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A Method for Determining the Location of Deep-Ocean Acoustic Sources

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ABSTRACT

A concept and method has been developed by which a vehicle can determine the location and acoustic source level of deeply submerged acoustic projectors. This concept was tested by using an acoustic source whose location and output level were known. A distribution of such known sources would provide a navigation system.

The method for locating the position of an unknown source is essentially the solution of triangulation equations by use of the time difference in the arrivals of the direct and surface reflected acoustic pulses. Usually three measurement stations are to be chosen in a triangular pattern with distances between the stations of at least 5 miles. An application of this method is feasible in concept as a passive ranging system in certain types of ASW situations.

PROBLEM STATUS

This is a complete report on one phase of the work relating to the Reliable Acoustic Path Problem.

AUTHORIZATION

NRL Problem S01-16
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A METHOD FOR DETERMINING THE LOCATION OF DEEP-OCEAN ACOUSTIC SOURCES

INTRODUCTION

It is expected that acoustic underwater navigating systems will become in the not too distant future an important means for submersibles to navigate the oceans. Such a navigating system might well be a number of beacons or transponders distributed on the ocean bottom. The determination of the location of such acoustic sources by the user will be one of the problems associated with underwater dead reckoning of vehicle position.

This paper presents a passive method by which the location of deeply submerged acoustic sources may be fixed. Further, it is feasible by this same technique to determine the range and depth of an unknown acoustic source by passive or active means. With a knowledge of the sound speed profile, it should also be possible to obtain with reasonable accuracy the acoustic output level of an acoustic source.

OBJECTIVE

One of the objectives of an April 1965 field trip south of Bermuda was to perform acoustic output measurements on a deeply submerged projector. Coupled with these measurements was to be an investigation of the possibility of determining the location and output level of an acoustic source when neither the location nor the output level of the source is known.

ACOUSTIC SOURCE INFORMATION

In this general area of the Atlantic Ocean there exists an excellent bottom-mounted acoustic source, the SNAP-7E beacon. The depth, location, and acoustic output of this source are sufficiently well known so that this source would more than suffice for the investigation being undertaken.

The SNAP-7E device is an acoustic beacon supported 2800 feet above the ocean floor in 15,800 feet of water. The power source for this beacon is obtained from heat generated by the decay of fissionable material. This heat drives a series of thermocouples, which provides the charging voltage to a bank of capacitors. At the time of emplantment the scroll-type magnetostrictive projector was reported to have an acoustic output level of 96 db re/μb/yd. The repetition rate of the 1750-cps signal was 59.7 seconds with a pulse length of 20 milliseconds.

TEST PROCEDURE

The geographical location of the beacon at the time of emplantment was established by loran C navigational fixes. On April 21, 1965, the NRL research ship Mizar was directed to take up a station about 6 miles from the beacon. After the ship had come to a full stop, a scroll-type magnetostrictive hydrophone, tuned for 1750 cps, was lowered

to a depth of 7200 feet. During the time that measurements were taken, the ship drifted with the wind. The wind velocity was practically constant throughout the day, varying in speed between 10 to 12 knots and in direction from 160° to 170° true. Figure 1 is a plot of the ship's track for this experiment. A well developed sea of state 1 to 2, with no swells, prevailed. The sea water temperature 15 feet below the surface was 62°F.

In order to determine the output level of a remote acoustic source it was considered necessary to (a) establish the geographical locations of the receiving hydrophone, and (b) make the distance of the hydrophone from the source sufficiently great that an error of 1 mile in range affects the received level by less than 1 db. Condition (a) can be satisfied by use of the ship's loran A navigational system, which is generally considered to have an accuracy of about 1 mile in this area. Condition (b) can be satisified by placing the hydrophone at least 50,000 feet from the projector. The error due to the lack of precision of the loran A equipment can be compensated by meeting this second condition. The 1-db value was selected as an acceptable data measurement tolerance for the receiving systems.

The test procedure involved taking acoustic measurements of the acoustic beacon pulses at several stations which were to be in-line and at known distances apart. It was planned to ascertain the output level of the beacon by extrapolating from the transmission loss between stations.

