NRL Report 6320

Mean Horizontal Sound Speeds to the First Convergence Zone in November

J. Cybulski

Electrical Applications Branch
Sound Division

December 9, 1965

U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
EXPERIMENTAL PROCEDURE	1
Data Stations	1
Environmental Conditions	5
RESULTS	5
Experimental	5
Analytical	7
REFERENCES	26
APPENDIX A - Calibration of Range and Travel Time Instrumentation	27
APPENDIX B - Horizontal Range and Travel Time Corrections	29
APPENDIX C - Treatment of Data to Obtain Mean Horizontal Sound Speed	32

ABSTRACT

Data on underwater one-way acoustic propagation times were collected during five traverses of the first convergence zone in the deep waters north of Puerto Rico. This data was obtained on three consecutive days in November 1958 by equipment located aboard two ships. The source ship utilized an acoustic transducer, transmitting 500-msec pulses at 1090 Hz, at depths of 20, 100, and 300 ft, and the receiving ship utilized a hydrophone at depths from 20 to 420 ft. The horizontal range between the ships varied from 68 to 79 kiloyards.

The values of sound speed obtained at all depths ranged from 1639 to 1647 yd/sec, increasing from the start to the end of the convergence zone. There was a significant change in the variability of sound speed values from one day to the next. Variations in the sound travel time measurements were least at the 420-ft depth.

The mean horizontal sound speed derived from the measured data was compared with values computed from an exact ray trace solution and also from an approximation utilized in the correction of sonar data. There is a general correspondence between these calculations and experimental data within the first convergence zone.

PROBLEM STATUS

This is an interim report on the problem; work is continuing.

AUTHORIZATION

NRL Problem S01-15
Projects SF 001-03-15-8133, and
RF 101-03-44-4064

Manuscript submitted July 6, 1965.

MEAN HORIZONTAL SOUND SPEEDS TO THE FIRST CONVERGENCE ZONE IN NOVEMBER

INTRODUCTION

Initial measurements were made in March 1958 (1,2) to obtain accurate sets of horizontal range and elapsed acoustic travel times for propagation paths out to the first convergence zone. Results of a more nearly complete coverage of this zone for the same deep waters (19°20'N latitude, 66°10'W longitude) north of Puerto Rico were obtained during the November 2-13, 1958, field trip are reported herein.

In the conduct of these experiments, primary instrumentation is utilized for an independent range measurement and the elapsed one-way travel time. The USS ROCKVILLE (EPCER 851) was the source ship, lying to, transmitting 500-msec pulses at 1090 Hz from an acoustic transducer. The USS SOMERSWORTH (EPCER 849) was the receiving ship, using a hydrophone to 420-ft depths at specified ranges provided by shoran distance-measuring equipment. The shoran equipment was operated in the hiran (high-range accuracy) mode by gain riding. Improvements in antenna and cables resulted in an overall gain for the range measurement equipment of 18 db above the March trip. Details on the calibration of the range and travel time instrumentation are given in Appendix A.

Oceanographic conditions were read by conventional bathythermographs (BT's) to a depth of 900 ft from both ships, while the deeper water was sampled by Nansen bottle casts taken from the ROCKVILLE.

EXPERIMENTAL PROCEDURE

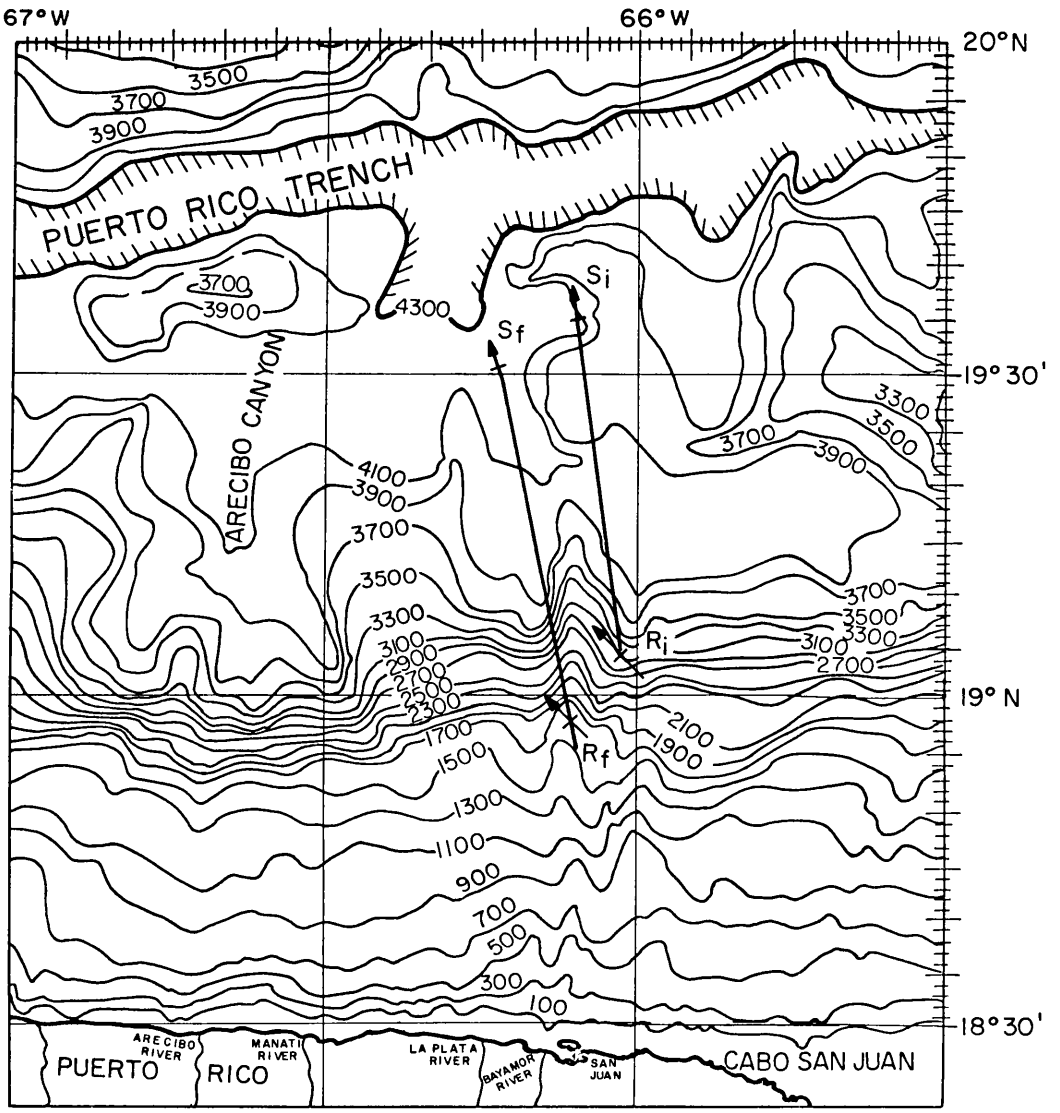
Data Stations

11 November – With the transducer in a well-defined surface channel, three separate traverses of the first convergence zone were made as rapidly as possible by lowering the hydrophone to take data at only one depth on each traverse: 20, 220, and 420 ft, successively.

12 November – With the transducer below the surface channel, a single traverse of the first convergence zone was made in more detail by lowering the hydrophone to take data in 100-ft increments between the 20- and 420-ft depths.

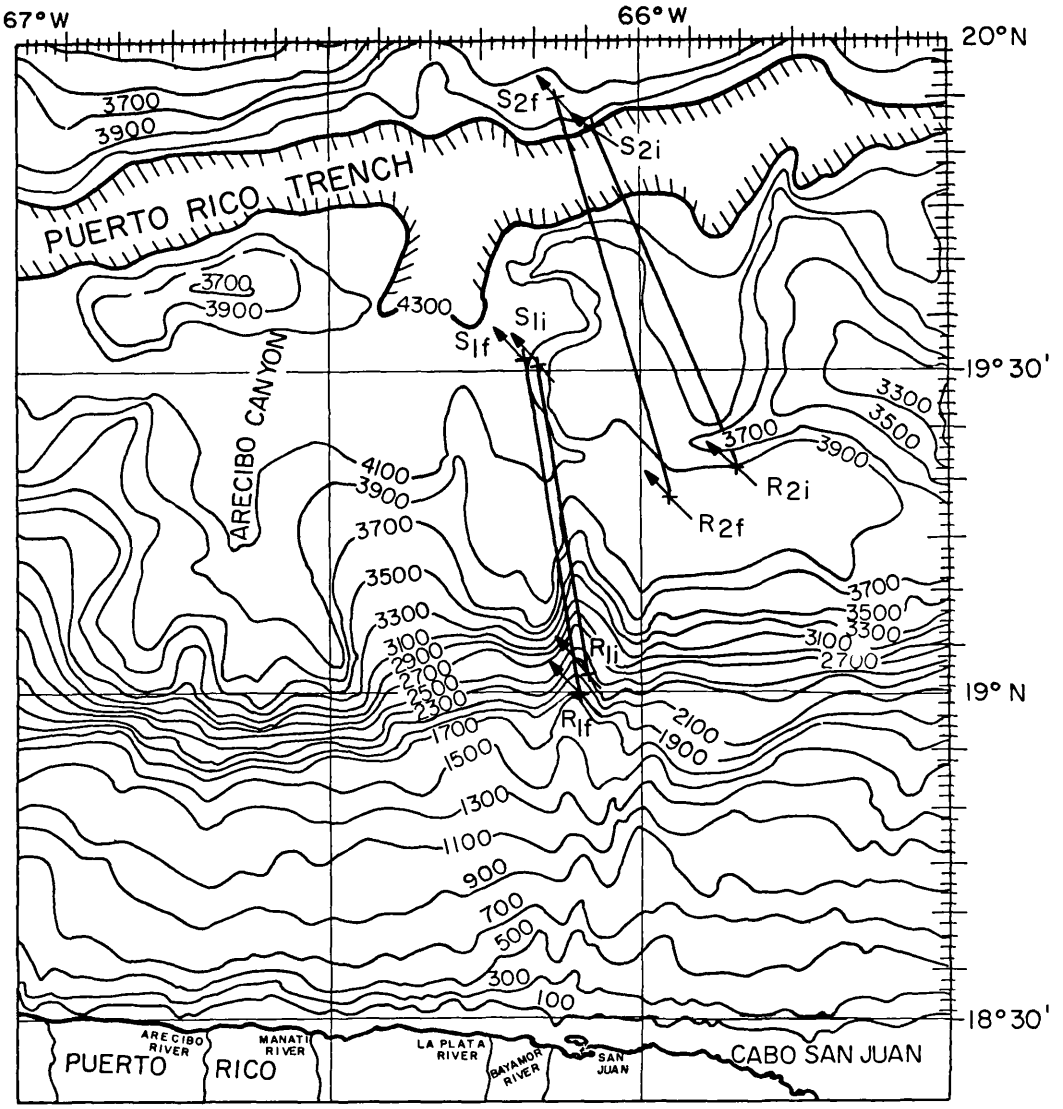
13 November – A single traverse of the first convergence zone was made in greater detail with the source close to the surface and with the hydrophone lowered to take data in 50-ft increments between the 20- and 420-ft depths.

Location – The geographical location of the ships and the ocean bottom topography are illustrated by Figs. 1(a)-(c), respectively, for the November 11-13 operations. Only the initial and final positions of the ship for each day are identified, except on November 12 when a relocation was necessary to prevent possible bottom cutoff of the transmissions from the ROCKVILLE.



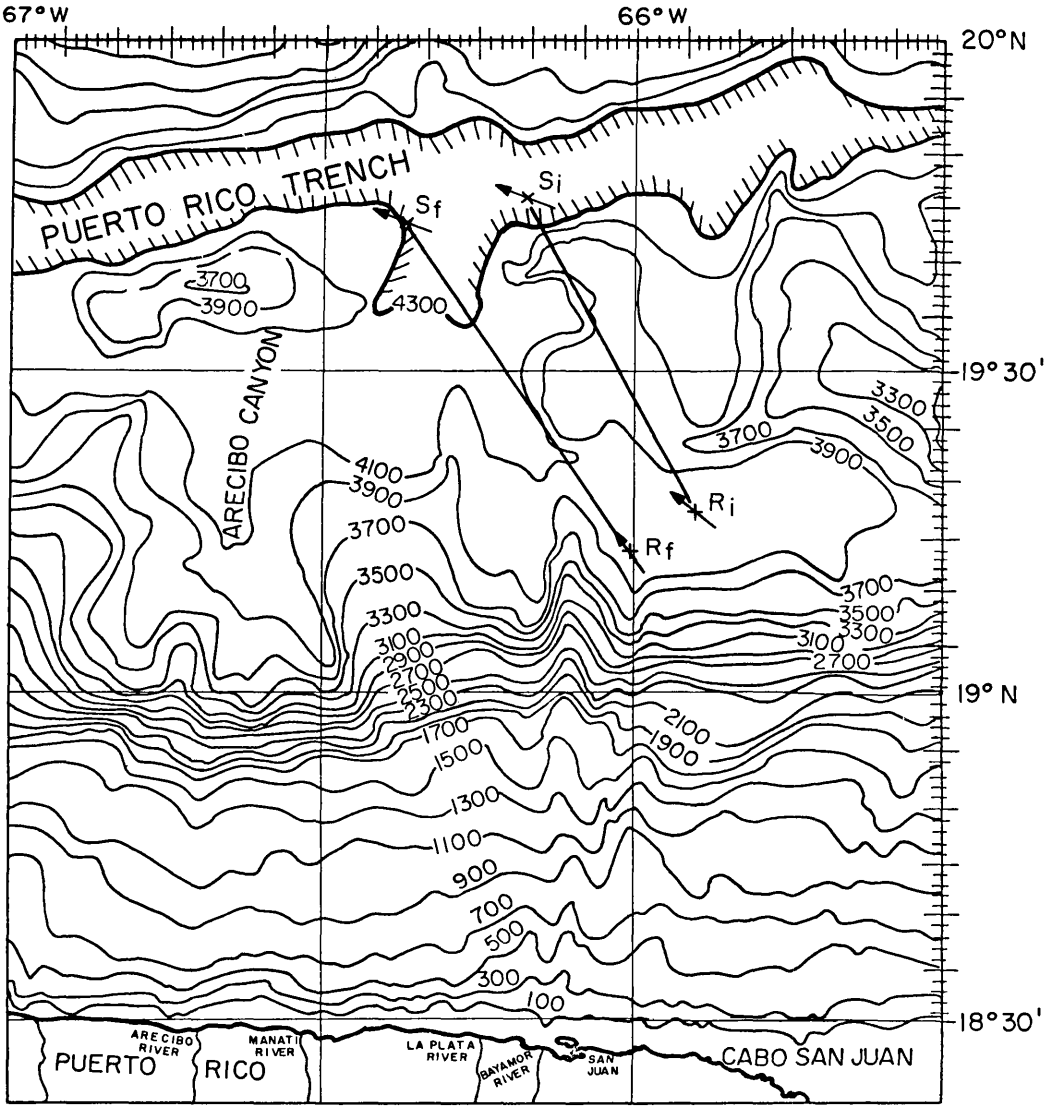
(a)

Fig. 1 - Mercator projection charts showing the initial and final positions of the source ship S (the USS ROCKVILLE) and the receiving ship R (the USS SOMERSWORTH). The source ship utilized an acoustic transducer as the source of acoustic energy; the receiving ship utilized a hydrophone. Measurements of the mean horizontal sound speeds to the first convergence zone were made from these ships in the deep waters north of Puerto Rico. The (average) initial and final headings for each ship are indicated by the short arrowheads for the days of (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13, 1958.



