CONDUCTING UNDERWATER SURVEYS WITH A MULTI-PURPOSE INSTRUMENT

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*IBH Note. — The De*cember 1961 number of the ISA Journal contained an article entitled « Conducting Underwater Surveys with a Multi-Purpose Instrument » by Arthur G. ALEXIOU of the U.S. Naval Oceanographic Office. This article presented the description of an instrument for measuring sound velocity in water. The original manuscript from which this article was prepared was a detailed report that included a considerable amount of field data that was not presented in the article.

Considering the interest this article aroused in oceanographic circles, the Bureau asked the author for the results of subsequent observations which would confirm the value of the instrument.

The article presented below is therefore a reproduction of the article from the December 1961 number of the ISA Journal, together with a report written specially by the author for publication in the International Hydrographic Review, referring particularly to the results of experiments.

The editor of the ISA Journal kindly authorized the reproduction of the article.

Note on author. — The author received his Electrical Engineer, Bachelor of Science degree from the University of New Hampshire in 1951. He served as a meteorologist with the U.S. Air Force and received one year of graduate study in meteorology at the Massachusetts Institute of Technology while with the Air Force. He has been employed at the U.S. Naval Oceanographic Office since 1953 as an oceanographer and electronic engineer specializing in oceanographic instrumentation with emphasis on acoustics and magnetics. His present capacity after return from one year of graduate work in electrical engineering at the University of New Hampshire is Project Manager for Field Programs requiring complex instrument systems.

He is a member of the National Political Science Honor Society, Research Society of America and has published articles in the Instrument Society of America Journal and Coastal Engineering Conference.

For rapid and accurate data collection at sea during routine surveys, the U.S. Naval Oceanographic Office has developed a Sound Velocity-Depth-Temperature recording system having an operating range of 0 to 9 000 ft of depth. The system provides for a simultaneous digital display of all three variables in any desired units, an X-Y plot of any two of these variables, and a printed record of any two variables.

The entire system, including cable, winch, recording equipment, and underwater unit was engineered with the underlying intention of presenting the data straightforwardly and precisely while keeping the system reliable.

The undesirable factors inherent in most instrumentation, such an nonlinearity and temperature instability, have been largely eliminated in the design of the system. No range changes are required to obtain accuracy and readability, or to minimize nonlinearity. Each parameter is displayed and printed in conventional units with no necessity for corrections or reference to calibration sheets. (A minor correction is necessary due to the change in path length caused by a temperature change; the correction for the stainless steel we used was less than 0.02 metre/sec/°C). The punched paper tape is prepared in binary-coded-decimal form, ready for direct entry into a computer.

Accuracies that can be achieved with this system are : sound velocity 0.3 m/sec, pressure 0.25 %, and temperature 0.04 °C.

THE UNDERWATER INSTRUMENT

The underwater instrument (Figure 1) contains transducers for measuring the three variables, the electronics and power supplies for the sound velocity and pressure oscillators, and an oven for the pressure gauge.

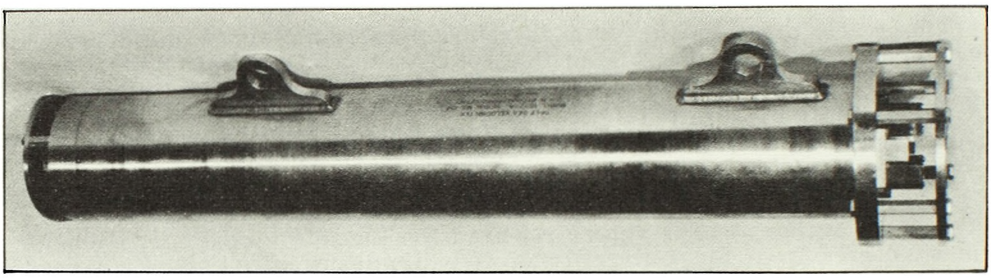

FIG. 1. — Multi-purpose underwater instrument for measuring sound velocity, depth, and temperature.

The entire instrument, shown in block diagram form in Figure 2 operates on 220 volts a.c. The housing, power supplies, and sound velocity portion of the instrument were built for the Hydrographic Office by ACF Industries.

Sound velocity

The Bureau of Standards TR-2 is the velocimeter used without modification, except for a power supply which was added to provide a — 6.5-volt d-c source. This device has an advertised inherent accuracy greater than 0.01 %. The method that must be used to calibrate the instrument, however, requires that the meter be calibrated in a liquid for which the velocity of sound is known accurately. Since there is some disagreement concerning the true value of sound velocity in distilled water, the system accuracy can be no greater than the discrepancy in the measured value; that is, 0.3 metre/sec over the 0-30 °C range. Repeated tests on several velocity meters in the laboratory indicated that this accuracy could be attained.