Measurements of the acoustic beacon signals were made at three stations established by the ship's loran A equipment. The first station was reported as being 6-1/2 miles from the acoustic source, the second 13-1/2 miles, and the third 18 miles. The three stations were in line and on a true bearing of 145° ± 5° to the acoustic source. The maximum depth of the receiving hydrophone at Station 1 was 7200 feet, at Station 2 – 4800 feet; and at Station 3 – 2200 feet. Based on the geographical fixes provided by the ship's navigator, these selected depths placed the hydrophone 5° to 10° above the horizontal axis of the

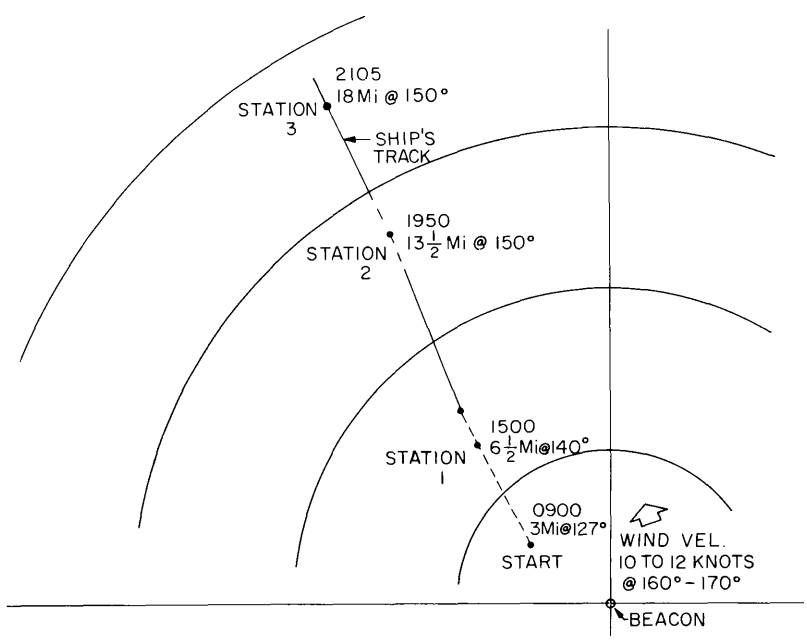


Fig. 1 - Ship's bearing and distances relative to the SNAP-7E beacon during the test with a known acoustic source. (The circular arcs are at 5-mile intervals.)

acoustic beacon. It was desired to maintain the same acoustic axial relationship between hydrophone and projector in order to obviate some of the errors due to nonuniform beam-pattern characteristics. The depth of the hydrophone was taken as being the length of cable payed out, since in the drifting mode of the ship the hydrophone cable hung almost vertically. Acoustic signal reception was excellent at all three stations. The receiver background noise level of -140 db re 1 volt was 40 to 60 db below the signal level.

The received signals from the SNAP beacon were recorded on a light-beam-type recorder which was operated at a paper-feed rate of 25 inches per second. In order to conserve paper, the Brush recorder was remotely controlled by programmed counters which started the recorder about 1/2 second before the gated acoustic signal arrived and stopped the recorder 1 second after the gated signal arrived. The repetition rate of the source signal was measured to be 59.4 seconds. This start and stop, or gated, mode of recorder operation conserved 120 feet of recorder paper every minute. The type of light sensitive paper used must be developed by further exposure to light in order that the recorded tracings can be distinguished. The development time is only a matter of seconds under exposure to a fluorescent light.

As often happens, serendipity plays a helpful role in research. In this experiment, the keystone to the problem of obtaining the range between the projector and the hydrophone was gratuitously provided through the excellent reception of two pulses every minute instead of only one.

The utility of this second pulse was not immediately recognized or considered, since only the direct pulse was planned for in our experiment. However, after ascertaining that the second pulse was the surface reflected ray, the possibility of its usefulness was explored. Data and information for this surface reflected pulse with all its necessary angular relationships were available. A determination of the straight path lengths for the two pulses gave the solution of the unknown range between projector and receiving hydrophone.

Figure 2 shows the geometric relations of the specular reflection configuration. In this figure, the known quantities are the depth of the beacon (D), the depth of the receiving hydrophone (d_1), and the time difference between arrivals of the direct and surface reflected pulses. The unknown quantity is the slant range between the projector and the hydrophone. The point Q is the image of the point P. Distance $MNP = MNQ$. If we let $MP = X_1$, $MNQ = X_2$, $ML = R$ and $d_2 = (D - d_1)$, we can write

$$X_2^2 = R^2 + (D + d_1)^2, \tag{1}$$

$$X_1^2 = R^2 + (D - d_1)^2, \tag{2}$$

$$X_2 = X_1 + \bar{c}\Delta t = X_1 + K_1, \tag{3}$$

where $\bar{c}$ is the harmonic average speed of sound and Δt is the difference in time between the direct and reflected pulse arrivals. Subtraction of Eq. (2) from Eq. (1) yields