(b)

Fig. 1 (cont'd) - Mercator projection charts showing the initial and final positions of the source ship S (the USS ROCKVILLE) and the receiving ship R (the USS SOMERSWORTH). The source ship utilized an acoustic transducer as the source of acoustic energy; the receiving ship utilized a hydrophone. Measurements of the mean horizontal sound speeds to the first convergence zone were made from these ships in the deep waters north of Puerto Rico. The (average) initial and final headings for each ship are indicated by the short arrowheads for the days of (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13, 1958.



(c)

Fig. 1 (cont'd) - Mercator projection charts showing the initial and final positions of the source ship S (the USS ROCKVILLE) and the receiving ship R (the USS SOMERSWORTH). The source ship utilized an acoustic transducer as the source of acoustic energy; the receiving ship utilized a hydrophone. Measurements of the mean horizontal sound speeds to the first convergence zone were made from these ships in the deep waters north of Puerto Rico. The (average) initial and final headings for each ship are indicated by the short arrowheads for the days of (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13, 1958.

Environmental Conditions

Time-series plots of the BT's taken from each ship are shown in Figs. 2(a)-(c), corresponding to November 11-13, respectively. All plots indicate a well-mixed surface isothermal layer with some trends of temporal and spatial changes, in particular the deepening layer of Fig. 2(c). To compare this BT data for three time periods corresponding to morning, early afternoon, and late afternoon, an average was computed for each 100-ft depth and is plotted in Figs. 3(a)-(c), respectively, for November 11-13. The point O in the lower left corner of each figure represents the average of the temperatures at a depth of 984 ft obtained from three Nansen casts. The greatest temperature differences between morning and afternoon readings appear at about the 400- and 800-ft depths.

Nansen bottle cast data to a maximum depth of 7434 ft were obtained at the transmitting ship during the period November 4-7. Temperature, salinity, and sound speed, as computed from tables of D.J. Matthews, have been reported (3).

A summary of the sea conditions as recorded at both these ships is shown in Table 1.

RESULTS

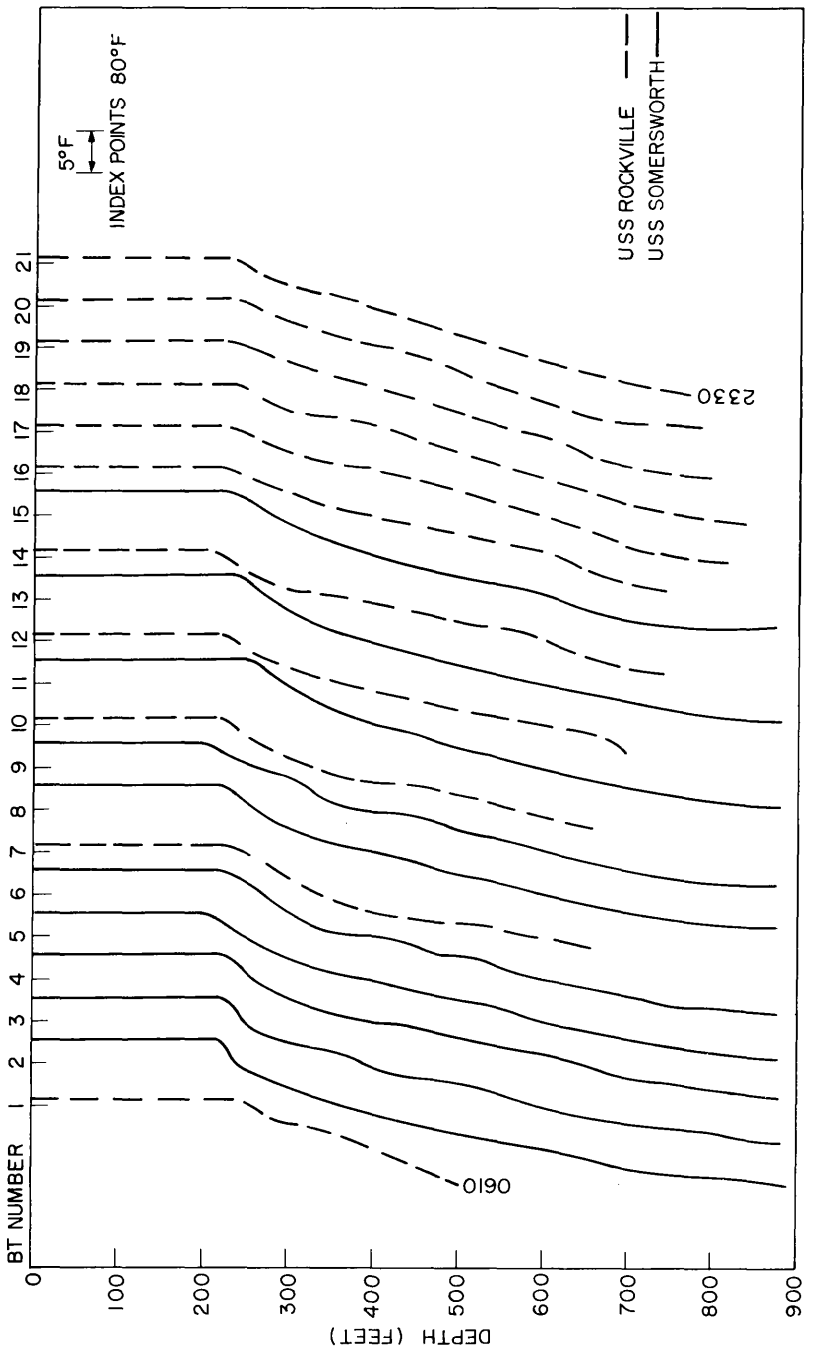
Experimental

Convergence Zone Limits – The characteristic of the first convergence zone can be developed by varying the depth of the source and the hydrophone. Zonal limits determined under these conditions are shown in the top half of Table 2 where ranges have been rounded off to the nearest ten yards and the days are arranged in order of increasing sound speed at the source depth. There is a definite indication that the earlier start of the zone is to be found at the deeper hydrophone depths and for the higher sound speed at the source. The extent or width of the zone is listed in the lower half of Table 2. For any given source (transducer) depth, the deeper hydrophone tends to increase the width of the convergence zone. Further relations are difficult to state qualitatively, since the trailing edge of the zone is not clearly defined. Any quantitative effects resulting from varying the depth of the source in the near-surface duct or from changes in the BT should best be ascertained from ray trace computations.

Horizontal Range and Travel Time – The quantity of experimental data obtained for first-convergence-zone paths and their plots are indicated in the following table.

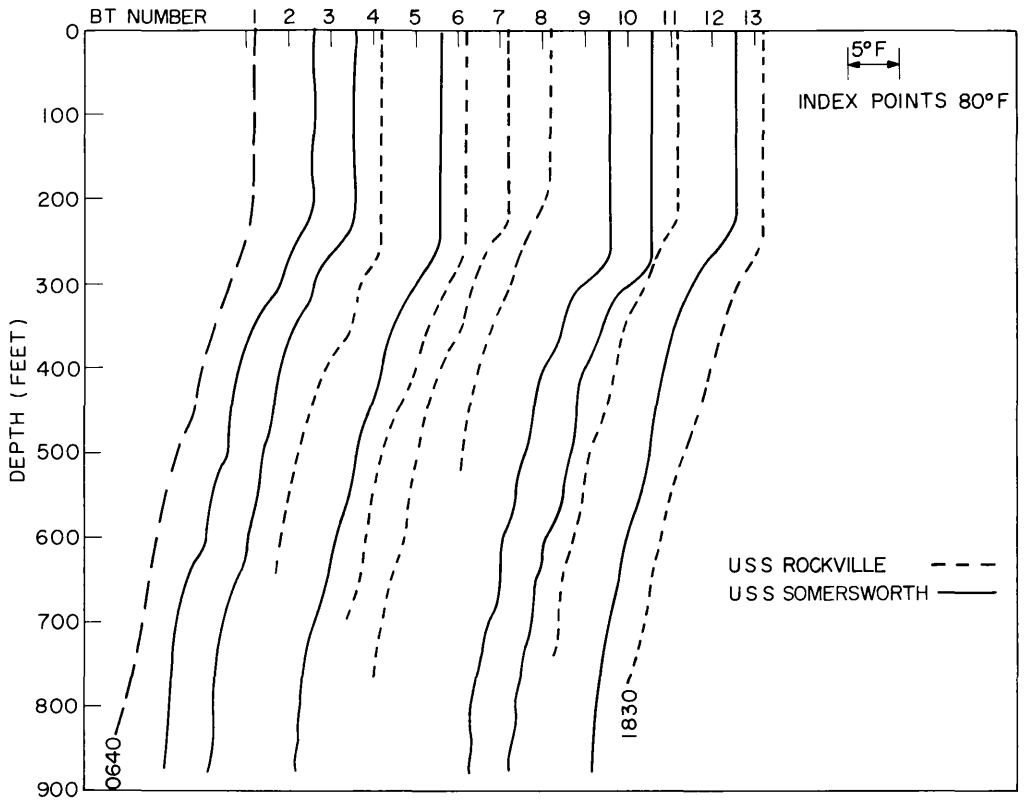
November Date	No. of Stations at Which Depth/Range Data Were Taken	Range and Travel Time Data Sets	Data Shown in Fig.
11	23	205	4(a)
12	45	250	4(b)
13	38	190	4(c)

These data were corrected as per Appendix B and grouped by station depth prior to plotting the travel time, in seconds, versus the horizontal range, in kiloyards, in Figs. 4(a)-(c). Where possible, the depth groups have been identified. In Fig. 4 the X's



(a)

Fig. 2 - Bathythermograms obtained on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13 at the two ships north of Puerto Rico. The initial and final time of each day's recordings and the BT number are indicated.



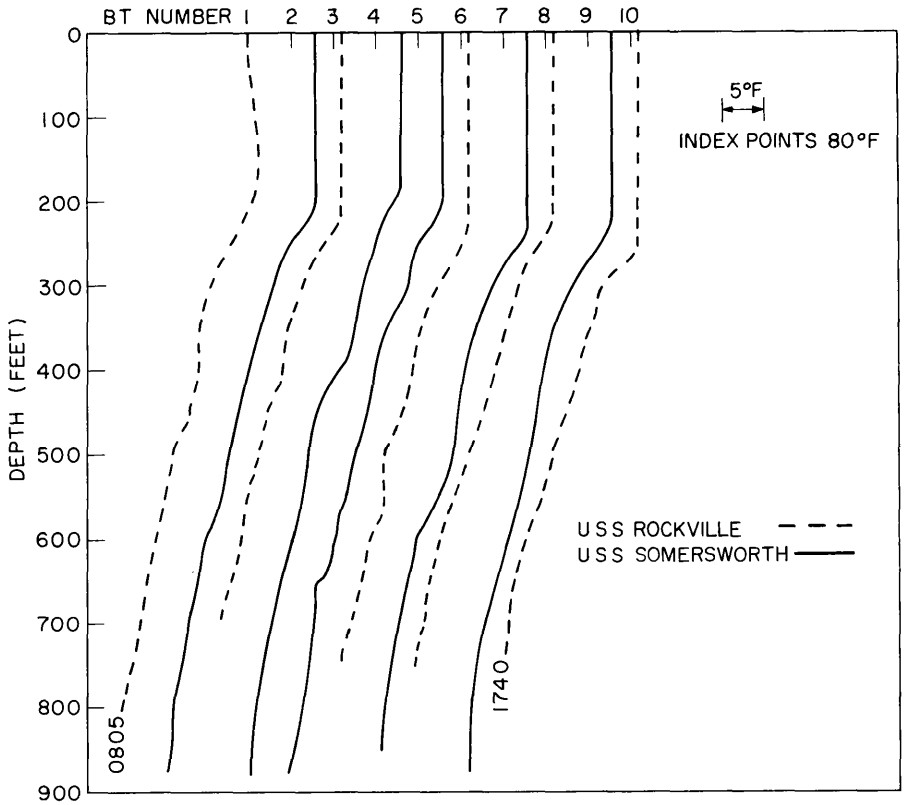
(b)

Fig. 2 (cont'd) - Bathythermograms obtained on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13 at the two ships north of Puerto Rico. The initial and final time of each day's recordings and the BT number are indicated.

represent discrete computed results for those depths noted and will be discussed later. A solid line defining the minimum travel time has been drawn to provide some measure of the observed and computed linearity. The dashed line represents the computed travel time for a direct path at the respective source sound speed listed at the top of Table 2.