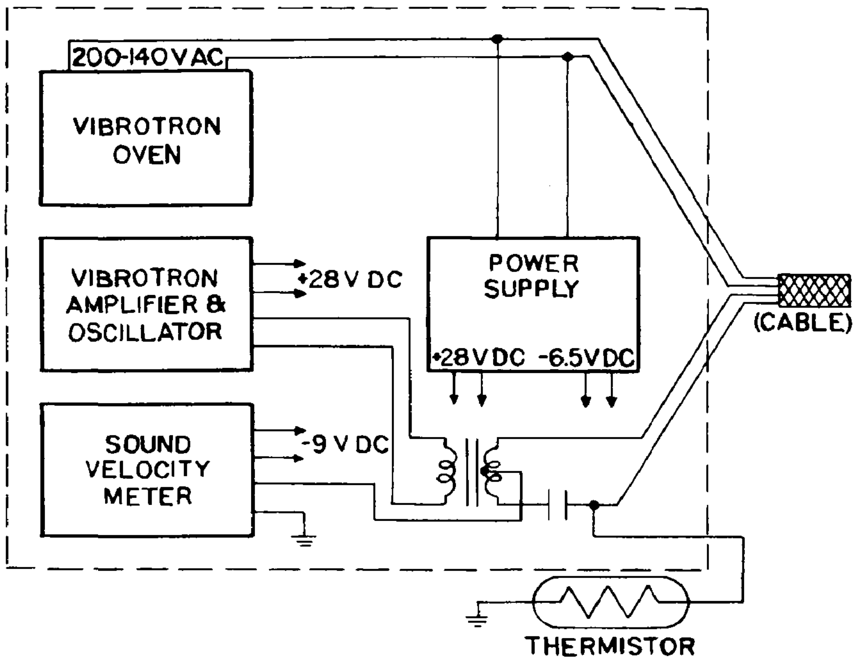

FIG. 2. — Block diagram of the entire multi-purpose instrument.

Depth

The depth gauge used is a Byron Jackson Vibrotron, temperature stabilized by means of a thermostatically controlled oven. Repeated calibrations in the laboratory with a dead-weight tester showed better than 0.25 % accuracy over the entire range. With the recording system used, the nonlinearity inherent in the transducer is overcome. Actually, the device is rather remarkable in its consistency; the Vibrotrons used in these meters apparently are quite improved over earlier models, which displayed very erratic frequency stability.

Temperature

In the underwater unit, there are no electronics associated with the temperature circuit. The temperature sensor is a thermistor connected through the telemetering cable to form one arm of a d-c bridge in the recording console. These thermistors can be replaced easily without any need for opening the pressure seals of the underwater instrument.

RECORDING CONSOLE

The recording console (Figure 3) has been engineered around commercial off-the-shelf components modified for this specific application.

It produces a printed record for any two parameters, an X-Y recording of these parameters, and a punched paper tape recording of all three parameters with a provision on the tape punch equipment for manual entry of up to 8 decimal digits for identification purposes. Essentially, the system (shown in block diagram form in Figure 4) consists of three electronic counters, a scanner, tape punch, digital recorder, and an X-Y recorder.

The sound velocity information frequency is fed into a standard Dymec Model 2500 N Computing Digital Indicator, an electronic counter having a provision for adjusting the gate time from 9.9999 to 0.001 second. If the velocimeter output frequency can be assumed to vary linearly and directly with sound velocity, then the counter display can be made to read in any desired units; that is, in ft/sec or metres/sec. This assumption is accurate to 1 ft/sec after a correction has been applied for the effect of temperature on the sound path length.

Fig. 3. — Recording console is comprised of commercially available, off-the-shelf components.

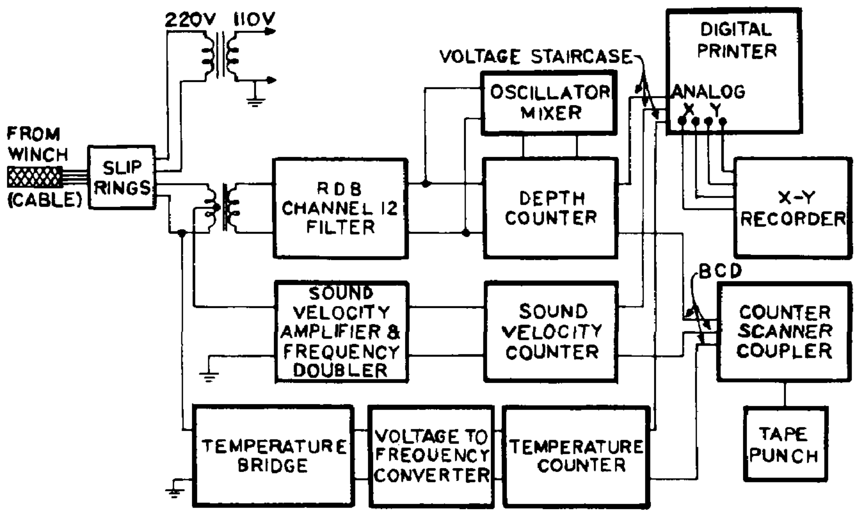

FIG. 4. — Block diagram of the recording console.

Depths are displayed on a similar counter that has become known as a Preset/Reset Counter. It is actually a Dymec Model 2500 N that has been modified to count backwards, since the Vibrotron frequency decreases with depth. This counter also has been modified to provide an adjustable reset number, which is used as a zero suppression to allow counting backwards from some number other than zero. Upon completion of the counting time, which is adjustable also, the display ends up with a number representing depth in any desired units — fathoms, feet, or metres. To provide a linear output from the essentially nonlinear Vibrotron, we employ a method for permuting the time base. Rather than counting against a standard time base, the counter counts against a varying external time base that is the difference frequency resulting from mixing the Vibrotron output frequency with some other appropriate fixed frequency. This mixing frequency can be computed using the values from the Vibrotron calibration data.