$$X_2^2 - X_1^2 = 4Dd_1, \tag{4}$$

which, after substitution of Eq. (3) for X_2, becomes

$$(X_1 + K_1)^2 - X_1^2 = 4Dd_1 \tag{5}$$

or

$$X_1 = \frac{4Dd_1 - K_1^2}{2K_1}. \tag{6}$$

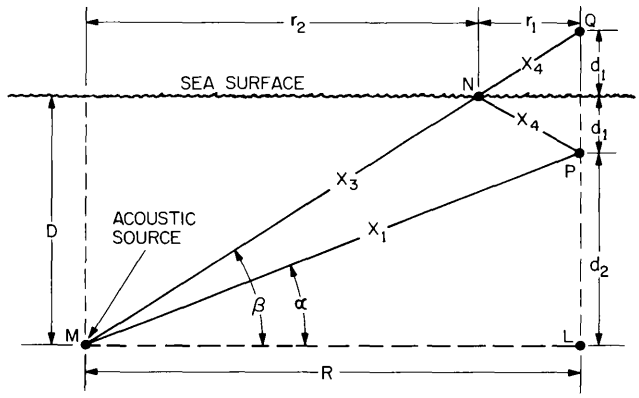


Fig. 2 - Geometry of specular reflection to the hydrophone at depth d_1. The direct path length is X_1, while the reflected path length is $X_2 = X_3 + X_4$.

From Eqs. (6) and (3) the values for the length of the direct and reflected straight line paths between the projector and the hydrophone were calculated.

Evaluating the angular relations depicted in Fig. 2 showed that the hydrophone had been 10°15' above the horizontal plane of the beacon at Station 1, 5°54' above at Station 2, and 5°9" above at Station 3. At all stations the navigational fix given by the ship's navigator was within the assumed accuracy tolerance of the loran A equipment. Table 1 is a compilation of the data pertinent to the three stations.

Table 1
Field Data and Path Lengths

Station	Hydrophone Depth (ft)	Direct Ray			Reflected Ray			Time Difference Between Pulses (msec)
		Length (yd)	Signal Level (db/v)	Sound Speed (ft/sec)	Length (yd)	Signal Level (db/v)	Sound Speed (ft/sec)	
1	7200	10,748	-71.2	4952.6	12,535	-73.5	4955.8	1083.0
2	4800	26,610	-82.0	4952.5	27,135	-83.2	4956.5	312.5
3	2200	40,095	-80.1	4948.3	40,253	-84.0	4960.2	95.8

The calculated values for the ranges between the acoustic source and the three stations shown in Table 2 assumed straight-line propagation. This assumption is, of course, incorrect. The angle formed by the horizontal and a line between the projector and hydrophone at Station 3 was calculated to have been an "up" angle of 5°9'. At this range and existing sound speed profile, the refracted ray actually left the projector at a downward angle of about 4°. The length of the refracted acoustic path between the beacon and hydrophone at Station 3 was determined. For this calculation, the depth profile of the ocean was divided into five layers. These layers were: surface to 1000 feet, 1000 feet to 2000 feet, 2000 feet to 4000 feet, 4000 feet to 5200 feet, and 5200 feet to 13,000 feet. Within each of these layers the sound speed gradient was linearized (Fig. 3). The calculated length of the refracted acoustic path was 35,634 yards, while the straight-line

Table 2
Acoustic Transmission Loss ($N_w = N_{ws} + \alpha R$ db/μb) from the Source to Each Station Assuming a Direct, Straight-Line Path

Path	Distance (yd)	Transmission Loss (N_w)		Attenuation, Calculated (αR) *	Spreading Loss (N_{ws})		
		Calc.	Meas.		Calc.	Meas.	Diff.
Source to Station 1	10,748	-83.4	-78.2	-2.83	-80.57	-75.37	5.2
Source to Station 2	26,610	-95.5	-88.8	-7.07	-88.43	-81.73	6.7
Source to Station 3	40,095	-102.5	-86.9	-10.64	-91.86	-76.26	15.6
		Differences Between Paths					
Sta. 1 to Sta. 2 (15,360 yd)		-12.1	-10.8	-4.24	-7.86	-6.56	1.3
Sta. 2 to Sta. 3 (13,485 yd)		-7.0	+1.9	-3.57	-3.43	+5.47	8.9
Sta. 1 to Sta. 3 (29,350 yd)		-19.1	-8.9	-7.81	-11.29	-1.09	10.2

* $\alpha R = (0.15f - 0.0015f^2)R$.

path length between these same end points was 35,541 yards. For the shorter ranges this difference would be less.

The distance between the acoustic beacon and the hydrophone for each of the three stations having been determined, the next step was to establish the acoustic output level of the beacon. Table 2 and Table 3 show two values for the transmission and spreading losses occurring between beacon and hydrophone for each station as well as the losses occurring between stations. One set of values was computed from the formula,

$$N_w = 60 + 20 \log R + (0.15f - 0.0015f^2)R.$$

The second set of values was arrived at indirectly.