Analytical

Mean Horizontal Sound Speed – The variation of the mean horizontal sound speed (1,4-7) as a function of the mean horizontal range for the November 11 data is shown in Fig. 5(a). The group of points labeled convergence is circumscribed broadly by the two solid curved lines where each point represents the average value of sound speed obtained from linear regression analysis for each depth/range station. A detailed treatment of this data is discussed in Appendix C. The vertical lines within this restricted region designate the extent of ±1 standard deviation of the data points about their respective mean values and represent 68 percent of such data if repeated trials were made of the same sample size (generally about ten points). Those points outside the convergence region represent individual point sets that had been screened out by setting approximate limits of less than 1630 yd/sec and greater than 1650 yd/sec. There were only a few exceptions permitted.

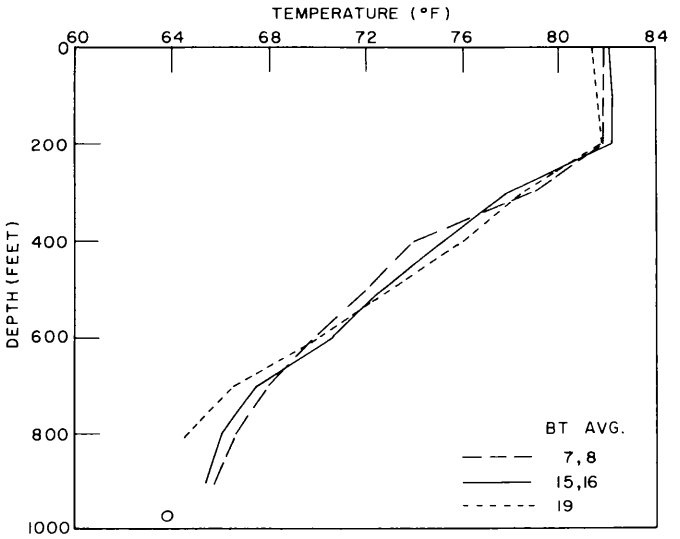


(c)

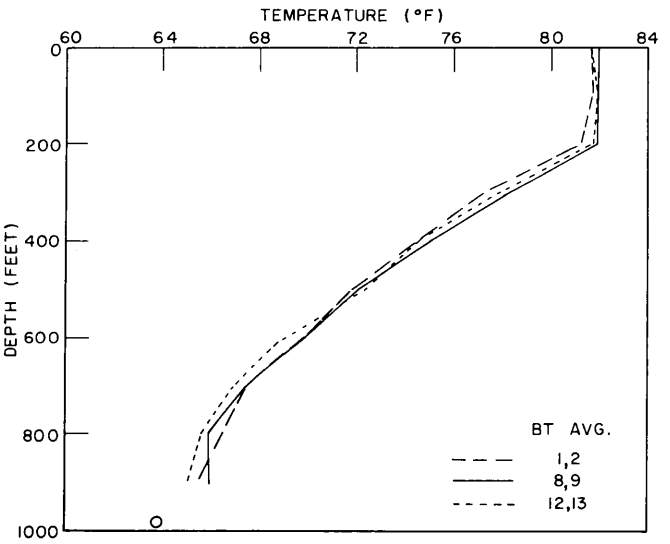
Fig. 2 (cont'd) - Bathythermograms obtained on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13 at the two ships north of Puerto Rico. The initial and final time of each day's recordings and the BT number are indicated.

Some direct surface channel paths are in evidence at a sound speed of about 1680 yd/sec, whereas other points are indicative of some combination of leakage paths. Below the convergence groups there are later times of arrival which might result from multipath interference or from reflection off the bottom. From a visual examination, there was only little evidence of alignment of points of the same hydrophone depth; thus, no best straight-line fit was attempted.

The dashed lines in Figs. 5(a)-(c) refer to computations which were made and are to be discussed later. Data is shown in Fig. 5(b) for November 12 with the transducer at 300 ft and the hydrophone at discrete depths between 20 and 420 ft. The data were screened, as before, prior to computation of the mean horizontal sound speed statistics for each depth/range station. The curved-line segments again delineate the convergence region; however, limit lines to data were not erected on this figure. Again, there were data at higher average sound speeds although not as many as for November 11. This is a direct result of the depth of the transducer which, as can be seen from Fig. 3(b), was below the isothermal layer. There were also some scattered data at lower mean sound speeds as

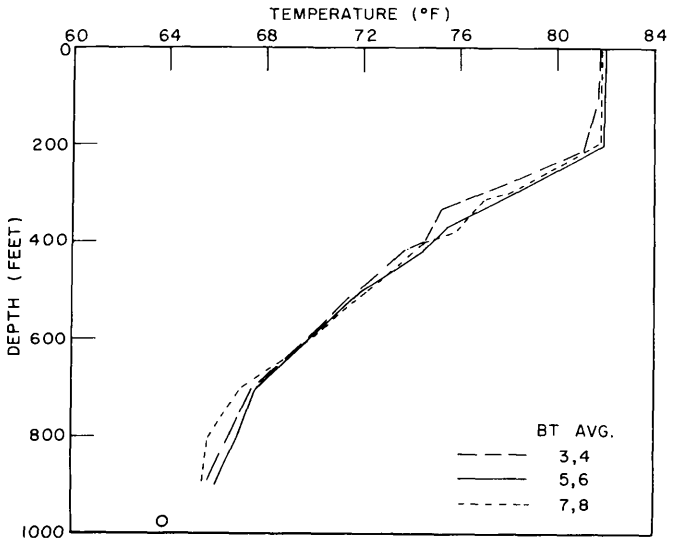


(a)



(b)

Fig. 3 - Average values of water temperature vs depth for three different periods of the day on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13. Long dashes represent morning readings, the solid line is for early afternoon readings, and short dashes represent late afternoon readings. These average values were obtained from the bathythermograms indicated at the lower right of each figure. (See Fig. 2).



(c)

Fig. 3 (cont'd) - Average values of water temperature vs depth for three different periods of the day on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13. Long dashes represent morning readings, the solid line is for early afternoon readings, and short dashes represent late afternoon readings. These average values were obtained from the bathythermograms indicated at the lower right of each figure. (See Fig. 2).

Table 1
Environmental Conditions that Existed
During the Mean Horizontal Sound Speed Measurements

Condition	Nov. 11	Nov. 12	Nov. 13
Wind speed (knots)	10-12*	10(15)†	10(13)
Wind direction (degrees)	50-60	50-60	60-120(60)
Sea swell (seconds)	4-6	5-6(2-4 ft)‡	5
Sea state	2	3(2-4)	2
Heading of ship 849 (degrees)	330-340	320-330	330
Heading of ship 851 (degrees)	320-330	310-320	325-025
Bearing of ship 849 from 851 (degrees)	350	340-350	330-340

*Unless otherwise stated, values are representative data from both ships.
†Significantly different values as reported by SOMERSWORTH are shown in parenthesis.
‡Sea swell measured in ft by one ship.

Table 2
First Convergence Zone Data

ZONE LIMITS								
Date	Transducer Depth (ft)	Source Sound Speeds (yd/sec)	Start and End of Zone for the Hydrophone Depth Indicated					
			20 ft		220 ft		420 ft	
			Min.*	Max.	Min.	Max.	Min.	Max.
12	300	1683.0-1686.0	70120	78040	68800	79140	68700	79160
13	20	1686.6-1687.2	70880	75100	70400	78500	68880	78240
11	100	1687.2-1688.2	71150	78100	70130	76860	69900	76980

ZONE EXTENT†				
Date	Transducer Depth (ft)	Convergence Zone Width for the Hydrophone Depth Indicated		
		20 ft	220 ft	420 ft
12	300	7920	10340	10460
13	20	4220	8100	9380
11	100	6950	6730	7080

*The minimum and maximum values for the zone are the ranges, in yards, where signals were received at the hydrophone depth listed and detected by the amplitude threshold processing system.
†Convergence zone extent, in yards, is defined as the difference between the minimum and maximum ranges listed.

the result of other paths. For the 420-ft hydrophone depth data, a regression analysis was made and yielded

$$v = 1642.47 + 0.000668\,(R - 73646.8) \quad \text{yd/sec} \tag{1}$$

for the mean horizontal sound speed v as a function of the mean horizontal range R in the convergence zone. This analysis included ten depth/range stations with a total of 55 individual point sets. The depth/range stations at the start and end of the zone do not contain as many points as those in the middle. If one were to construct confidence limits to this mean line at the 95-percent level at the center of this region, the limits would be no more than 0.7 yd/sec wide, whereas the standard deviation of all 420-ft depth data relative to the same line is 2.4 yd/sec.

The data for November 13, obtained from nine discrete hydrophone depths between 20 and 420 ft with the transducer at 20 ft, are shown in Fig. 5(c). The data were also screened, as before, with the curved segments defining the essential convergence zone. It is interesting to note the concentration of data for surface duct propagation as enhanced by this, the shallowest, transducer placement. Associated with this fact, there is less evidence of the combination leakage-type paths evident on November 11 and 12. There were also a number of arrivals which might be attributed to bottom reflections. For this day the entire group of data for all depths attaining convergence via the deep refracting paths was taken for a best straight-line analysis. The equation which resulted,

$$v = 1641.93 + 0.000557\,(R - 74336.3) \quad \text{yd/sec,} \tag{2}$$

represents 38 depth/range stations with a total of 190 individual point sets. Confidence limits constructed to this mean line at the center region for the 95-percent level would be no more than 0.5 yd/sec wide, while the standard deviation of all the data with respect

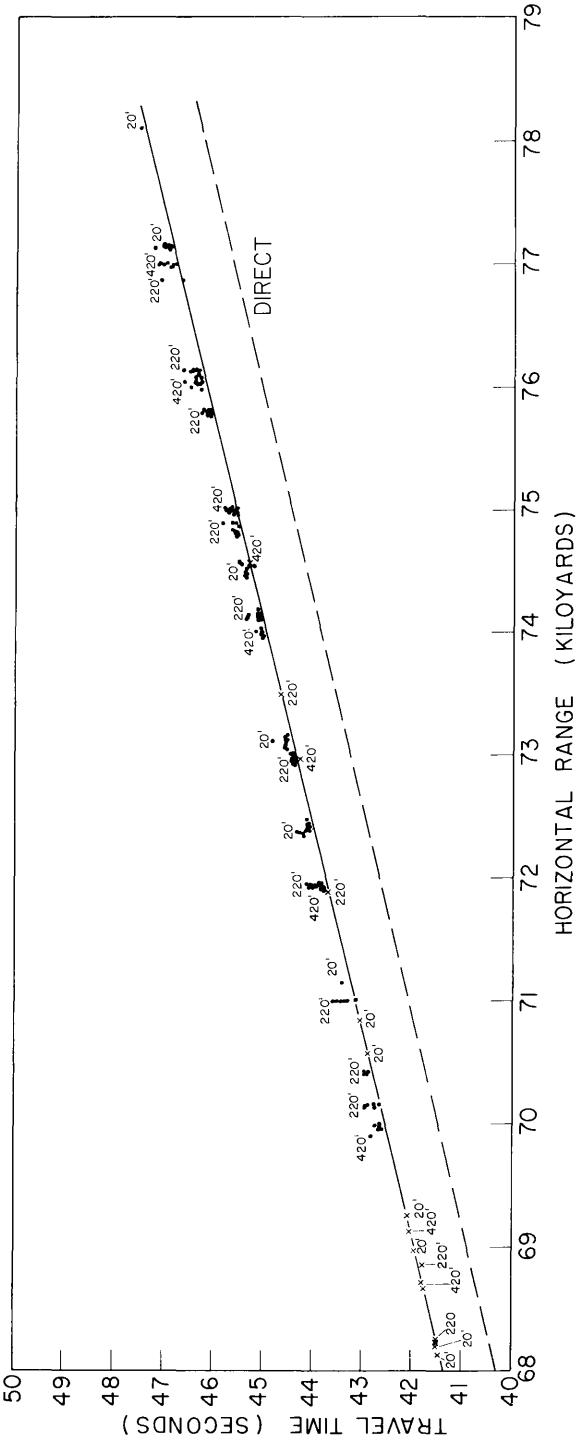


Fig. 4 - Travel time vs horizontal range to the first convergence zone for sound waves. The data are grouped according to the hydrophone depth at the receiving station. Experimental values are indicated by dots, and theoretical results are indicated by X's. The data were obtained on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13.

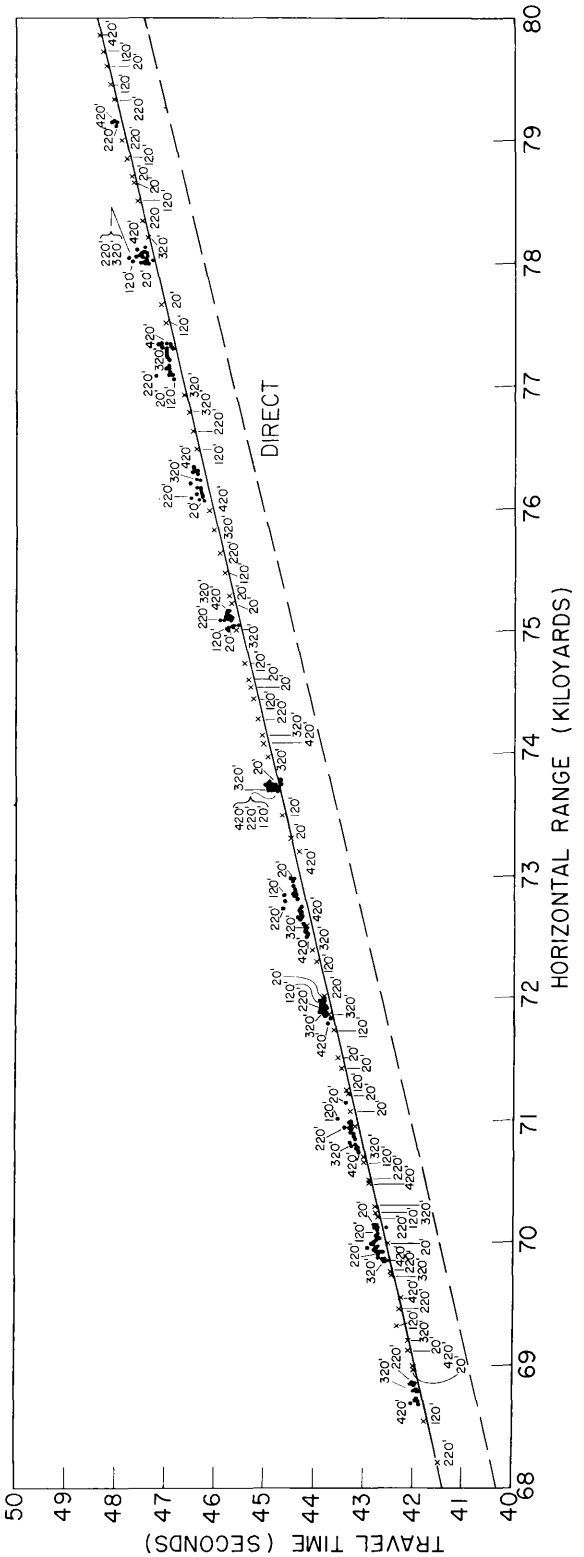


Fig. 4 (cont'd) - Travel time vs horizontal range to the first convergence zone for sound waves. The data are grouped according to the hydrophone depth at the receiving station. Experimental values are indicated by dots, and theoretical results are indicated by X's. The data were obtained on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13.