To define the nonlinearity that we want to correct, we use the following two equations :

$$d_1 = j\frac{f_0}{n - f_0} - j\frac{f_1}{n - f_1} \qquad (1)$$

$$d_2 = j\frac{f_0}{n - f_0} - j\frac{f_2}{n - f_2} \qquad (2)$$

where :

d_1 is the linear difference number desired for a pressure change from sea level to 50 % of full scale.

d_2 is the linear difference number desired for a pressure change from sea level to 100 % of full scale.

f_o is sea level pressure frequency.
f_1 is 50 % of full scale pressure frequency.
f_2 is 100 % of full scale pressure frequncy.
(f_o, f_1, and f_2 are obtained from deadweight calibration).
j is the gate time.
n is the mixing frequency.

The expression $(n—f)$ represents the time base and varies with f. Solving equation (1) for j yields :

$$j = \frac{d_1 (n - f_0)(n - f_1)}{f_0 (n - f_1) - f_1 (n - f_0)} = \frac{d_1 (n - f_0)(n - f_1)}{n (f_0 - f_1)} \quad (3)$$

Substituting (3) in (2) yields

$$d_2 = \frac{d_1 (n - f_0)(n - f_1)}{n (f_0 - f_1)} \left[\frac{f_0}{n - f_0} - \frac{f_2}{n - f_2} \right] = \frac{(n - f_1)(f_0 - f_2)}{(n - f_2)(f_0 - f_1)} d_1 \quad (4)$$

Solving (4) for n yields

$$n = \frac{f_2 d_2 (f_0 - f_1) - f_1 d_1 (f_0 f_2)}{d_2 (f_0 - f_1) - d_1 (f_0 - f_2)} \quad (5)$$

If d_1 is linearly related to d_2,

$$d_2 = 2d_1 \quad (6)$$

Then substituting (6) in (5) simplifies the expression for n to

$$n = \frac{2 f_0 f_2 - f_1 f_2 - f_0 f_1}{f_0 - 2 f_1 + f_2} \quad (7)$$

This method of permuting the time base may be used for many applications to get linear outputs from nonlinear devices.

The temperature signal is a varying *d-c* voltage linearly proportional to temperature. It is converted to frequency through the use of a Voltage to Frequency Converter, Dymec Model 2210. This frequency is displayed in °C on a Dymec Model 2500 N. The display contains four digits; and although the resolution is in hundredths of degrees C, the absolute accuracy is only as good as the calibrated accuracy of the probe and measuring circuit plus the accuracy of the Voltage to Frequency Converter (+ 0.1 % full scale).

The temperature circuit itself is rather unique. It provides linearity over the entire 0-30°C range by connecting a switching diode and two resistors R_a and R_b to the bridge. As the thermistor voltage drops below a certain point, the diode will conduct and switch additional load resistance into the bridge. If the proper values of resistance are used, the inherent S-shaped bridge response caused by the thermistor characteristics will be straightened. Since only one thermistor is used in the probe, the problem of providing matched spares is greatly simplified. Calibration checks can be made easily with a decade resistance box either at the console input or at the probe end of the cable.

Each counter has a binary-coded-decimal (BCD) output used for the Scanner/Coupler, the output of which is fed to a Friden Motorized Tape Punch, Model 2. Each counter also has a staircase voltage output for use with the printing recorder. Any two of the three counters can be connected to a Hewlett-Packard 560A Digital Recorder to give a simultaneous print out of any two parameters. The HP-560 A has been modified to provide two analog outputs for recording on a Mosely Model 5S X-Y Recorder. Each analog output signal is arranged so that any three adjacent columns on the printer can be selected for plotting by a front-panel selector. For readings having a large number of significant figures, this method provides an expanded scale feature that can provide a graphic presentation having a resolution of one part in one-hundred million. Under these conditions, the output is as accurate as the displayed number. Each output has a range and resolution of 0 to 999 in one-thousand voltage or current steps.

The X-Y recorder provides a graphic display of depth versus sound velocity or depth versus temperature. Automatic range changing results when either axis reaches a value divisible by 100 or 1000. Scale expansion can be accomplished easily by changing the selection of the significant digits to be graphed. The plotted data, although very accurate (0.25 % of scale), include those errors introduced by the X-Y recorder itself. The same data also are printed and recorded simultaneously on punched paper tape, however; and these data are free from the plotter error. The chart record shown in Figure 5 illustrates the automatic range changing of both sound velocity and depth. Both scales can be expanded by a factor of ten simply by changing a switch position. Figure 6*a* shows an expansion of the depth scale for the first 300 metres of a 1640-metre lowering. Figure 6*b* shows a segment of the printed data from which the plot of Figure 6 was made.