TEST RESULTS

From the data recorded aboard ship, and assuming spherical spreading, the acoustic output level of the beacon was calculated to be greater than its design output level (Table 3). The value of the transmission loss between the beacon and Station 1 was indirectly obtained by subtracting the receiving system level from the beacon's design output level. Using this value as a point of orientation, the losses between the beacon and the other two stations were obtained by applying the differences of the received signal levels measured at the three stations to this point of orientation. The attenuation loss was subtracted from its respective transmission loss, giving the spreading loss to each station. These spreading loss values are tabulated under the column heading indicated as "measured" in Table 2. The differences between the calculated values for spherical spreading and the "measured"

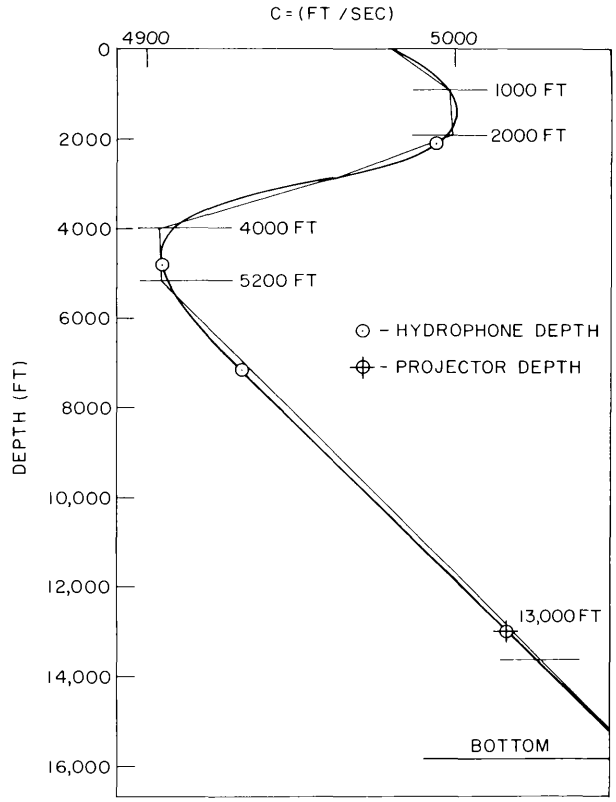


Fig. 3 - Depth profile of sound speed and the linearization of this profile in each of five segments. These values were taken from "Sound Velocity Profiles in an Area South of Bermuda," L. M. Jones and W. A. Von Winkle, Underwater Sound Laboratory Report 632, May 3, 1965.

values are shown in the last column of Table 2. These values represent the signal enhancement due to convergence of the sound pressure.

Spreading loss values were plotted for both modes of calculation. Figure 4 shows curves for $15 \log R$ and $20 \log R$. A curve passing through the spreading loss values for Stations 2 and 3 was faired into the $15 \log R$ curve; this segment of the curve is of the form $15 \log R_1^2/500$. The range R_1 is in kiloyards and for this segment of the curves takes on values between 22.5 and 40. For the particular measurements made at the three stations the spreading loss is determinable by the formula

$$N_{ws} = 60 + 15 (\log R - \log R_1^2/500).$$

It is to be understood that this formula applies only to these particular measurements.

Table 3
Acoustic Output Level of the Beacon

Station	Range to Source (yd)	Received Signal Level (db/v)	Cable Gain (db/v)	Hydrophone Sensitivity (db/μb/v)	Transmission Loss (N_w) (db/μb)			Source Level (db/μb/yd)	
					N_{ws}	aR	N_w	When Installed	Calc.
1	10,748	-71.2	+3.8	-93	80.57* 75.39†	2.83	83.4 78.2	96	101.4 96.2
2	26,610	-82.0	+3.8	-93	88.43* 79.13†	7.07	95.5 86.2	96	102.7 98.6
3	40,095	-80.1	+3.8	-93	91.86* 76.46†	10.64	102.5 87.1	96	111.6 96.2

*$N_{ws} = 60 + 20 \log R$.
†$N_{ws} = 60 + 15 (\log R - \log R_1^2/500)$, where $45 > R > 1.0$ kyd and $45 > R_1 > 22.5$ kyd.