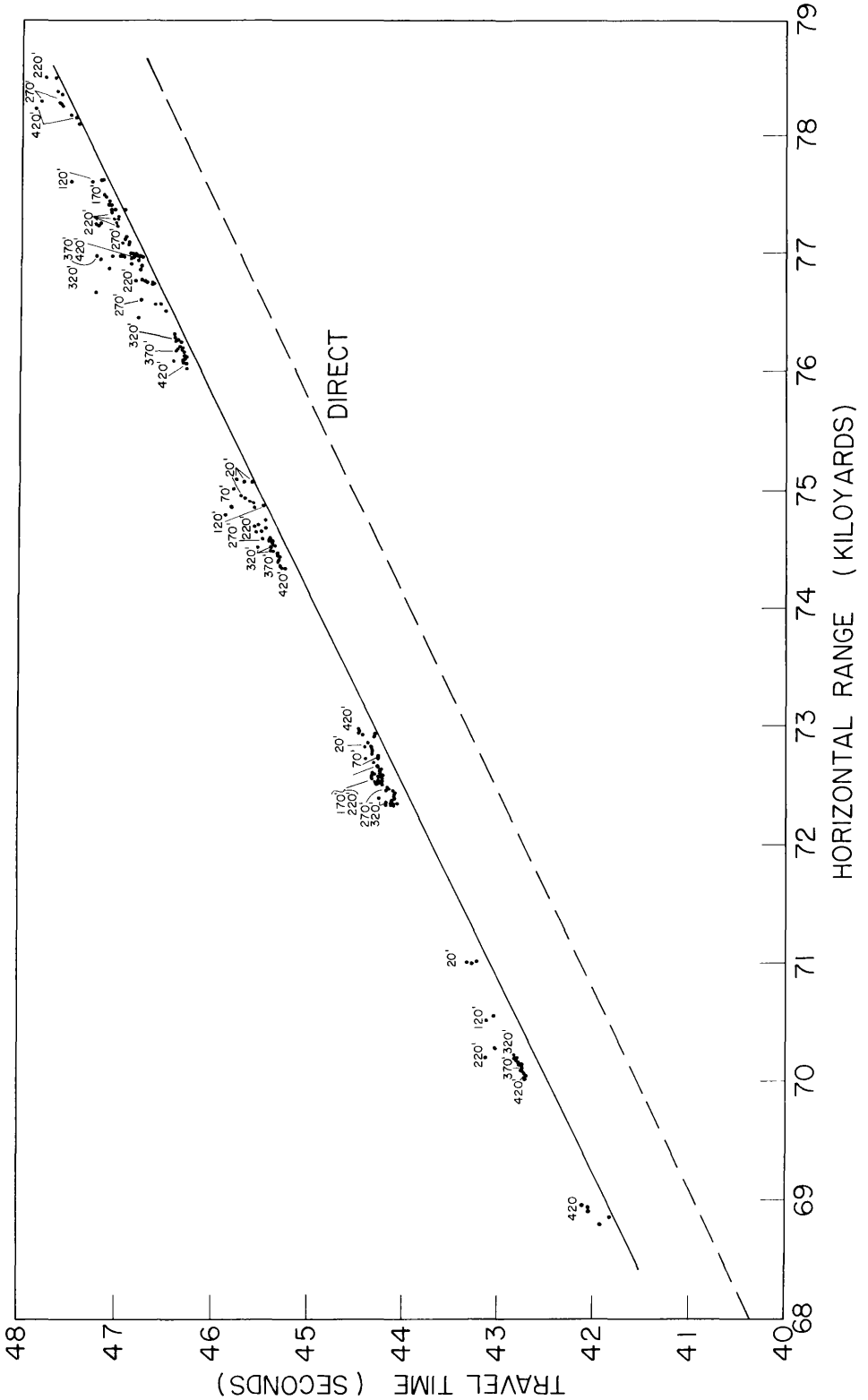


Fig. 4 (cont'd) - Travel time vs horizontal range to the first convergence zone for sound waves. The data are grouped according to the hydrophone depth at the receiving station. Experimental values are indicated by dots, and theoretical results are indicated by X's. The data were obtained on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13.

to the same line is 3.0 yd/sec. By their very nature, the confidence limits to a line increase as one goes out from the center of the data to the outer extent of range coverage, and the limits permit other lines to exist with different slopes.

The analysis at 420 ft on November 12 showed an increase in mean horizontal sound speed of 0.67 yd/sec/kyd as compared to 0.56 yd/sec/kyd for all the data on November 13. Over a convergence extent of ten kiloyards (kyd), their difference would be 1.1 yd/sec. As might be expected, the slopes of these lines are statistically not significantly different, although the line for the 420-ft data of November 12 appears distinct from the line for all the data of November 13. In fact, most of the data at the 420-ft depth for the 13th is also well represented by the same line obtained for the 12th. No attempt was made to similarly analyze the data at any other depth.

A summary of the mean horizontal sound speed data is given in Table 3. Even though the range (max.-min.) of sound speed values is large, there is an unmistakable increase in sound speed from the start to end of the first convergence zone at any one hydrophone depth.

Computation – The travel time, mean horizontal range, and horizontal sound speed were computed to the first convergence zone using eikonal equations for acoustic ray paths for a sound speed profile comprised of linear gradients. The sound speeds were determined from equations applicable for zero hydrostatic pressure (8), to which a two-term expression for depth,

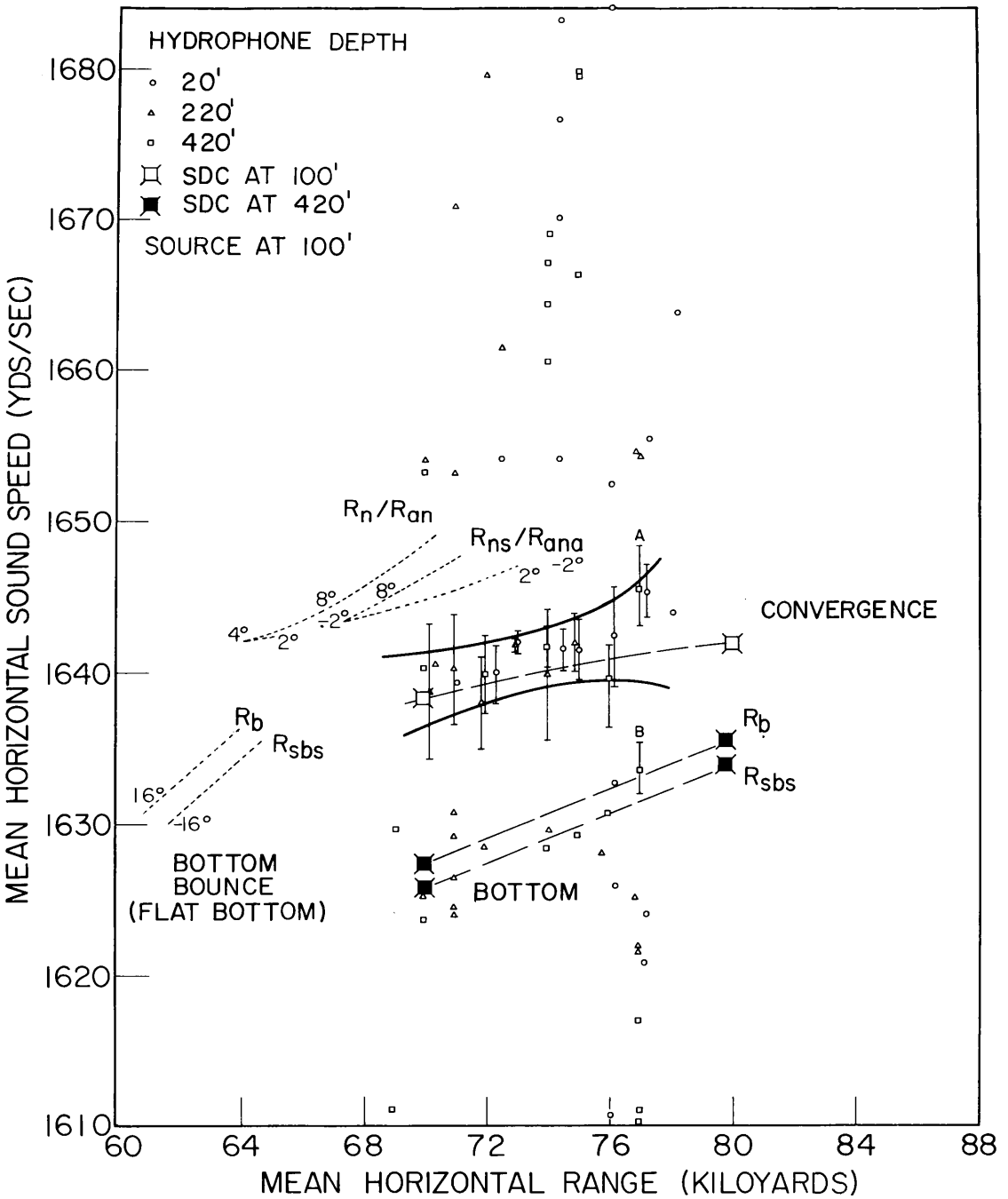
$$1.815 \times 10^{-2} D - 5.29 \times 10^{-12} D^3$$

was added.

For the first 900 ft below the ocean's surface the BT data beneath each ship were averaged, and an average salinity was determined at these depths from Nansen bottle casts obtained during the field trip. Below 900 ft, only the Nansen cast data were employed, and for the last gradient beneath the maximum 7434-ft cast a constant gradient of 0.01815 was assumed. The computed sound speed profiles for November 11-13 are shown in Figs. 6(a)-(c), respectively. The region down to 900 ft (Region A) has been expanded to show the transformation of the BT data contained in Figs. 3(a)-(c).

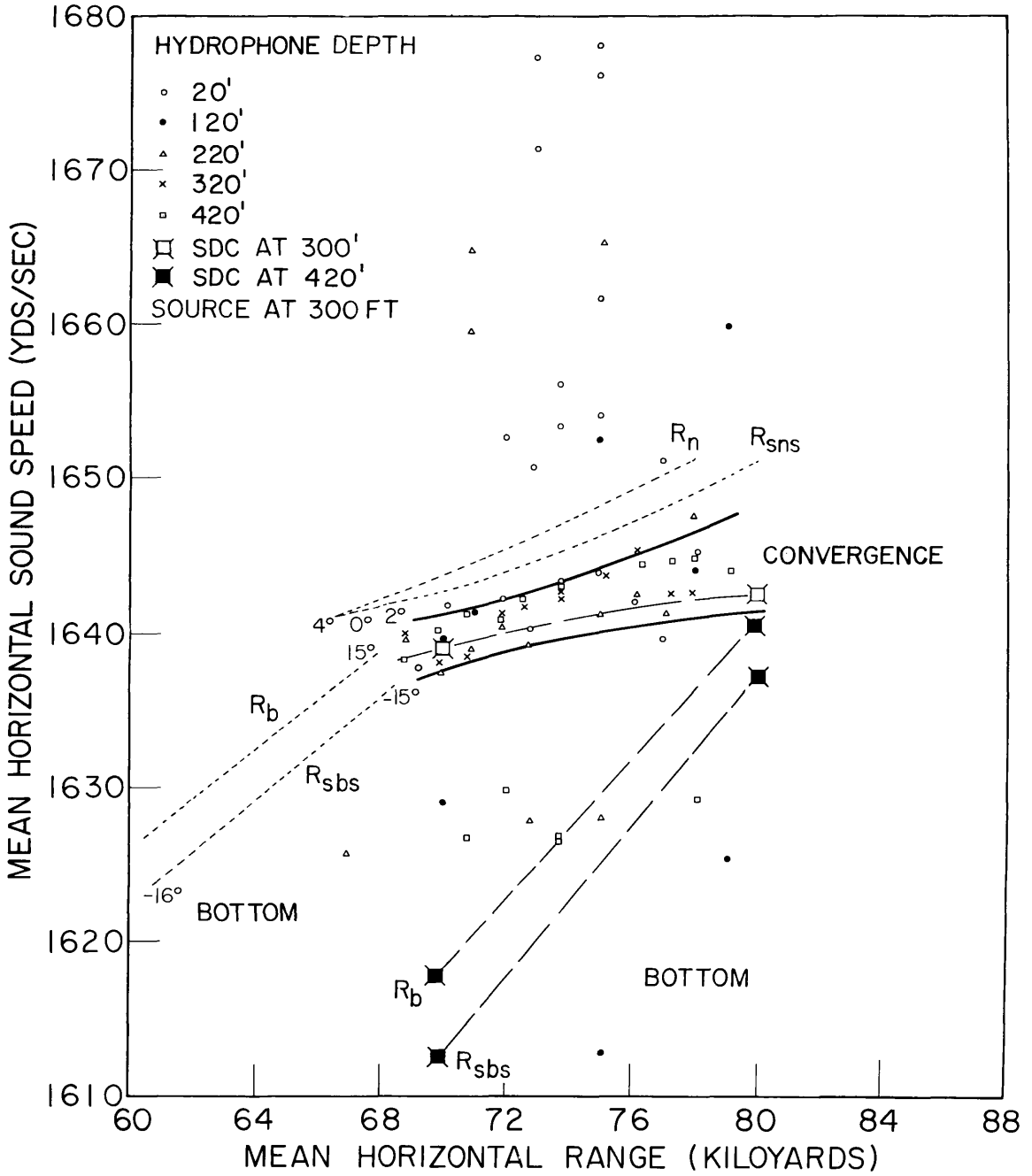
Ray diagrams were computed for various angles at the transducer for November 11 and shown as discrete travel times for depths and ranges in the first convergence zone, as shown in Fig. 4(a). This overall presentation of travel time versus range, to the scale shown, is difficult to assess except to note that experimental arrivals (dots) are later than theoretical predictions (X's). When the parameter, mean horizontal velocity, is used and the theoretical points are plotted as shown in Fig. 5(a), a clearer comparison can thus be made between the theoretical and experimental results. Those depression angles at the transducer which are measured from the horizontal downward are defined as positive.