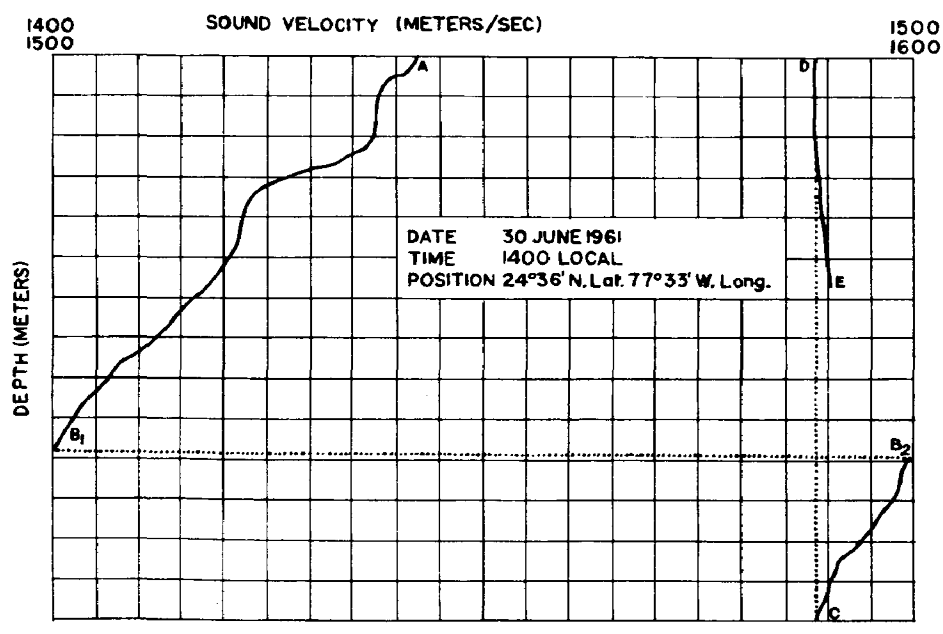

FIG. 5. — Chart record of depth versus sound velocity. Start trace at A and move downward toward B_1. During this segment of the trace, the sound velocity scale is 1 500 to 1 600, and the depth scale is 0 to 1 000. Recorder moved from B_1 to B_2 where sound velocity scale changed to 1 400-1 500 for remainder of trace. Follow trace from B_2 to C where depth scale changed to 1 000-2 000 for segment D to E.

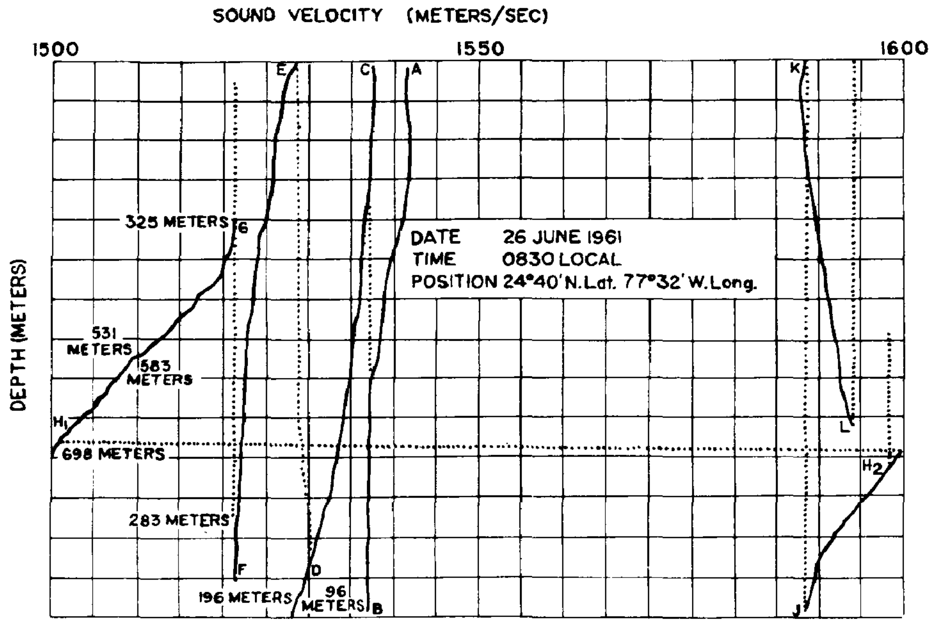

FIG. 6*a*

DEPTH m					SOUND VELOCITY m/s				
0	0	8	3	0	1	4	9	3	2
0	0	8	3	0	1	4	9	3	0
0	0	8	3	1	1	4	9	3	0
0	0	8	3	0	1	4	9	3	0
0	0	8	3	0	1	4	9	2	9
0	0	8	3	1	1	4	9	3	1
0	0	8	3	1	1	4	9	3	1
0	0	8	3	0	1	4	9	3	1
0	0	8	3	0	1	4	9	3	1
0	0	8	3	1	1	4	9	2	9
0	0	8	2	9	1	4	9	2	9
0	0	4	3	6	1	4	7	8	4
0	0	8	0	9	0	9	6	4	2
0	0	7	9	9	1	4	9	5	0
0	0	7	8	8	1	4	9	5	5

FIG. 6*b*

FIG. 6. — Chart record of depth versus sound velocity. Note the changes in scale for depth. Start trace at A and move downward toward B. From A to B, the range was 0-100. At B, the range changed to 100-200 for the segment from C to D. At D, the range changed to 200-300 for the segment from E to F. At F, the ranged to 0-1 000 for the segments from G to H_1, and H_2 to J. At J, the range changed to 1 000-2 000 for the segment K to L.