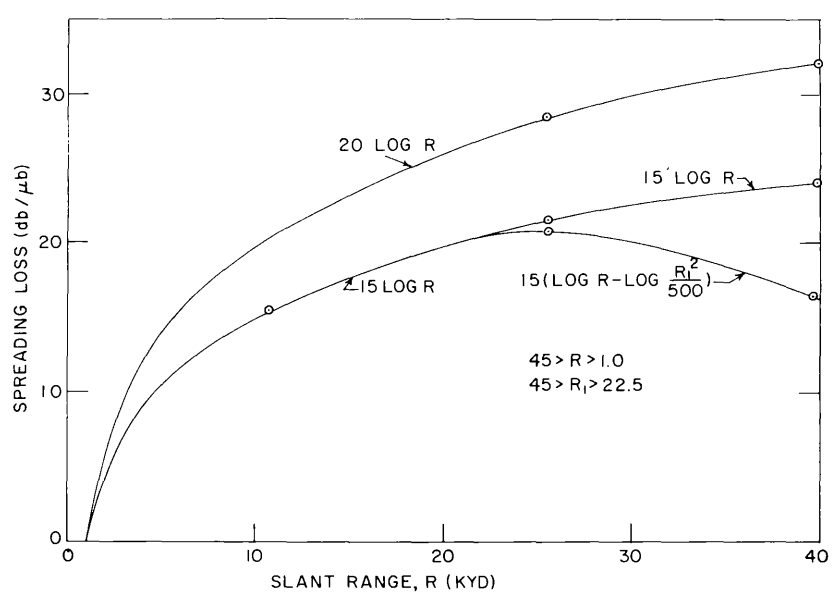


Fig. 4 - Effect of the mode of calculation on the spreading loss values

GENERAL APPLICATION OF THE METHOD

While this experiment dealt with a source of known characteristics, the more important consideration is whether an unknown source can be located and evaluated. The following description outlines how this can be done. The method for locating an unknown acoustic source is essentially one of triangulation; hence the three stations from which measurements are to be made must not be in line. The triangular pattern formed by the stations should have sides that are at least 5 miles long. The relative position for the third station should be selected after the measurements from the second station have been analyzed.

The distance and bearing between stations, which are obtained from the ship's navigational equipment, can be ascertained from acoustic data recorded at the three stations. Depth and range to the location of the unknown source can be independently established at each of the three stations. The distance between stations can also be verified acoustically.

The depth of and the range to an unknown acoustic source may be determined by two sets of measurements of the time difference between the arrivals of the direct and the surface reflected pulses. With one additional set of measurements at each of the other two stations, the location of the acoustic source can be fixed (Fig. 5). Where the two sets of measurements are made at any one station, the hydrophone must, of course, be at different depths. If both range and depth is desired at each of the stations, a minimum of two sets of measurements are needed at each station.

The Appendix shows the steps used to develop the general equation for the solutions of range and depth to an acoustic source. The depth at which the receiving hydrophone is placed does not affect the determination of range or depth of the source. The calculation of the acoustic source level, however, requires a knowledge of the beam pattern of the source. The vertical beam pattern of the source can be arrived at by probing with the hydrophone. If the beam pattern of the projector can be reasonably established, the measuring hydrophone depths should be selected so as to be coincident with the acoustic beam axis at each of the stations. This depth selection should facilitate calculation of the transmission loss between projector and receiver.

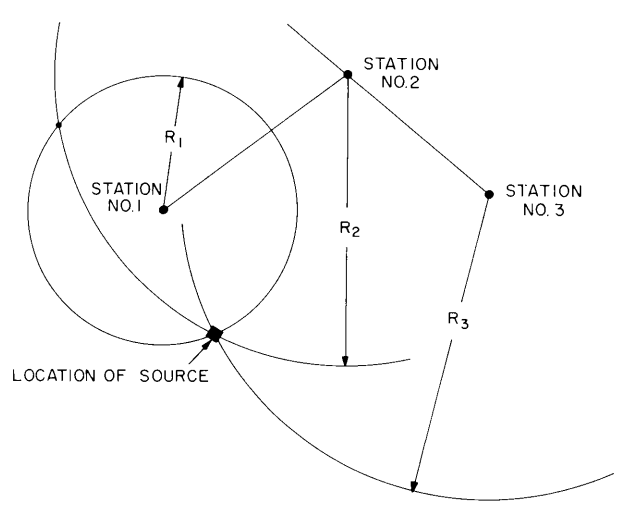
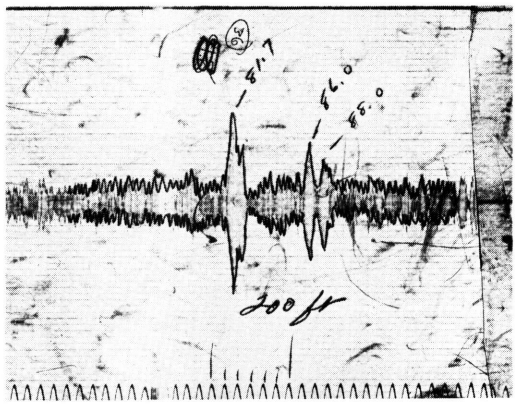


Fig. 5 - Geometry of locating a point in space by triangulation (intersection of 3 spheres)