The discrete ray trace arrivals thus generate points whose locus on Fig. 5(a) is a curve labeled R_n/R_{an} and includes those rays having a deep-refraction-turnaround, nadir-type vertex before ascending to the 420-ft depth. Another curve labeled R_{ns}/R_{ana} is for similar rays, except for a surface reflection or an apex-type vertex just prior to descent to the 420-ft depth. A complete nomenclature is illustrated in Figs. 7(a)-(c), respectively, for surface and bottom reflections, refraction paths, and combinations of the two. In



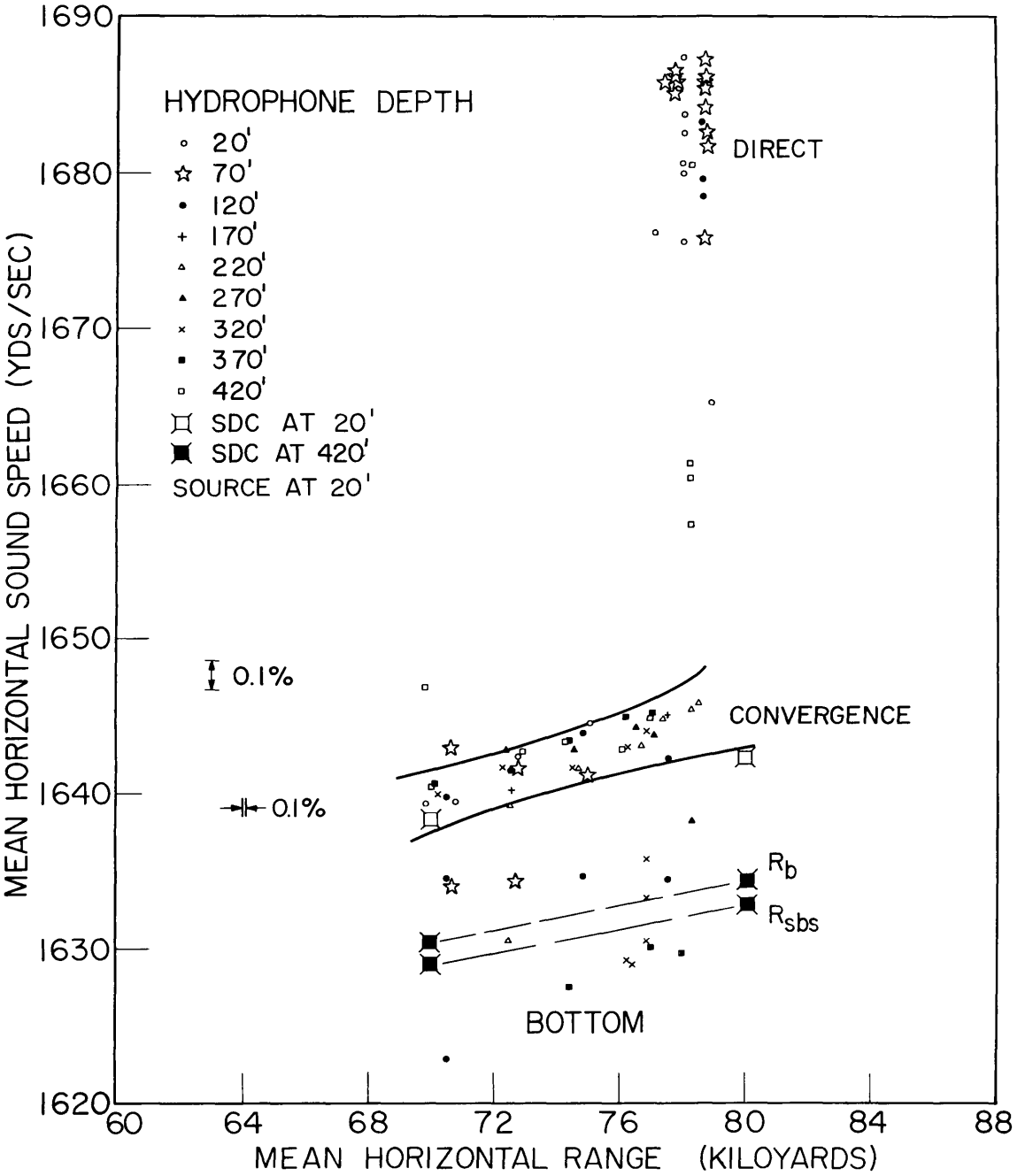
(a)

Fig. 5 - Mean horizontal sound speed vs mean horizontal range as determined from field measurements and by calculations for each depth/range station. The data are identified by the receiving station hydrophone depth and were obtained for a source depth of (a) 100 ft on Nov. 11, (b) 300 ft on Nov. 12, and (c) 20 ft on Nov. 13. The solid lines enclose those data points with sound values between 1630 and 1650 yd/sec. The short dashes represent the results obtained by performing an analysis based on ray theory; the long dashes are for results obtained with a sonar data correction (SDC) formulation based on the assumption of an isovelocity medium.



(b)

Fig. 5 (cont'd) - Mean horizontal sound speed vs mean horizontal range as determined from field measurements and by calculations for each depth/range station. The data are identified by the receiving station hydrophone depth and were obtained for a source depth of (a) 100 ft on Nov. 11, (b) 300 ft on Nov. 12, and (c) 20 ft on Nov. 13. The solid lines enclose those data points with sound values between 1630 and 1650 yd/sec. The short dashes represent the results obtained by performing an analysis based on ray theory; the long dashes are for results obtained with a sonar data correction (SDC) formulation based on the assumption of an isovelocity medium.



(c)

Fig. 5 (cont'd) - Mean horizontal sound speed vs mean horizontal range as determined from field measurements and by calculations for each depth/range station. The data are identified by the receiving station hydrophone depth and were obtained for a source depth of (a) 100 ft on Nov. 11, (b) 300 ft on Nov. 12, and (c) 20 ft on Nov. 13. The solid lines enclose those data points with sound values between 1630 and 1650 yd/sec. The short dashes represent the results obtained by performing an analysis based on ray theory; the long dashes are for results obtained with a sonar data correction (SDC) formulation based on the assumption of an isovelocity medium.

Table 3
Mean Horizontal Sound Speed Values Obtained in First Convergence Zone*

Date and Transducer Depth	Position in the Zone at Which Mean Speed was Obtained	Values of Mean Speed at the Hydrophone Depth Indicated		
		20 ft	220 ft	420 ft
Nov. 11 (100 ft)	Start	1639.2†	1634.0-1641.0	1639.4-1640.8
	End	1644.0	1647.4	1636.1-1647.4
Nov. 12 (300 ft)	Start	1640.9-1641.4	1637.7-1640.1	1637.9-1639.7
	End	1644.4-1647.5	1648.5	1646.5-1648.1
Nov. 13 (20 ft)	Start	1637.6-1641.2	1630.4-1635.9	1636.9-1640.8
	End	1642.8-1647.2	1644.2-1647.4	1646.3-1647.9

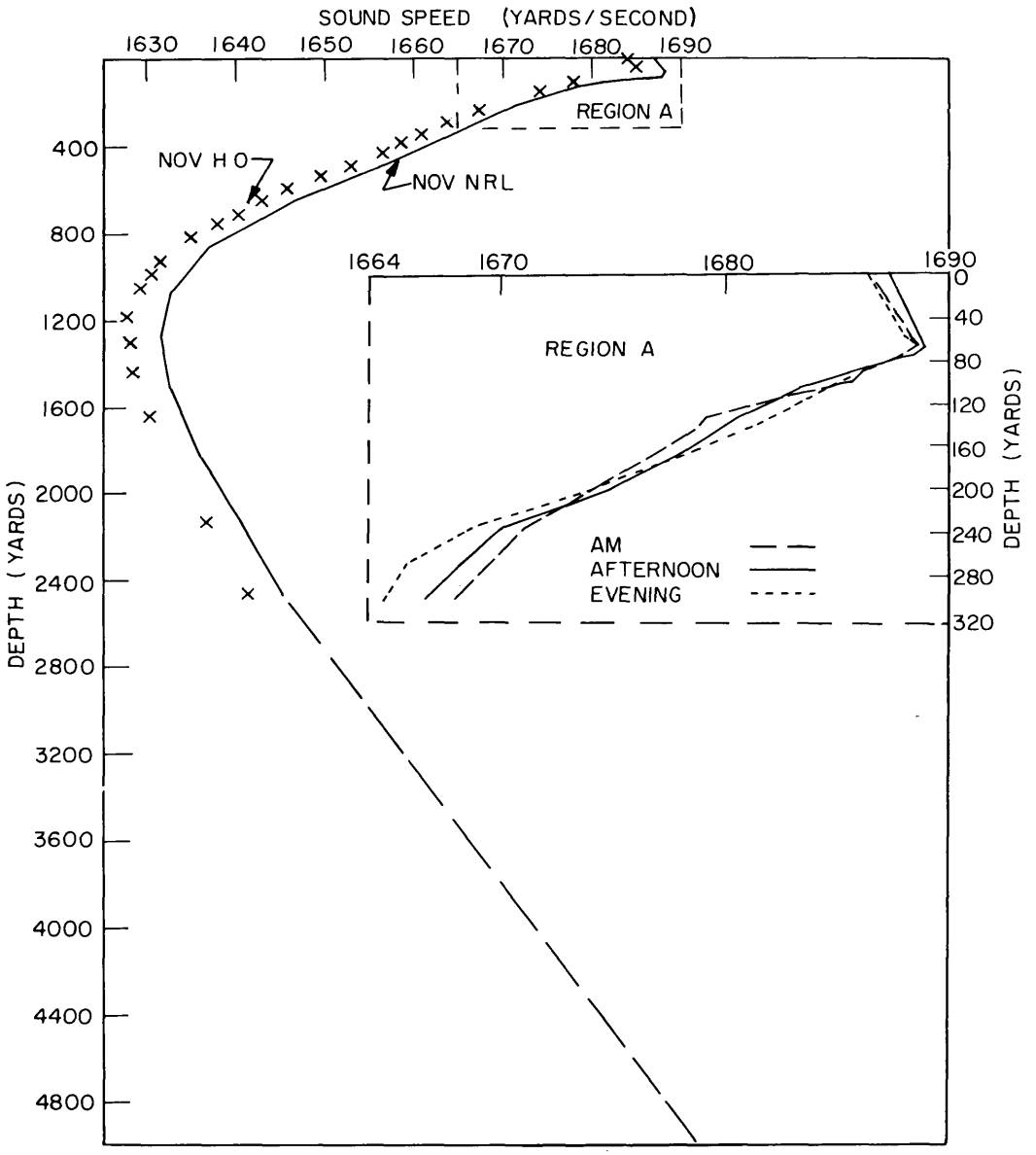
*Only those values between 1630 and 1650 yd/sec are given.
†Where only one value is listed, only one point was available; otherwise, the entire range is given. Sound speed values are given in yd/sec.

between these loci should lie all the signal paths from the surface down to 420 ft, except for those which may be reflected at the surface above the source. There is an indication of surface duct trapping for angles below two degrees. The singular points at 16 degrees were returns from a flat bottom assumed to exist between the two ships.

It is evident that these computations are considerably in error. Another set of calculations was made retaining the linear segmented sound speed profile and eikonal equations, but with the following modifications. (a) The sound speeds were calculated from Del Grosso surface terms supplemented by terms from the Mackenzie polynomial (9). (b) The shallow water differences were taken into account by employing the 300-yd BT data from beneath each ship and matching it up with the field trip Nansen cast. (c) In addition, temperature/salinity data was obtained from the U. S. Naval Oceanographic Office on depths between 2478 and 5468 yd. The final layer gradient of 0.01763 in this data was taken to be valid all the way to the bottom at 8040 yd. (d) To the values of depth and sound speed obtained, corrections factors were next applied to take into account curved earth effects. This sound speed profile modification for the deep depths can best be seen by comparing the two curves in Fig. 6(b).