SHIPBOARD HANDLING EQUIPMENT

Winch

The winch used for the system is a Commercial Engineering Corp. Series 600 Hoist. Designed for shipboard environment, it offers an infinite choice of drum speed between zero and maximum, and a provision for interchangeable cable drums. The drum shaft houses a six-conductor slip ring which is not disturbed when a drum change is made.

The hoist is powered by a constant speed, reversing type, 5 HP electric motor (220/440 volts, 3 phase, 60 cycles per second). The 2600-lb hoist (not counting cable weight) is 55 inches long $\times$ 52 inches wide $\times$ 58 inches high. The maximum hoisting speed of the winch varies from 136 to 310 ft/min, depending upon the amount of wire remaining on the drum. Drum capacity is 10 000 ft of 0.190-inch diameter wire.

Cable

The cable used in raising and lowering the underwater instrument is a four-conductor double-armored type having an outside diameter of 0.190 inches. It is manufactured by American Steel and Wire Division of U.S. Steel under the brand name of Amergraph Cable, type 4-H-O. Each conductor is constructed of 7 wires of 0.008-inch copper insulated with 0.008 inches of polypropylene. Conductor resistance is 24 ohms/1 000 ft, and insulation resistance is 50 megohms/mile in sea water.

The armor consists of two counter-wound layers of galvanized plow steel, the first layer being 18 wires of 0.018-inch diameter, the second being 18 wires of 0.025-inch diameter; the breaking strength is 2700 lbs. Cable weight is approximately 60 lbs/1 000 ft.

FIELD EXPERIENCE (*)

The sound velocimeter has been operated successfully in the field for more than a year. The entire system including the overside unit, winch and cable, and recording system have proven to be a reliable, accurate and precision tool in oceanography. The weakest link in the system has proven to be the cable which begins to deteriorate after approximately 100 lowering cycles. Cable problems have been and continue to be one of the most difficult obstacles in the way of reliable electronic oceanographic instrumentation. The sound velocimeter fortunately can withstand a considerable deterioration in cable insulation without affecting the sound velocity and depth data accuracy since signal frequency and not amplitude carries this intelligence along the cable.

The maximum depth which the instrument has been repeatedly subjected to in the field is approximately 1500 metres. During many of the field exercises water samples were taken with Nansen casts together with temperatures from reversing thermometers to determine velocities in an independent manner to correlate with the sound velocimeter system data. This data correlation was quite impressive and is listed in this report, Table 2. Because of the excellent results and the long term reliability of the instrument at sea, a high degree of confidence in the instrument has been engendered in all who have had occasion to use it. There are few, if any, other electronic oceanographic instruments that enjoy such status.

(*) This section and following sections were written by the author in November 1962 and replace the section on " Field Results " of the article that appeared in the *ISA* Journal of December 1961.

In the Instrument Society of America Journal article a temperature circuit was described as a part of the system. Regretfully, this part of the system has been too vulnerable to the cable problem to be of any significant value thus far. Its operation depends on a high insulation resistance in the cable that thus far has not been attainable except with new cable. The problem is not an insurmontable one but has not received the attention it requires for many reasons, the principal one of which is the great need for sound velocity depth data and for this reason every velocimeter system this Office has is utilized for data acquisition. Until very recently no time has been devoted to further engineering and improvements to this system, especially in the design of a higher performance cable whose specifications unfortunately are intimately tied to the winch in the system.

This Office has no experience to report on the performance of this system in depths much greater than a mile. Information has been received from other sources that problems have been experienced with the type of configuration used in the present model velocimeter at depths greater than 10 000 ft. The main factor apparently is the possibility of dishing which changes the sound path length. This and the elimination of the small correction due to thermal contraction on the sound path are areas which will be investigated in the near future.

Procedure

Nansen casts were taken with protected and unprotected reversing thermometers. As soon as practical after the cast was retrieved the velocimeter was lowered as rapidly as possible (approximately 5 ft/sec) and readings were obtained on both lowering and raising. As mentioned in the previous report there was a noticeable effect on sound velocity readings due to relative flow through the sound path and therefore up and down readings were averaged to cancel this effect. This averaging process was spot checked in the field at several depths by holding the meter at a given depth for a few readings and comparing these data with the average of full speed up and down readings through that depth. These values compared within $\pm$ 0.1 m/sec.

Most of the casts made with the Nansen bottles were made with zero wire angle. Thermometric depths agreed within 2 or 3 metres with meter wheel readings.

The Vibrotron on repeated calibration with a dead weight tester displayed excellent results deviating from the standard by no more than $\pm$ 2 metres at any pressure and at any temperature in the 4 000 psi range. Significantly, at depths less than 500 metres the deviation was not greater than 1 metre. The dead weight tester used was accurate to within 0.1 % of the reading. Although specifications on the Vibrotron do not advertise this high an accuracy, there is no doubt that the gauges used performed in the field as well as exhibited during laboratory calibrations and considerably better than the specifications imply.