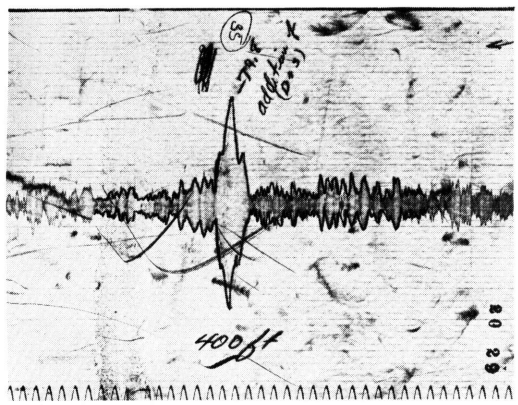
Oscillograms of the recorded acoustic signals taken at the three stations are shown in Fig. 6. The depth at which the hydrophone was placed is indicated for each oscillogram. Oscillogram (e) is of interest in that it shows the direct, the surface reflected, and the bottom reflected signals for one of the transmitted pulses. As can be seen, there is very little deterioration of the signal due to a boundary reflection–whether surface or bottom.

CONCLUDING REMARKS

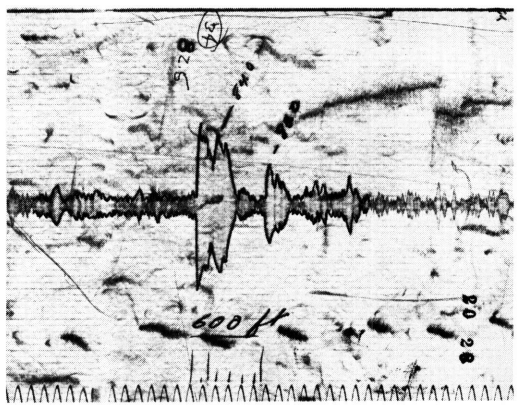
The data obtained for this experiment were limited to one acoustic source and measured during one field trip only. The equipment used for measuring the arrival time of the pulses was rather crude. It was not intended that precision type data be obtained–only that the data be sufficiently accurate to evaluate the concept. Based on the results obtained the described method of determining the range, depth, and location of an acoustic source is considered feasible for such applications as navigation systems in the case of known sources. This method may have merit in its ASW implications. While there is much to be desired in the described method with regard to obtaining the acoustic source level of an unknown projector, the data obtained indicate that the method holds good promise of applicability.



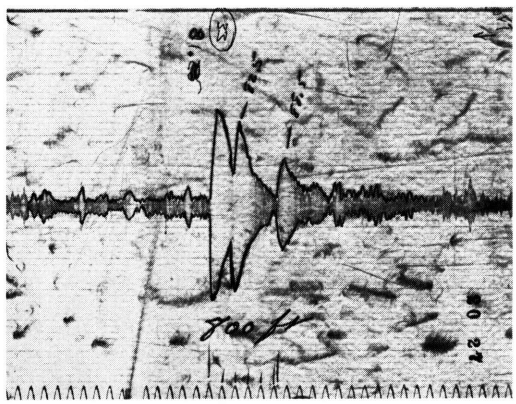
(a) Receiver 200 ft deep
40,000 yd from the source



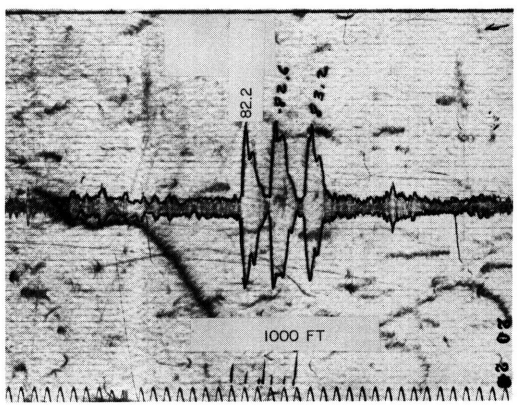
(b) Receiver 400 ft deep
40,000 yd from the source



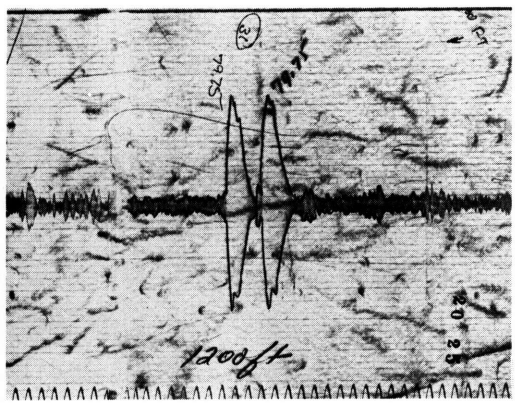
(c) Receiver 600 ft deep
40,000 yd from the source