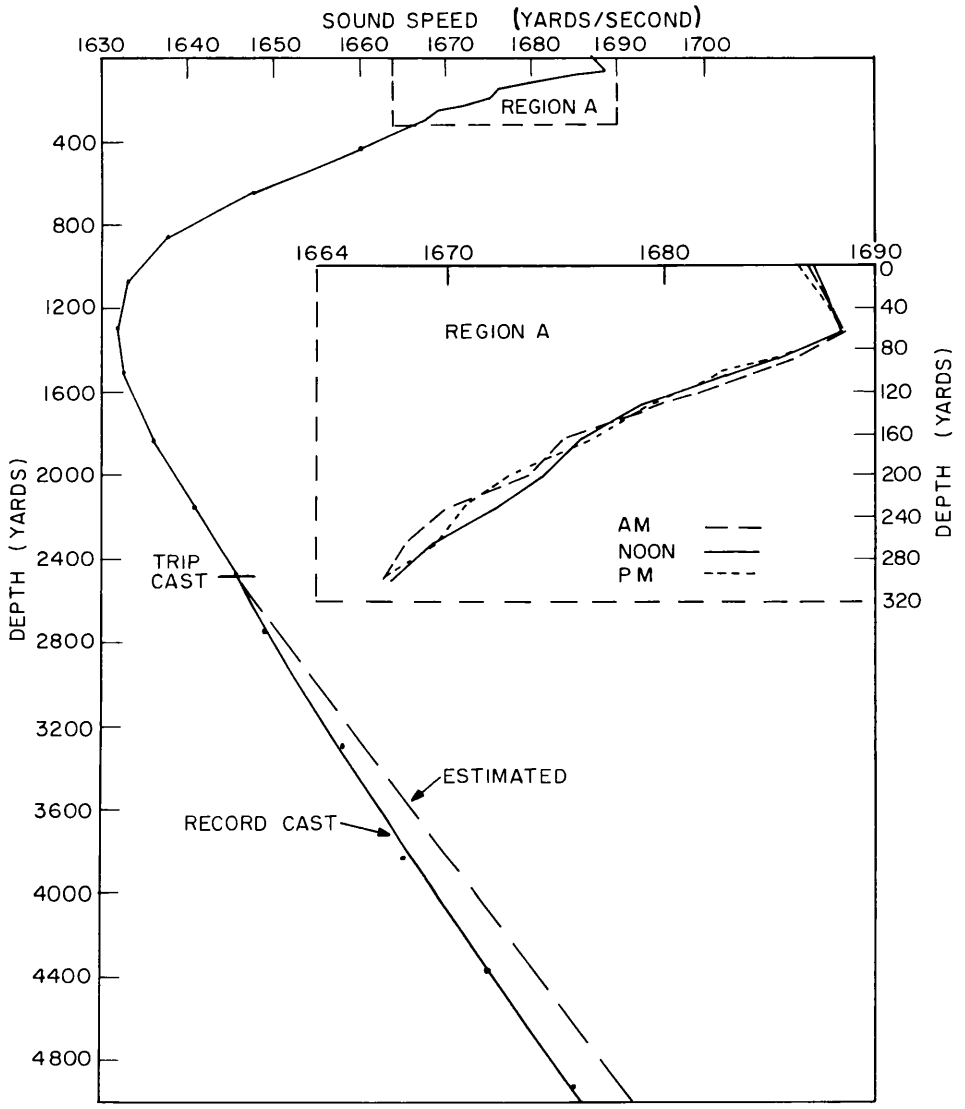
In the ray trace computations, a changeover to the second sound speed profile for the shallow depths is made after a ray has executed a deep-water nadir vertex. Rays were computed for various angles at the transducer and the results are shown by X's for discrete depths in Fig. 4(b). A collection of these points, the loci for the 420-ft depth, was also replotted (the short-dash lines in Fig. 5(b)) with surface reflections at the source included. A comparison between the predicted and experimental data indicates that a distinct bias remains.

These ray trace computations out to convergence may not be accurate because (a) the sound speed profiles are not obtained correctly and manipulated properly, or (b) simplified ray acoustics is not adequate when surface duct and Sofar channel leakage and deep scattering layers are present. Computations for bottom reflections would be in error for these same reasons, and also because of the omission of unknown and irregular topographic details.



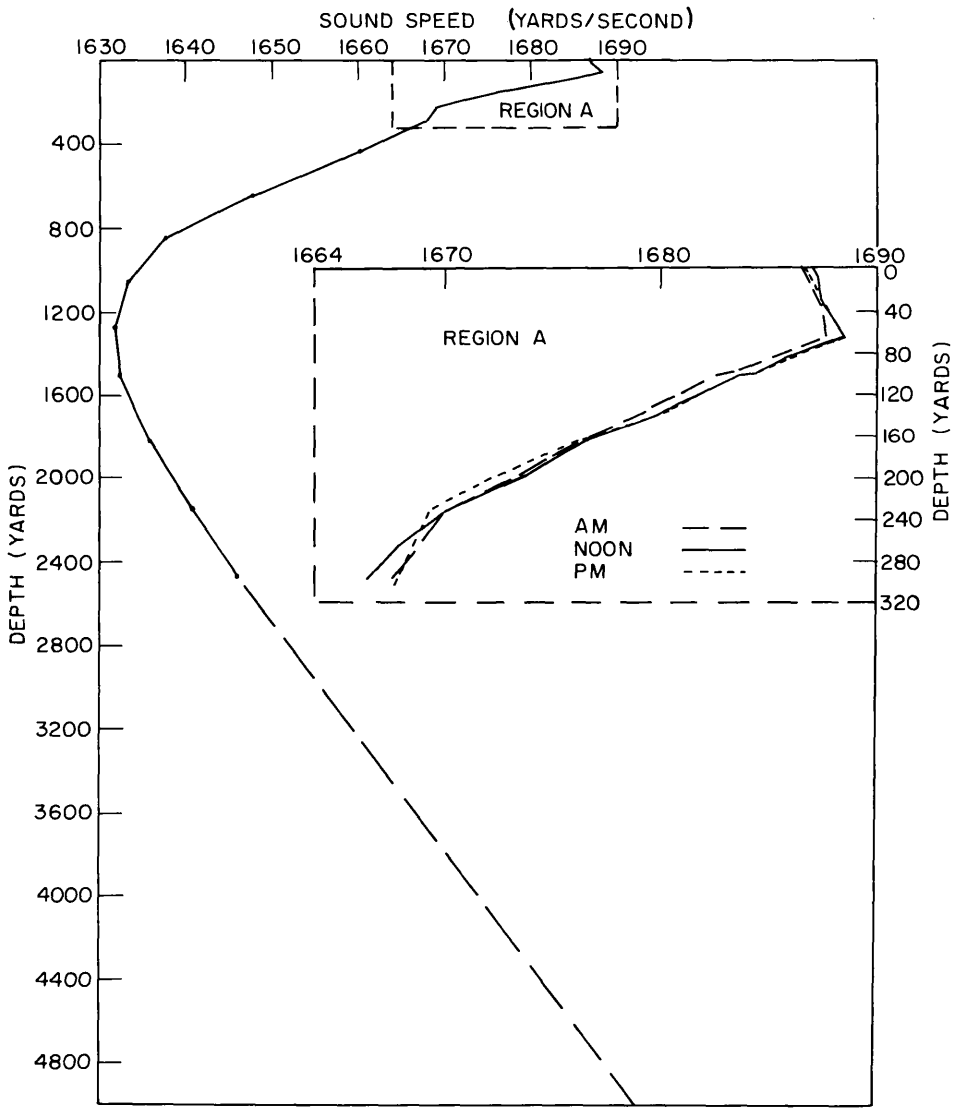
(a)

Fig. 6 - Sound speed vs depth as calculated from bathythermograms and Nansen bottle casts on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13



(b)

Fig. 6 (cont'd) - Sound speed vs depth as calculated from bathythermograms and Nansen bottle casts on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13



(c)

Fig. 6 (cont'd) - Sound speed vs depth as calculated from bathythermograms and Nansen bottle casts on (a) Nov. 11, (b) Nov. 12, and (c) Nov. 13

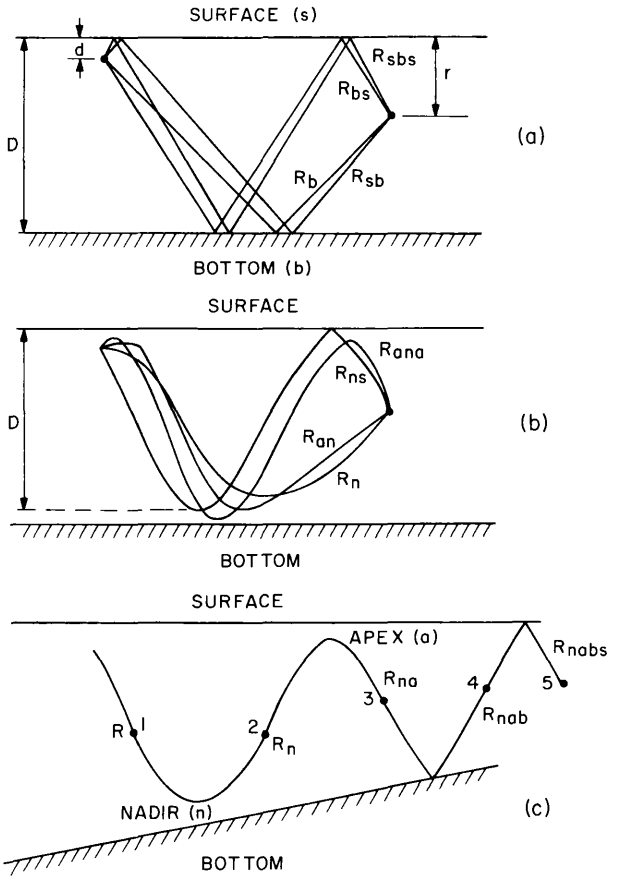


Fig. 7 - Illustration of acoustic ray paths from the source at a depth d to the receiver at a depth r for (a) the case of reflections only, (b) the case of refraction only, and (c) combinations of types (a) and (b)

Sonar Data Correction – In place of the more exact computation of travel time and range via refractive ray paths, including possible returns from a sloping bottom, there is a considerably simpler approximation stemming from an isovelocity medium hypothesis. An equation has been proposed (10) for a sonar data computer to obtain corrected ranges for this condition; the results are straight-line approximations to the ray paths. The corrected range R_c for this condition is given by

$$R_c = (R_s^2 - 4\delta^2)^{1/2} - 2\delta a \tag{3}$$

for down-slope propagation, where

R_s = slant range defined by the product $V_s T$ (yd),

V_s = mean slant velocity, computed empirically from a formula (11) for the North Atlantic, given by

$$0.00538D + 1628 \text{ (yd/sec)}, \tag{4}$$

T = one-way travel time (sec),

r = receiver (or target) depth (yd),

δ = depth factor dependent upon path. Nominally $\delta = D - d$ when the source and target are supposed to be at the same keel depth d below the surface and in water of depth D both in yards. For the condition where this is known not to hold and for a target at a depth r, δ is different for the four possible surface/bottom returns shown in Fig. 7(a), assuming the same path for outgoing and incoming signals. The values of δ for these four returns are:

$$(\text{path } R_b)\ \delta = D - \frac{d+r}{2},$$

$$(\text{path } R_{sb})\ \delta = D - \frac{d-r}{2},$$

$$(\text{path } R_{bs})\ \delta = D + \frac{d-r}{2},$$

$$(\text{path } R_{sbs})\ \delta = D + \frac{d+r}{2}.$$

α = bottom slope at the point of reflection, measured in the direction of propagation (radians).

Equation (3) can be rearranged to solve for the mean horizontal velocity V_{mhv} as

$$V_{mhv} = \frac{V_s\left[1 + \left(\frac{2\,\delta}{R_c + 2\,\delta\alpha}\right)^2\right]^{-1/2}}{1 + \frac{2\,\delta\alpha}{R_c}}, \tag{5}$$

and the travel time as

$$T = \frac{\left[(R_c + 2\,\delta\alpha)^2 + 4\,\delta^2\right]^{1/2}}{V_s}. \tag{6}$$

In applying Eq. (3), a return signal or echo is assumed to have been received and a travel time $2T$ is measured. In Eqs. (5) and (6) an independent measure or estimate of the corrected range R_c is required.

For convergence zone work the nominal water depth below the keel is replaced by the depth at which nadir is executed by a ray departing at a zero depression angle at the source. A similar extension for targets at depths other than the source depth and for other paths is possible where, in essence, vertexing is now commensurate with reflection from a real boundary. The zero-degree ray is chosen, although it does not determine the start of the first convergence zone as would the first caustic at some depth. Similarly, the zone end at the upper ranges is not determined by the bottom limiting ray but would be related to the limits of signal detection capability corresponding to a constant propagation loss contour of, say, 90 db at the same depth.

An application of Eq. (5) with zero slope was made for November 11 where the water depth $D = 5055$ yd and the source depth $d = 100$ ft at the 70- and 80-kyd ranges. The result (the long-dash lines in Fig. 5(a)) is shown to be within the outlined convergence region bounds. Similarly, for November 12, with $D = 4860$ yd and $d = 20$ ft, the results for the

same ranges are as shown by the long-dash lines in Fig. 5(b). Also, on November 13, with D = 4995 yd and d = 20 ft, the results are as shown by the long-dash lines in Fig. 5(c), all within bounds. In all three cases the source and the receiver depths were equal.

Bottom reflection returns in these same convergence zones require an estimate of the bottom slope in the vicinity of the expected point of reflection. Such estimates were obtained from bottom contour charts and computations made employing Eq. (5). An attempt was made to see how well agreement could be found between an empirical procedure with the best available input data and the experimental results. Therefore, instead of employing the water depth D beneath the source ship, a value determined by an extrapolation from the water depth at the estimated point of reflection was made at an average slope back to the source ship. The results for November 11 are illustrated by the lines drawn between the R_b and R_{sbs} point sets at 70 and 80 kyd, as shown by the long-dash lines in Fig. 5(a). A similar computation for the mean horizontal velocity at 70 and 80 kyd was made for the November 12 and 13 conditions and the results are displayed by the long-dash lines in Figs. 5(b) and (c), respectively. Thus, the computations based upon isovelocity approximations and a hydrophone depth of 420 ft appear to represent better those returns ostensibly from the bottom than calculations with refractive rays which were based on other approximations.

These simplified computations have been made with equations derived from a sonar data correction formulation and depend to a large degree on the constants within Eq. (4). Their empiricism is seen in other areas, for example in the Norwegian Sea where

$$V_s = 0.00926\ D + 1578\ (\text{yd/sec}). \tag{7}$$

A comparison was made of the empirical formulation for V_s with a value obtained by a time-average velocity profile integration. The time-average value is defined by

$$V = \frac{Z}{\int_O^Z [dZ/c(Z)]} \tag{8}$$

where Z is the depth variable. For a zero-degree vertexing ray, the application of Eq. (4) provides a V_s value of 1655 yd/sec, whereas profile integration by Eq. (8) develops a value of 1650 yd/sec, which would have produced a slightly poorer "prediction" for the experimental data presented.