The data obtained by both methods was compared by using depth as an absolute reference for comparing sound velocities at these observed depths. This procedure is the only method one could use under the

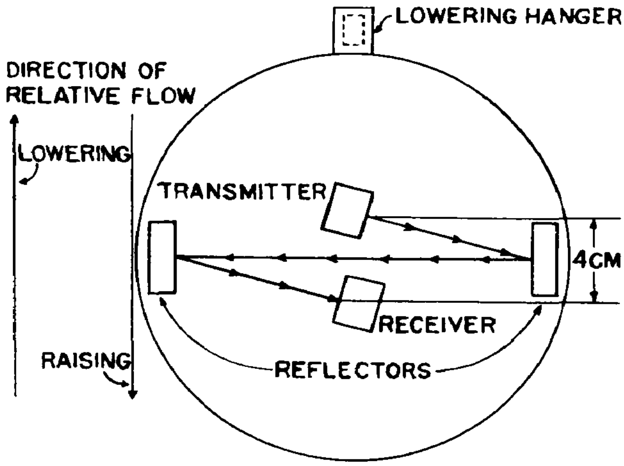

FIG. 7. — Schematic diagram of the velocimeter sound path.

circumstances. It is realized that thermometric depths are limited by accuracies of .5 % but because of the ideal conditions of zero wire angle in many cases the depth figures are probably considerably better than this. This assumption is validated by the excellent correlation of the data obtained by both methods especially at depths where conditions were very stable. The temperatures used to correct for sound path length changes were obtained from the reversing thermometers. Sound velocities were computed using WILSON,s equation [2].

TABLE 1

Summation of differences between computed values and sound velocimeter readings from 367 observations

Diff. ± m/sec	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0	1,1	1,2	1,3	1,4 à 2,0	> 2,0
% of Obs.	11,0	26,5	20,2	11,1	9,6	3,0	4,6	1,9	0,8	0,8	0,8	0,6	0,3	0,6	1,6	6,6
Cumul. %	11,0	37,5	57,7	68,8	78,4	81,4	86,0	87,9	88,7	89,5	90,3	90,9	91,2	91,8	93,4	100,0

ACKNOWLEDGEMENTS

The author wishes to acknowledge the excellent cooperation provided by Mr. Willis HAMMOND of the Marine Surveys Division of the U. S. Naval Oceanographic Office as senior scientist aboard the USS *San Pablo* in coordinating the collection of a major portion of the temperature, salinity and sound velocity data used in this report.

TABLE 2

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
Date : 26 June 1961 Time : 1400 Local Position : 24° 40′ N Lat. 77° 32′ W Long.			
0	1 543.2	1 543.1	+ 0.1
500	1 513.1	1 513.5	— 0.4
1 000	1 487.9	1 487.9	0
1 500	1 492.1	1 491.8	+ 0.3
Date : 26 June 1961 Time : 1800 Local Position : 24° 40′ N Lat. 77° 32′ W Long.			
0	1 538.7	1 538.6	+ 0.1
500	1 512.6	1 512.8	— 0.2
1 000	1 487.2	1 486.9	+ 0.3
1 500	1 492.0	1 491.8	+ 0.2
Date : 26 June 1961 Time : 2200 Local Position : 24° 40′ N Lat. 77° 32′ W Long.			
0	1 538.7	1 538.4	+ 0.3
500	1 512.9	1 512.6	+ 0.3
1 000	1 487.7	1 487.5	+ 0.2
1 500	1 492.1	1 491.9	+ 0.2
Date : 6 July 1961 Time : 2000 Local Position : 24° 25′ N Lat. 77° 34′ W Long.			
0	1 543.6	1 543.4	+ 0.2
10	1 543.6	1 543.3	+ 0.3
20	1 543.6	1 543.3	+ 0.3
30	1 543.5	1 542.1	+ 1.4
50	1 541.4	1 541.0	+ 0.4
75	1 540.1	1 539.9	+ 0.2
100	1 539.8	1 539.3	+ 0.5
150	1 538.2	1 538.6	— 0.4
200	1 531.6	1 532.6	— 1.0
250	1 524.9	1 525.5	— 0.6
300	1 522.9	1 523.1	— 0.2
350	1 521.8	1 522.0	— 0.2
400	1 520.6	1 520.4	+ 0.2
450	1 518.1	1 517.5	+ 0.6
500	1 515.3	1 514.9	+ 0.4
550	1 513.0	1 510.7	+ 2.3
600	1 508.8	1 508.3	+ 0.5
650	1 505.2	1 503.2	+ 2.0
700	1 501.8	1 500.0	+ 1.8
750	1 497.5	1 496.2	+ 1.3
800	1 493.5	1 492.5	+ 1.0
850	1 490.8	1 490.2	+ 0.6
900	1 488.6	1 488.0	+ 0.6
950	1 487.3	1 487.0	+ 0.3
1 000	1 487.0	1 487.1	— 0.1
1 100	1 487.4	1 487.5	— 0.1
1 200	1 488.4	1 488.3	+ 0.1
1 300	1 489.8	1 489.8	0
1 400	1 491.0	1 490.8	+ 0.2
Date : 7 July 1961 Time : 0900 Local Position : 24° 20.7′ N Lat. 77° 26.5′ W Long.			
0	1 543.4	1 542.8	+ 0.6
10	1 543.5	1 543.1	+ 0.4