(d) Receiver 800 ft deep
40,000 yd from the source

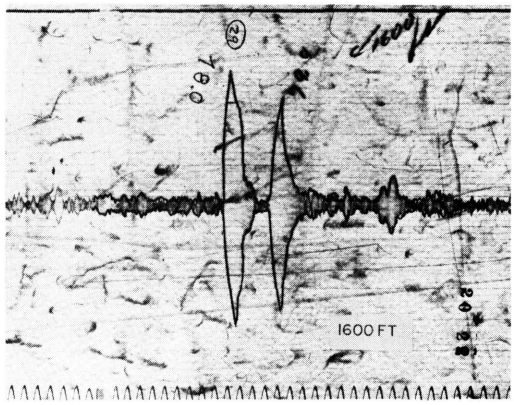


(e) Receiver 1000 ft deep
40,000 yd from the source

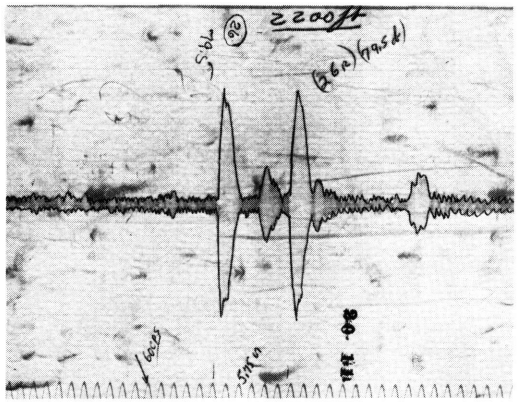


(f) Receiver 1200 ft deep
40,000 yd from the source

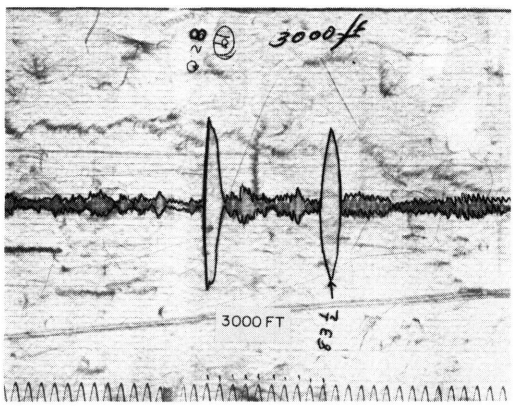
Fig. 6 - Oscillograms of (from left to right in each oscillogram) the direct, surface reflected, and (if present) bottom reflected pulses (figure continues on the next page)



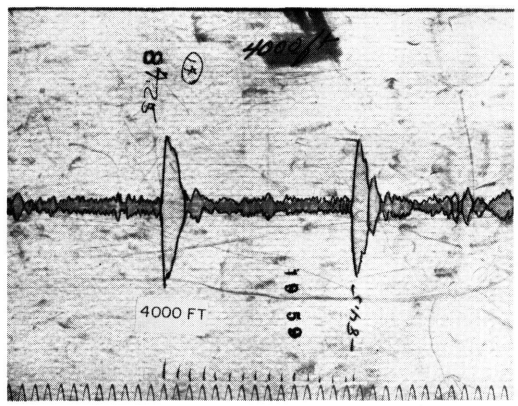
(g) Receiver 1600 ft deep
40,000 yd from the source



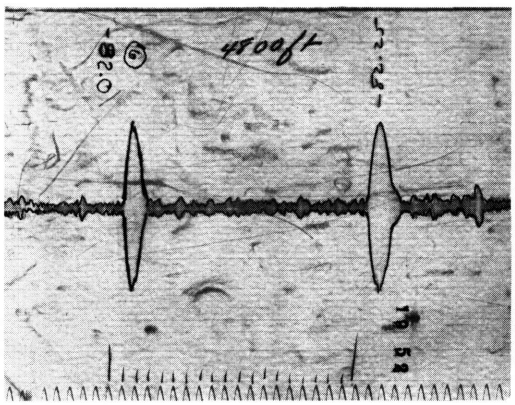
(h) Receiver 2200 ft deep
40,000 yd from the source



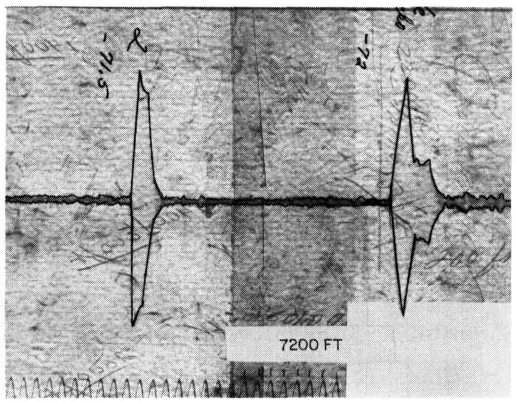
(i) Receiver 3000 ft deep
26,600 yd from the source