Other Approaches – The location of, and the measurement of an effective or mean horizontal velocity in, the first convergence zone has been examined (7,11-13), and data have been obtained from Atlantic, Pacific, and Mediterranean sea regions. Significant parameters have been identified as defining these regions, including combinations of the sound speed at the surface, sound speed and gradient at the acoustic source, temperature at 3000 m, acoustic range for zero-degree ray, minimum travel time to zone, bottom limiting and excess depths, first caustic, and 95-db propagation loss contours. The ultimate user, whether he be involved in long-range planning or tactical and operational decision-making, can best decide those procedures which have the most merit and thus dictate the specific knowledge required of the medium, its boundaries, and expected geometry.

REFERENCES

1. Rafferty, R.J., Cybulski, J., and McClinton, A.T., "Effects of the Ocean Medium on Sonar Range Accuracy," NRL Memorandum Report 887 (Confidential Report, Unclassified Title), Jan. 1959

2. Rafferty, R.J., Cybulski, J., and McClinton, A.T., "Effects of the Ocean Medium on Sonar Range Accuracy," USN J. Underwater Acoust., 9(No. 1):83-89, Jan. 1959 (Confidential Journal, Unclassified Title)

3. "NRL Acoustic Survey, Nov. 1958," U.S. Naval Oceanographic Office, Miscellaneous Oceanographic Data Report 16794, Dec. 1958

4. Pedersen, M.A., "LORAD Test Results 1956-1958," U.S. Navy Electronics Laboratory, NEL Report 927 (Confidential Report, Unclassified Title), Apr. 1960

5. Haupt, C.R., "LORAD Status Report," U.S. Navy Electronics Laboratory, NEL Report 1060 (Confidential Report, Unclassified Title), Oct. 1961

6. McClinton, A.T., and Cybulski, J., "Computed Travel Times, Ranges and Velocities Through the First Convergence Zone," USN J. Underwater Acoust., 12(No. 1):107-113, Jan. 1962 (Confidential Journal, Unclassified Title)

7. Pedersen, M.A., and Brucker, H.P., "Effective Velocity in the First Convergence Zone," presented at 20th Navy Symposium on Underwater Acoustics, Nov. 13-15, 1962, at U.S. Navy Electronics Laboratory (Confidential)

8. Del Grosso, V.A., "The Velocity of Sound in Sea Water at Zero Depth," NRL Report 4002, June 1952

9. Mackenzie, K.V., "Formulas for the Computation of Sound Speed in Sea Water," J. Acoust. Soc. Am., 32(No. 1):100-104 (1960)

10. "Computer Group, Sonar Data Correction, AN/BQA-4( )," (Unclassified Title), Military Specification MIL-C-22289A (BuShips), May 10, 1961 (Confidential)

11. Hanrahan, J.J., and Bell, T.G., "A Study of the Occurrence of Convergence Zones in the North Atlantic Ocean," U.S. Navy Underwater Sound Laboratory, USNUSL Report 452 (Confidential Report, Unclassified Title), Feb. 18, 1960

12. Randlett, W.B., "Sonic Convergence in the North Atlantic;" U.S. Naval Oceanographic Office, USNOO Report TR-72 (Confidential Report, Unclassified Title), Oct. 1960

13. Anderson, E.R., and Pedersen, M.A., "Oceanometric and Acoustic Predictions for FASOR I Experiments," presented for Proceedings of 1st U.S. Navy Symposium on Military Oceanography, June 17-19, 1964, pp. 313-339, U.S. Naval Oceanographic Office, 1964 (Confidential)

APPENDIX A

CALIBRATION OF RANGE AND TRAVEL TIME INSTRUMENTATION

On November 10 a check on the calibration of the shoran and the acoustic transmission and receiving loops was performed while both ships were berthed in the San Juan Channel of San Juan, Puerto Rico. The source ship was along the north bulkhead, portside to, and the receiving ship was about 870 yd aft across the channel along the south bulkhead, starboard side to. The channel is approximately 250 yd wide at this point and the optically surveyed range between the antennae rotors atop the respective mast extensions was determined to be 906.2 yd. This basic measurement was translated to the distance between the underwater sound projectors 1 and 2 and the receiving hydrophone as 926.2 and 917.2 yd, respectively, corresponding to their actual positions while immersed in 16 ft of water, about half the existing water depth.

The elapsed travel time for the acoustic pings was measured for both projectors using three different receiving systems at three different signal levels. Table A1 contains a summary of this data, in groups of ten pulses, as obtained with the coincidence, amplitude-squelch, and amplitude detection systems.

Table A1
Calibration Travel Times for Acoustic Signals

Detection System	Relative Signal Level (db)	f_1 = 1090 Hz		f_2 = 2000 Hz	
		Mean Time (msec)	Standard Deviation (msec)	Mean Time (msec)	Standard Deviation (msec)
Coincidence*	0	578.4	1.3	560.4	0.5
	-12	599.8	7.0	565.3	0.9
	-24	594.1	7.7	569.9	1.4
Amplitude Squelch	0	576.7	1.2	559.3	0.7
	-12	600.9	3.8	564.5	0.8
	-24	605.7	10.9	568.9	9.3
Amplitude	0	576.5	1.1	560.7	0.9
	-12	588.0	4.1	570.3	3.5
	-24	615.8	14.1	578.5	8.2

*Set to 75 percent of threshold.

To reduce noise emanating from the subject surface ships during calibration, they were operated from shore power. There was an occasional interruption to data-taking whenever channel traffic produced a large noise interference. For the same signal-to-interference ratio, the best system under these conditions, although critical in adjustment, is the one utilizing the coincidence detection. Thus, all subsequent data at sea was taken using this system with a receiving hydrophone and preamplifier having a sensitivity of -71 db relative to 1 v for 1 μbar.

The temperature and salinity were determined for water samples taken from the channel, and application of Del Grosso's equation (8) yields a computed sound speed of 1690.04 yd/sec. Utilizing this sound speed and the applicable path lengths involved, the minimum time for f_1 and f_2 signal transmissions were computed as 548 and 543 msec, respectively. A comparison of values in Table A1 for the highest signal-to-noise ratio yields overall electroacoustic delays of 30.4 and 17.4 msec with computed standard deviations of 1.3 and 0.5 msec, respectively, for the two sources. These delays include the driver/transducer buildup, the hydrophone/receiver response, and the (common to both) radio link equipment delay of 5.6 msec with a standard deviation of 0.1 msec. An increased delay for the lower frequency system was expected since the amplifier filter stages had the same Q value. The delay of a receiver and detector for the highest signal level conditions should approach zero asymptotically in a simulated loop check. An actual minimum delay of 5 msec (shown in Fig. 31 of Ref. 3) results from the operating time of a relay in the test instrumentation loop. Thus, under optimum signal conditions during calibration, the minimum delay attributable to the driver/transducer combination is approximately 25 and 12 msec, respectively, for the nominally 1- and 2-kHz sources.

To ascertain gross amplitude effects of the signal upon system performance, a reduction in the signal level to that estimated for the first convergence zone was made corresponding to -24 db. There was an increase in overall delay by 16 to 46 msec, with an increase in the standard deviation of data by almost 8 msec. This increase in variability by a factor six times as great is an important characteristic of the travel time measurements. The 1090-Hz source, a Raytheon variable reluctance transducer, was driven without polarization current at one-half the frequency to produce an output of 95 db referenced to 1 μbar at 1 yd and was employed exclusively during these range accuracy measurements.

From this cross-channel calibration it was determined that the shoran distance measuring equipment had a net systematic error of 19.6 yd for a reduced signal intensity as simulated by a back-to-back antenna lobe configuration at the surveyed range. These measurements and the correction for the zero-set equipment condition had standard deviations of 0.9 and 1.1 yd, respectively. The motion of the antenna atop the mast at 90 ft above the waterline was estimated to be 6 in. or less. However, a reflection from the channel surface at a point midway between the ships would account for 1 yd of the systematic error at this range. The index of refraction correction for an electromagnetic propagation path between the antennae was made utilizing deck-mounted measurements of dry and wet bulb temperatures and was found to be less than 0.1 yd.

APPENDIX B

HORIZONTAL RANGE AND TRAVEL TIME CORRECTIONS

GENERAL CONSIDERATIONS

The data obtainable at each depth/range station, besides the overall elapsed travel time (in msec) and the range between project ships (in statute miles), included the ship's heading, the bearing from respective ships, and the cable inclination at the ocean surface to the hydrophone and acoustic source. In addition, at each station, estimates of ship position and drift were made by the bridge. An independent estimate of the source ship relative drift and direction through the ocean was obtained by determining the payout of light line from the bow of the ship to a glass gallon container ballasted to be awash in the ocean. The assumption of a similar drift magnitude at the receiving ship permits a calculation of a displacement from the shipboard davit sheaves of the hydrophone and transducer source to the end of their respective cables to be made, based on a flexible cable with a depressor at the end.*,†

In general, those corrections reflecting ship orientation and cable displacements were such that there were some cancellations, and the only significant corrections in excess of several yards were when the difference in depth between the source and receiving hydrophone was greater than 200 ft. In addition, corrections reflecting the shoran distance measuring equipment, as determined from calibration data taken on November 10 and zero-set conditions of each operative day, were also applied. A correction is applied to the elapsed travel time data to take into account the gross known electroacoustic delay also established during the calibration period.

RANGE MEASUREMENT CORRECTIONS

The sources of major corrections associated with the distance measurements are those connected with the equipment proper and the geometry of the experiment. The shoran system calibration provides one basis for correction under the assumption that the gain riding techniques keep the system at a set level for propagation paths beyond the normal radar horizon. This condition is difficult to verify except by an independent calibration performed at separations of 35 naut mi over water paths. The zero-set procedures yield a quantity of the order of several yards, which further modifies the station range readings. Each such determination has its own standard deviation.

Another first-order distance correction factor results from the relative location (to the shoran antenna mast) of the sheaves in the over-the-side handling of the line out to the respective source and receiving hydrophone on the transmitting and receiving ship. These actual distances amount to 10-13 yd for the subject vessels. During the operations, if the relative bearing of the receiving ship is not greater than ±50 degrees from the transmitting ship and the difference in the headings of these ships is no greater than ±40

*L. Pode, "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," David Taylor Model Basin, DTMB Report 687, Mar. 1951.
†L. Pode and L. Rosenthal, "Cable Function Tables for Small Critical Angles," Supplement to DTMB Report 687, Sept. 1955.

degrees, the correction to be applied to the range measurement at 75,000 yd is between -5 and +9 yd. However, the correction was generally less than this as these sister ships lie to at a difference of heading of only 10-20 degrees and on such relative bearings that the correction is considered insignificant. The remaining correction is the horizontal distance and bearing angle of the cable from the sheave point out to the respective source or hydrophone. The procedure is to estimate the relative motion through the ocean from computed drifts over the bottom (0.5 to 1.5 knots) and from chart ocean currents (0.5 knot) or from bottle drift estimates (0.5-0.8 knot) directly. At about 0.5 knot relative drift, the hydrophone cable is calculated to be smoothly displaced 15 ft at a depth of 420 ft while the transducer is displaced 10 ft at 300 ft. An assumption is made that the drift relative to the ocean has the same magnitude and direction at both ships even though the opening range rate at one depth/range station was as great as 0.4 knot. It is difficult to establish which of the two ships is drifting more, although it may have been the ROCKVILLE since her effective sail area should be greater by virtue of the extension of the original 01 level deck completely to the stern to form a balloon launching platform. There is another variability associated with both the source and the hydrophone and that is their depths. The hydrophone assembly carries a conventional depth transducer of one percent accuracy, whereas the depth of the source is known only to the extent of the separate strain and electrical cable paid out. The length of the former is nominally taken to the the source depth also.

Mention has already been made of the shoran beyond-the-horizon transmissions, in the diffraction region, which must be reached via a surface or elevated duct, or possibly from tropospheric scattering volumes. A range correction factor reflecting this condition at the time of the expedition was not possible. However, this variability may be estimated from the regression analysis of the grouped depth/range data for November 11 and 12. On these two days the slopes of the best straight lines ranged from -13 yd/min (closing) to +15 yd/min (opening). The average relative rate for all 61 depth/range stations was only -1.9 yd/min (closing). When a histogram is made of the standard deviations of the range data relative to these lines, there appear to be peaks at about 5 and 9 yd. It is proposed that the peak at 5 yd reflects the equipment/operator characteristics under at-sea motion conditions, while the peak at 9 yd represents these effects plus the beyond-the-horizon transmission stability. The average value for all range standard deviations was ±7.1 yd. Variations of shoran signal intensity even with the reasonable gain riding can contribute as much as ±3 yd.

Several other effects contribute to the random nature of these distance measurement data. For example, a roll of ±15 degrees for one ship results in changes of ±8 yd range in the direction of roll for the shoran antenna located 90 ft above the ocean surface. This effect is reduced considerably when two ships are located for-aft of one another with their bearing line perpendicular to the wind (roll) rather than upwind (or downwind) of each other. The latter condition minimizes the opening (closing) rates on a station. With the bearing line between the two ships perpendicular to their drift through the ocean, the error associated with the "catenary" correction displacements of cable from each ship is a minimum. For the deep hydrophone and transducer locations, this displacement correction is feasible, particularly when subsurface currents are uniform and constant.

In addition, there are small and usually insignificant offset of bias effects which will be noted here for completeness. At 90 ft above the water the average range measurement is greater than the surface distance by one part in 250,000. For a hydrophone depth at 420 ft, the distance is less than that at the surface by about one part in 50,000. The index of refraction of the atmosphere is generally greater near the surface than the nominal shoran system value of 1.0003365, and this means that all range readings are too great by several parts in 100,000.

A significant effect which can be applied to the computed mean horizontal velocity is the computed net opening or closing range rates. These have been as large as 0.25 yd/sec, and for a travel time of 44 sec this amounts to 11 yd, more than one part in 10,000.

