erosion takes place and what is more important, should show where the sediment is being deposited. If erosion at the bottom of the stream becomes active when the velocity of flow exceeds a certain minimum value (as is believed by some engineers), and if it can be determined what this minimum velocity is, then it is quite possible that the proper method of controlling the stream will be to narrow its confines rather than to widen them or raise the dykes, for by so doing the required cross-section to carry the flow will be gained by deepening the stream through the process of erosion. The possibilities of the depth-sounding devices for use in this way are perhaps far greater than we can now appreciate.

The "echo method" of determining depths is not confined to determining submarine depths. It should serve equally well for determining the depth below the earth's surface of abrupt changes or discontinuities in, the earth's crust such as are offered by coal and oil deposits or subterranean caverns. These surfaces of discontinuity will reflect to the surface a part of any sound disturbance that may be transmitted to them. And though it may seem far-fetched, there is a possibility that the methods outlined may also be utilized for locating cracks and blow-holes in large castings.

The apparatus employed with the "echo method," which has been described as a means for determining the distance between two points in a uniform medium when the velocity of sound is known, serves equally well for determining the velocity of sound between two points in any medium when the distance they are separated is known. In, this connection this apparatus may serve to determine the velocity of sound through the rock formation of a mountain or between borings or workings in mining operations. And since the velocity so determined is equal to the square root of the elasticity of the formation divided by its density, this information may lead to the identification of valuable ore.

Of the above-named applications of the acoustical depth-finding devices that have been described, only two have been put to practical test. Their ability to aid and safeguard navigation during conditions of low visibility has been repeatedly demonstrated on ships of the Navy, and the survey of the sea floor off the California coast together with a more recent survey of a region off the entrance to the Panama Canal has proved that the sea floors can now be accurately and easily mapped. An idea of the value of these devices resulting from these two applications alone can perhaps be best conveyed by quoting from a prominent captain of the U. S. Navy, who states, “If it became necessary to dispense with the gyro compass or acoustical depth-finder on my ship, I should much prefer to keep the depth-finder apparatus,” and finally from one of our well-known geologists who says, “Now for the first time in, history the practicability of securing a map of the vast unknown area of the ocean floors is assured, with a promise of such a wealth of scientific data of prime importance as to make these developments of the U. S. Navy rank very high among those which have advanced our knowledge of the earth.”

Three Generations of Acoustic Research

Harvey C. Hayes' son and step-grandsons have continued his tradition of acoustic research.

His son Gordon B. Hayes, a self taught electronic engineer, followed his childhood interest in amateur radio and began his career working on the proximity fuse. Later he joined the Naval Research Laboratory, without his father's knowledge, and worked on identification friend-or–foe and radar beacon programs. Following World War II, he worked at the Naval Underwater Sound Laboratory in New London Connecticut, where he worked on torpedo countermeasures, the SQS 35, 36 and 38 operational sonar systems as well as acoustic environmental measurements. Gordon Hayes was granted a patent (3,140,462) on an RF based transducer that can operate as a hydrophone, microphone or pressure sensor, etc [1].

Bernard F. Cole, a step-grandson of Harvey C. Hayes, began his career in 1959 working under a Navy scholarship as a cooperative education student for the Underwater Sound Laboratory. Mr. Cole's early research consisted of defining those physical acoustic properties of the ocean bottom that most significantly influence bottom-reflected sound [2]. This led to a career of technical studies aimed at relating sonar propagation, reverberation and performance effects (in both deep and shallow waters) to environmental acoustic phenomena [3]. The notion for a sonar system that continuously characterizes its surrounding environment grew out of one such study [4]. Another study culminated in a recent article on a unique form of reverberation coherence that accompanies hull-mounted sonar operation in shallow water [5]. Mr. Cole retired from the New London Laboratory in 1995 and from a position at Planning Systems Incorporated in 2004. He currently performs research as an independent consultant.

James H. Cole, also a step-grandson of Harvey C. Hayes, began his career investigating acousto-optic imaging and optical detection of sound. He first proposed the use of fiber optic interferometers for acoustic detection in 1975 [6] and then demonstrated laboratory operation [7]. After joining the Naval Research Laboratory, he and his coworkers from the Acoustics and Optical Sciences Division demonstrated the first all fiber interferometer and the first fiber optic hydrophone to be field tested [8]. Fiber optic interferometric sensor technology has now been transitioned to the hull mounted arrays of the *Virginia* *(SSN-774)* class submarines [9], and is currently in engineering development for other operational systems. Mr. Cole has also developed fiber optic microphones and accelerometers [10]. He is now with the Optical Sciences Division of Naval Research Laboratory and is currently secretary of the Washington Academy of Sciences.

[1] US Patent 3,140,462 (July 7, 1964)
[2] B. F. Cole, “Marine Sediment Attenuation and Ocean-Bottom-Reflected Sound”, J. Acoust. Soc. Amer. V 38, pp. 291-297, (August 1965)
[3] B. F. Cole and E. M. Podeszwa, “Shallow-water bottom reverberation under downward refraction conditions”, J. Acoust. Soc. Amer. V 56, pp. 374-377, (August 1974)
[4] US Patent 5,568,450 (October 22, 1996)
[5] B. Cole, J. Davis, W. Leen, W. Powers and J. Hanrahan, “Coherent bottom reverberation: Modeling and comparisons with at-sea measurements”, J. Acoust. Soc. Amer. V116, pp. 1985-1994, (October 2004)
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[7] J.H. Cole, R.L. Johnson and P.G. Bhuta, “Fiber Optic Detection of Sound” J. Acoust., Soc. Amer. V 62, p. 1136, (November 1977)
[8] J. H. Cole and J. A. Bucaro, “Measured noise levels for a laboratory fiber interferometeric hydrophone,” J. Acoust. Soc. Amer., V. 67(6), pp. 2108-2109, (June 1980)
[9] James H. Cole, Clay Kirkendall, Anthony Dandridge, Gary Cogdell and T. G. Giallorenzi, “Twenty-five Years of Interferometric Fiber Optic Acoustic Sensors at Naval Research Laboratory”, J. Washington Academy of Sciences, V. 90(3), p. 40 (2004)
[10] US Patents 5,517,303 (May 14, 1996) ,5,012,088 (April 30,1991) and 5,094,534 (March 10, 1992)

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