(j) Receiver 4000 ft deep
26,600 yd from the source



(k) Receiver 4800 ft deep
26,600 yd from the source



(l) Receiver 7200 ft deep
10,700 yd from the source

Fig. 6 (continued) - Oscillograms of the direct and reflected pulses

Appendix

DEVELOPMENT OF THE GENERAL EQUATION FOR RANGE AND DEPTH TO AN ACOUSTIC SOURCE

The geometric relations shown in Fig. A1 are used to develop the equations for the range and depth of an acoustic source whose location is unknown. The depths of the receiving hydrophone are d_1 and d_{11}, and the time differences between arrival of the direct and surface reflected signals for d_1 and d_{11} are Δt_1 and Δt_{11}. From Fig. A1, and letting

$$\bar{c} = \text{harmonic average speed of sound}$$

$$X_2 = X_3 + X_4$$

the following equations may be written:

$$R^2 + (D + d_1)^2 = X_2^2, \tag{A1}$$

$$R^2 + (D - d_1)^2 = X_1^2, \tag{A2}$$

$$X_2 = X_1 + \bar{c}\Delta t_1 = X_1 + K_1. \tag{A3}$$

Subtracting (A2) from (A1) yields

$$X_2^2 - X_1^2 = (D + d_1)^2 - (D - d_1)^2, \tag{A4}$$

and squaring (A3) yields

$$X_2^2 - X_1^2 = K_1^2 + 2X_1K_1. \tag{A5}$$

From (A4) and (A5)

$$(D + d_1)^2 - (D - d_1)^2 = K_1^2 + 2X_1K_1, \tag{A6}$$

which after expansion may be rewritten as

$$X_1 = \frac{2d_1 D}{K_1} - \frac{K_1}{2}. \tag{A7}$$

or

$$X_1^2 = \frac{4d_1^2 D^2}{K_1^2} - 2d_1D + \frac{K_1^2}{4}. \tag{A8}$$

Substituting (A8) into (A2) and rearranging gives

$$R^2 = \left(\frac{4d_1^2 - K_1^2}{K_1^2}\right) D^2 - \left(\frac{4d_1^2 - K_1^2}{4}\right). \tag{A9}$$

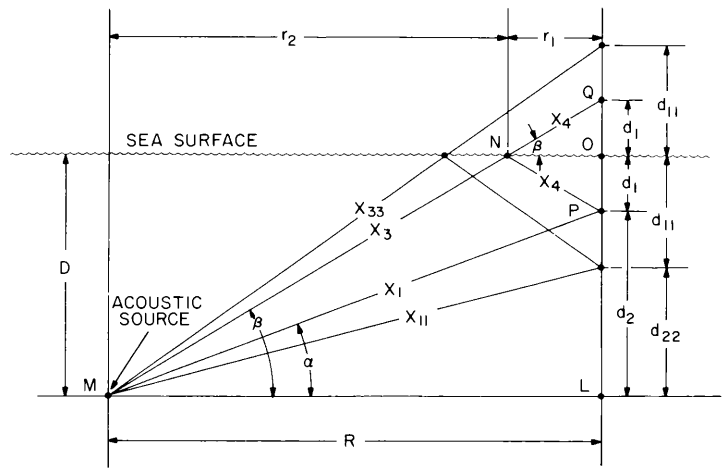


Fig. A1 - Geometry of transmission from a source to a hydrophone at two depths

Letting

$$L_1^2 = 4d_1^2 - K_1^2$$

and multiplying Eq. (A9) by $1/L_1^2$ permits Eq. (A9) to be written as

$$\frac{R^2}{L_1^2} - \frac{D^2}{K_1^2} = -1/4. \tag{A10}$$

Furthermore, letting

$$A_1^2 = K_1^2/4$$

and

$$B_1^2 = L_1^2/4$$

permits the equation to be written as

$$\frac{D^2}{A_1^2} - \frac{R^2}{B_1^2} = 1. \tag{A11}$$

When at the same station the hydrophone is placed at the second depth, d_{11}, the new time difference Δt_{11} is obtained and the following equation may be written:

$$\frac{D^2}{A_{11}^2} - \frac{R^2}{B_{11}^2} = 1. \tag{A12}$$

The simultaneous solution of Eqs. (A11) and (A12) will give the range and depth of the acoustic source from the receiving hydrophone.

Taking similar readings at two other stations and obtaining new values for R and D will fix the location of the source (see Fig. 5).

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Security Classification

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13. ABSTRACT

A concept and method has been developed by which a vehicle can determine the location and acoustic source level of deeply submerged acoustic projectors. This concept was tested by using an acoustic source whose location and output level were known. A distribution of such known sources would provide a navigation system.

The method for locating the position of an unknown source is essentially the solution of triangulation equations by use of the time difference in the arrivals of the direct and surface reflected acoustic pulses. Usually three measurement stations are to be chosen in a triangular pattern with distances between the stations of at least 5 miles. An application of this method is feasible in concept as a passive ranging system in certain types of ASW situations.

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Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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