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
20	1 543.5	1 543.2	+ 0.3
30	1 542.8	1 543.4	— 0.6
50	1 540.1	1 540.4	— 0.3
75	1 539.2	1 539.0	+ 0.2
100	1 538.6	1 538.5	+ 0.1
150	1 537.6	1 537.7	— 0.1
200	1 533.0	1 532.3	+ 0.7
250	1 525.0	1 525.4	— 0.4
300	1 523.5	1 523.5	0
350	1 520.1	1 521.9	— 0.8
400	1 520.2	1 520.2	0
450	1 517.7	1 517.4	+ 0.3
500	1 514.7	1 514.6	+ 0.1
550	1 511.5	1 511.7	— 0.2
600	1 508.0	1 507.8	+ 0.2
650	1 504.5	1 504.4	+ 0.1
700	1 501.3	1 500.6	+ 0.7
750	1 498.2	1 498.2	0
800	1 494.8	1 494.0	— 0.8
850	1 491.7	1 492.0	— 0.3
900	1 490.1	1 490.8	— 0.7
950	1 489.0	1 489.4	— 0.4
1 000	1 488.6	1 488.8	— 0.2
1 100	1 488.6	1 488.4	+ 0.2
1 200	1 489.3	1 489.1	+ 0.2
1 300	1 490.1	1 490.0	+ 0.1
1 400	1 491.1	1 490.9	+ 0.2
1 500	1 492.2	1 491.9	+ 0.3

Date : 25 June 1961
Time : 1400 Local
Position : 24° 40′ N Lat.

150	1 537.3	1 537.1	+ 0.2
200	1 528.7	1 528.6	+ 0.1
250	1 524.2	1 524.0	+ 0.2
300	1 522.5	1 522.5	0
400	1 520.0	1 520.2	— 0.2
500	1 515.2	1 515.2	0
600	1 509.2	1 509.1	+ 0.1
700	1 502.7	1 503.6	— 0.9
800	1 498.0	1 498.3	— 0.3
900	1 491.9	1 492.3	— 0.4
1 000	1 489.2	1 489.7	— 0.5
1 100	1 488.5	1 488.6	— 0.1
1 200	1 489.9	1 489.2	+ 0.7
1 300	1 490.2	1 490.1	+ 0.1
1 400	1 491.1	1 491.1	0
1 600	1 493.9	1 493.7	+ 0.2

Date : 12 Sept. 1961
Time : 1526 Local
Position : 23° 59′ N Lat. 77° 16′ W Long.

30	1 546.3	1 546.1	+ 0.2
100	1 539.7	1 538.9	+ 0.8
150	1 536.8	1 537.3	— 0.5
200	1 529.9	1 529.5	+ 0.4
250	1 524.9	1 524.5	+ 0.4
300	1 523.2	1 523.0	+ 0.2
400	1 521.2	1 520.8	+ 0.4

Date : 13 Sept. 1961
Time : 1450 Local
Position : 23° 59′ N Lat. 77° 16′ W Long.

0	1 545.9	1 546.0	— 0.1
10	1 545.8	1 545.9	— 0.1

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
20	1 546.0	1 546.0	0
30	1 546.1	1 546.2	— 0.1
50	1 544.9	1 545.1	— 0.2
75	1 542.4	1 542.3	+ 0.1
100	1 539.9	1 539.7	+ 0.2
150	1 537.1	1 537.3	— 0.2
200	1 529.4	1 529.1	+ 0.3
250	1 525.1	1 524.7	+ 0.4
300	1 522.9	1 522.3	+ 0.6
400	1 521.2	1 520.9	+ 0.3

Date : 13 Sept. 1961
Time : 2100 Local
Position : 23° 59′ N Lat. 77° 16′ W Long.

0	1 546.4	1 546.3	+ 0.1
10	1 545.7	1 545.8	— 0.1
20	1 546.0	1 546.1	— 0.1
30	1 546.2	1 546.2	0
50	1 544.9	1 544.7	+ 0.2
75	1 542.9	1 542.8	+ 0.1
100	1 540.0	1 539.8	+ 0.2
150	1 536.8	1 536.9	— 0.1
200	1 528.9	1 528.8	+ 0.1
250	1 524.9	1 524.5	+ 0.4
300	1 523.2	1 522.9	+ 0.3
400	1 521.2	1 521.0	+ 0.2

Date : 14 Sept. 1961
Time : 0307 Local
Position : 23° 59′ N Lat. 77° 16′ W Long.

0	1 546.4	1 546.4	0
10	1 546.0	1 546.1	— 0.1
20	1 546.0	1 546.1	— 0.1
30	1 546.2	1 546.3	— 0.1
50	1 544.3	1 544.4	— 0.1
75	1 542.8	1 542.7	+ 0.1
100	1 539.7	1 539.6	+ 0.1
150	1 536.9	1 537.4	+ 0.5
200	1 529.8	1 529.2	+ 0.4
250	1 524.8	1 524.6	+ 0.2
300	1 523.1	1 522.9	+ 0.2
400	1 520.9	1 520.7	+ 0.2

Date : 14 Sept. 1961
Time : 0855 Local
Position : 23° 59′ N Lat. 77° 16′ W Long.