TRAVEL TIME MEASUREMENT CORRECTIONS

The sources of major corrections associated with travel time measurements are those produced by the equipment and its operation. The acoustic equipment system calibration provides one basis for correction under the assumption that the signal levels encountered at first convergence will be at about the level predicted. Because of the many propagation paths (direct, bottom bounce, surface reflected, and refracted) and their combination with partial nulls and reinforcements, it is difficult to separate them out without any supplementary analog record of the acoustic pulse trains received at the hydrophone. It is recognized that the true minimum travel time is somewhat less than these measured values which form a delay-time distribution dependent on the signal strength and the set threshold level. While the magnitude of the delay can only be estimated from values determined during calibration, the time variability can be examined from the best straight-line analysis data for November 11 and 12. On these two days the slopes of the best straight lines obtained ranged from -42 to +55 msec/min, with an average of -1.8 msec/min for the 61 depth/range stations obtained. Because of the different arrival paths possible, the constraint of a best straight line imposed on travel time is probably unrealistic at the depth/range station level, and the resultant slopes are not easily interpreted. At the middle of the zone there can be more than four distinct arrivals, each producing a different mean horizontal velocity at the same depth and range without including a bottom reflection. Where many arrivals occur the envelope of the signal builds up and is detected at a time which can be no greater than some maximum value at a given range and for a specific geometry. For example, in the computed loci for convergence on Fig. 5(a), a separation of 2 yd/sec exists at 75,000 yd corresponding to hydrophone depths of 420 ft. This resulted from an arrival time difference of 55 msec between two rays following these paths. Considering the approximate travel time of 45 sec, the maximum slopes for a change between these two points would be ±73 msec/min, exceeding the values obtained by linear regressions on the experimental results.

When a histogram is made for the standard deviation of the travel time data relative to the best straight line for each depth/range station of November 11 and 12, there appear to be two peaks: one at about 20 and another at 90 msec. This histogram contains a minimum of 2.9 and a maximum of 181 msec giving a mean of 61 msec for all this data. It is proposed that the 20-msec peak expresses equipment performance under poor signal-to-background-interference conditions, while the 90-msec peak represents that effect plus multiple paths with the variable delayed-type interference wavefront buildup. It is not expected that the observed motion of the ships upon the ocean surface will reflect directly as large relative range excursions of the transducer and hydrophone beneath the seas. For example, an antenna motion of 8 yd would contribute about 5 msec to travel time if these two parameters were correlated perfectly.

APPENDIX C

TREATMENT OF DATA TO OBTAIN MEAN HORIZONTAL SOUND SPEED

MEAN VALUES AND VARIANCE

For each depth/range station, there exist sets of figures indicating an elapsed travel time in milliseconds and a horizontal range in yards. These data can be handled in several ways to yield a mean horizontal sound speed in yards per second and an estimate of its variability. Three methods were evaluated. By method A, a value for the speed of sound was computed for each pair of range and travel time data. For each depth/range station, values can then be averaged and a standard deviation computed. In method B, the average range and average travel time can be calculated for each depth/range station from which an overall average sound speed and standard deviation are determined. A best straight line (method C) is computed through the range data as a function of time, which will reflect accurately the relative drift rate. Similarly, a best straight line is computed for the travel time data. A variability of the data about these lines is obtained.

A comparison of the above three methods of analyses was made for three depth/range stations taken on November 11 and is shown in Table C1. Insofar as the range, travel time, and sound speed statistics are concerned, there is very little difference between methods A and C for the average range and time values, although the variability computed for these same parameters will be different. Method A provides a gross standard deviation for range and travel time for each depth/range station which ignores any trends, particularly those evidenced by range changes which a best straight line can minimize (for example, in runs 1 and 6). When run 20 was processed by method C its standard deviations appear larger because the estimate of variance, as computed, was not reduced as much as in runs 1 and 6 to compensate for the extra degree of freedom (five versus six) of method A, which tends to decrease the variance. In run 20 an examination of the travel time data alone reveals the existence of two distinct groupings, each of which has a smaller variability associated with it than the value listed. When this travel time separation was carried out, the data appear in Fig. 5(a), identified as A and B, respectively, for convergence and nonconvergence paths.

In the computation of the statistics representing the variability of sound speeds, method B is simplest, based on the computed sets of sound speeds at each depth/range station. For methods A and C, the variance σ_v^2 is developed from Eq. (C1):

$$\sigma_v^2 = \left(\frac{\partial v}{\partial T}\right)^2 \sigma_T^2 + \left(\frac{\partial v}{\partial R}\right)^2 \sigma_R^2, \tag{C1}$$

where $v = R/T$ is the mean horizontal velocity in yd/sec, assuming that the variance of range σ_R^2 and travel time σ_T^2 are not correlated. By performing the required substitutions in Eq. (C1) and employing estimates s, there results

$$s_v = \frac{1}{\overline{T}} \left(\overline{v}^2 s_T^2 + s_R^2\right)^{1/2}, \tag{C2}$$

where

s_v = estimated standard deviation of sound speed (yd/sec),

s_T^2 = estimated variance of travel time,

s_R^2 = estimated variance of range,

$\bar{T}$ = average travel time (sec), and

$\bar{v} = \bar{R}/\bar{T}$ = average mean horizontal sound speed (yd/sec).

A computation using Eq. (C2) is essentially the same as combining the respective variances by conversion to a percentage and then applying the square root of the resultant percentage to the computed average sound speed.

There is a significant reduction in the variance of the mean sound speeds by using method C over A and B. Method C was employed for the depth/range stations of November 11 and 12 and, for expediency, methods A and B were used for November 13.

Table C1
Comparison of Range, Travel Time, and Sound Speed Obtained by Three Different Methods of Analysis of Selected Data Taken on Nov. 11

Method	BT Run	Hydrophone Depth (ft)	Data Sets	Range (yd)		Travel Time (msec)		Sound Speed (yd/sec)	
				Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
A	1	20	11	72397.1	40.1	44149.8	72.0	1639.81	2.95
	6	220	7	70412.4	11.8	42914.0	10.4	1640.78	0.48
	20	420	7	76975.2	8.3	46930.6	171.0	1640.19	5.39
B	1	20	11	–	–	–	–	1639.85	3.22
	6	220	7	–	–	–	–	1640.78	0.32
	20	420	7	–	–	–	–	1640.23	5.79
C	1	20	11	72398.4	12.3	44149.8	51.5	1639.83	1.93
	6	220	7	70412.3	4.8	42915.4	9.6	1640.72	0.37
	20	420	7	76975.4	9.3	46930.6	180.7	1640.20	6.32

CORRELATION COEFFICIENTS

One can compare the relative effects of range and travel time measurements. For the first convergence zone an error in the mean horizontal sound speed of 1 yd/sec, representing about 0.06 percent, can result from either an error in travel time of 25 msec or an error in range of 45 yd. Allowing for a maximum range error of 10 yd after all corrections for geometry have been made, the dominant factor which remains is the elapsed travel time. It is of interest to determine the correlation that may exist between some derived characteristics of the two parameters, range and travel time.

Because there were 61 applicable depth/range stations from the two days of analysis, it is not clear whether the distribution of the standard deviations are normal or whether they can be represented by a Rayleigh distribution, or another function. Under the assumption of a normal distribution a calculation of the coefficient of correlation was made between the slopes and the standard deviation statistics as computed by regression methods on the range and travel time parameters for each depth/range station.

A computation for correlation coefficient between the time rate of change of travel time with range rate yields a value of 0.38. Other computations show that the correlation coefficient between the standard deviation of travel time and range rate to be only 0.25, a little greater than the correlation coefficient of 0.19 between the standard deviations of travel time and range. There is a significant improvement when the correlation is sought between the mean horizontal sound speed and the horizontal range; for example, all the convergence data from a regression analysis for November 13 yields a correlation coefficient of 0.63. Because of the large number of variables which affect the variability of travel time measurements, for example, noise interference, sound speed profile, hydrophone depth, and the multiple paths, a greater quantity of data would have to be taken and analyzed before those errors which are contributed by the instrumentation and those which may be attributed to the medium and to any experimental error can be separated out in this manner.

ANALYSIS OF VARIANCE

An analysis of variance was made on the mean horizontal sound speed data to determine if there were statistically significant factors other than the obvious range dependence. The data were separated out by days, as there were different transducer depths and resulting sound speed changes at the source depth, by hydrophone depth and by range. Other possible factors would include time of day (for sound speed profile changes) and sea conditions. Unavoidably, the range stations taken each day are not identical, and at best this data can be grouped into 2-kyd range intervals.

A gross comparison, by days, of the sound speed measurements for all ranges and depths by means of the analysis of variance* produces a significant ratio in the χ^2 distribution.† This ratio indicates that there is a real difference in the mean horizontal sound speed between days as compared to within days, as shown at the left side of Table C2. However, a significant value of this ratio may not only be the result of different mean values but may also reflect different variances. To examine this possibility, Bartlett's test‡ was applied to determine whether the variances s^2 can be considered as estimates of the true variance σ^2. The latter test result, which gave $\lambda^2 = 231$, exceeds the 99.95 percent level¶ of 15.2, indicative that there is a considerable difference.

To improve this situation, the analysis was restricted to the data from the three common hydrophone depths of 20, 220, and 420 ft, and a large ratio (center tabulation of C2) was obtained. Thus, it appears that some transformation should be made to effect a greater uniformity of variances. In a rearrangement of data for all days and all ranges by common depths, the ratio is still significant, as shown by the right side of Table C2 where the variances indicate a depth dependence. A more detailed presentation of the data is shown in Table C3 for each day for each of the common depths. Although there is some displacement of average range and sound speeds compared with the larger data groups in Table C2, there is a close enough correspondence to permit some generalization to be made. There was least variability of this data for November 13 and greatest for November 11 at each of the common depths. In addition, the variability at the 420-ft depths was least, although the greatest variability was not always evidenced at 20 ft. Such results

*A. Hald, "Statistical Theory with Engineering Applications," p. 423, New York: Wiley and Sons, 1952.
†A. Hald, "Statistical Tables and Formulas," Table VII, New York: Wiley and Sons, 1952.
‡"Statistical Theory with Engineering Applications," op. cit., p. 230.
¶"Statistical Tables and Formulas," op. cit., Table V.

Table C2
Analysis of Variance s^2 for Sound Speed

Quantity	All Ranges, All Depths By Days			All Ranges, Three Common Depths By Days			All Days, All Ranges, By Three Common Depths		
	11	12	13	11	12	13	20 ft	220 ft	420 ft
$\bar{R}$ (yd)	73870	73620	74340	73870	73910	74280	74240	73690	73740
$\bar{v}$ (yd/sec)	1640.8	1641.7	1642.4	1640.8	1641.7	1642.4	1642.0	1640.8	1641.6
s^2 (yd/sec)^2	15.8	9.9	9.0	15.8	11.4	9.3	15.4	14.7	11.3
n*	202	244	187	202	146	74	115	170	137
Between days, s_2^2	355 (yd^2/sec^2)			213			59.9		
Within days, s_1^2	11.6 (yd^2/sec^2)			13.2			13.9		
$\mathcal{F}^2 = s_2^2/s_1^2$	30.8			16.2			4.3		
Significant to	99.9%			99%			97.5%		

*Number of data point sets.

Table C3
Summary of First Convergence Zone Data for the Three Days at Three Common Depths

Hydrophone Depth (ft)	Quantity	Nov. Dates and (Source Depths)		
		11 (100 ft)	12 (300 ft)	13 (20 ft)
20	$\bar{R}$ (yd)	74720	74080	72920
	$\bar{v}$ (yd/sec)	1641.8	1642.5	1641.6
	s^2 (yd/sec)^2	19.5	12.2	8.8
	n*	60	41	14
220	$\bar{R}$ (yd)	73170	73270	75840
	$\bar{v}$ (yd/sec)	1640.4	1640.3	1642.6
	s^2 (yd/sec)^2	15.4	13.1	12.7
	n*	91	50	29
420	$\bar{R}$ (yd)	74070	73610	73430
	$\bar{v}$ (yd/sec)	1640.1	1642.5	1642.5
	s^2 (yd/sec)^2	13.0	9.6	6.5
	n*	51	55	31

*Number of data point sets.

reflect the ranges between the source and receiving hydrophone, their location relative to the surface channel, and the improved signal-to-interference ratio as the hydrophone is lowered further away from proximity to the surface vessel. At about a 20-ft depth there often is less background noise as undoubtedly the ship offers some acoustic shielding to a hydrophone suspended from the fantail. It is expected that the distribution of signal intensity with range and depth would offer an additional parameter for effecting a correlation with the data variability.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* U.S. Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION 2b. GROUP 3

3. REPORT TITLE (Unclassified)
MEAN HORIZONTAL SOUND SPEED TO THE FIRST CONVERGENCE ZONE IN NOVEMBER

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
An interim report on one phase of the problem.

5. AUTHOR(S) *(Last name, first name, initial)*
Cybulski, J.

6. REPORT DATE December 9, 1965	7a. TOTAL NO. OF PAGES 40	7b. NO. OF REFS 13

8a. CONTRACT OR GRANT NO. NRL Problem S01-15 b. PROJECT NO. RF 101-03-44-4064 c. SF 001-03-15-8133 d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6320 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* None

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Dept. of the Navy (ONR and BuShips)

13. ABSTRACT

Data on underwater one-way acoustic propagation times were collected during five traverses of the first convergence zone in the deep waters north of Puerto Rico. This data was obtained on three consecutive days in November 1958 by equipment located aboard two ships. The source ship utilized an acoustic transducer, transmitting 500-msec pulses at 1090 Hz, at depths of 20, 100, and 300 ft, and the receiving ship utilized a hydrophone at depths from 20 to 420 ft. The horizontal range between the ships varied from 68 to 79 kiloyards.

The values of sound speed obtained at all depths ranged from 1639 to 1647 yd/sec, increasing from the start to the end of the convergence zone. There was a significant change in the variability of sound speed values from one day to the next. Variations in the sound travel time measurements were least at the 420-ft depth.

The mean horizontal sound speed derived from the measured data was compared with values computed from an exact ray trace solution and also from an approximation utilized in the correction of sonar data. There is a general correspondence between these calculations and experimental data within the first convergence zone.

DD FORM 1 JAN 64 1473

Security Classification

14. KEY WORDS (Unclassified)	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Atlantic Ocean						
Puerto Rico						
Underwater sound						
Velocity						
Propagation						
Time						
Refraction						
Measurement						
Statistical analysis						
Mathematical models						
Acoustic ranges						
Shoran (distance-measuring equipment)						
Hiran (mode of operation of shoran)						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through _____."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through _____."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through _____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.