10	1 546.1	1 546.0	+ 0.1
20	1 546.2	1 546.0	+ 0.2
30	1 546.0	1 546.1	— 0.1
50	1 544.6	1 544.4	+ 0.2
75	1 542.3	1 542.0	+ 0.3
100	1 539.8	1 539.4	+ 0.4
150	1 536.7	1 536.1	+ 0.6
200	1 528.9	1 528.7	+ 0.2
250	1 524.5	1 524.6	+ 0.1
300	1 522.8	1 522.9	— 0.1
400	1 521.0	1 521.1	— 0.1
500	1 516.3	1 516.2	+ 0.1
600	1 509.7	1 509.9	— 0.2
700	1 504.5	1 504.4	+ 0.1
800	1 499.0	1 499.6	— 0.6
900	1 494.0	1 494.3	— 0.3
1 000	1 490.0	1 490.5	— 0.5
1 100	1 488.4	1 489.1	— 0.7
1 200	1 488.9	1 489.1	— 0.2

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
Date : 14 Sept. 1961 Time : 1421 Local Position : 23° 59′ N Lat. 77° 16′ W Long.			
0	1 545.9	1 545.7	+ 0.2
10	1 545.8	1 545.9	— 0.1
20	1 546.0	1 545.9	+ 0.1
30	1 546.0	1 546.0	0
50	1 545.2	1 544.9	+ 0.3
75	1 542.3	1 541.9	+ 0.4
100	1 539.6	1 539.6	0
150	1 536.3	1 536.9	— 0.6
200	1 528.8	1 529.0	— 0.2
250	1 524.9	1 524.9	0
300	1 522.4	1 522.9	— 0.5
400	1 521.4	1 521.3	+ 0.1
Date : 15 Sept. 1961 Time : 0313 Local Position : 23° 59′ N Lat. 77° 16′ W Long.			
10	1 545.9	1 542.2	+ 3.7
20	1 546.0	1 542.9	+ 3.1
30	1 546.1	1 544.4	+ 1.7
50	1 545.8	1 545.5	+ 0.3
75	1 540.8	1 540.7	+ 0.1
100	1 539.3	1 539.3	0
150	1 535.9	1 536.1	— 0.2
200	1 529.2	1 529.1	+ 0.1
250	1 524.9	1 524.7	+ 0.2
300	1 523.4	1 523.2	+ 0.2
400	1 521.4	1 521.4	0
Date : 15 Sept. 1961 Time : 1500 Local Position : 23° 59′ N Lat. 77° 16′ W Long.			
0	1 546.0	1 545.9	+ 0.1
10	1 545.8	1 545.7	+ 0.1
20	1 545.9	1 545.9	0
30	1 545.9	1 546.0	— 0.1
50	1 545.4	1 545.8	— 0.4
75	1 541.6	1 541.5	+ 0.1
100	1 539.2	1 539.1	+ 0.1
150	1 535.4	1 536.3	— 0.9
200	1 528.1	1 527.8	+ 0.3
300	1 523.6	1 524.8	+ 1.2
400	1 521.9	1 523.3	— 0.4
Date : 17 Sept. 1961 Time : 1300 Local Position : 24° 18′ N Lat. 77° 28′ W Long.			
10	1 546.0	1 539.7	+ 6.3
20	1 546.3	1 540.5	+ 5.8
30	1 546.3	1 540.8	+ 5.8
50	1 546.5	1 544.0	+ 1.5
75	1 541.6	1 542.0	— 0.6
100	1 539.4	1 539.8	— 0.4
150	1 536.6	1 537.9	— 1.3
200	1 529.6	1 529.7	— 0.1
250	1 524.7	1 524.6	+ 0.1
300	1 524.2	1 523.6	+ 0.6
400	1 521.3	1.521.0	+ 0.3

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
Date : 17 Sept. 1961 Time : 1835 Local Position : 24° 18′ N Lat. 77° 28′ W Long.			
0	1 546.7	1 511.8	+ 34.9
10	1 546.5	1 526.3	+ 20.2
20	1 546.3	1 529.3	+ 17.0
30	1 546.3	1 530.1	+ 16.2
50	1 546.5	1 538.1	+ 8.4
75	1 542.3	1 533.7	+ 7.6
100	1 539.9	1 539.5	+ 0.4
150	1 537.2	1 535.8	+ 1.4
200	1 530.0	1 530.1	— 0.1
250	1 525.1	1 524.8	+ 0.3
300	1 524.1	1 523.8	+ 0.3
400	1 521.4	1 521.1	+ 0.3
500	1 516.7	1 516.5	+ 0.2
600	1 510.0	1 510.9	— 0.9
700	1 503.6	1 503.9	— 0.3
800	1 498.3	1 498.5	— 0.2
900	1 492.4	1 493.5	— 1.1
1 000	1 489.6	1 489.7	— 0.1
Date : 18 Sept. 1961 Time : 0112 Local Position : 24° 18′ N Lat. 77° 28′ W Long.			
0	1 546.6	1 546.7	— 0.1
10	1 546.8	1 516.7	+ 30.1
20	1 546.4	1 522.7	+ 23.7
30	1 546.3	1 527.7	+ 18.6
50	1 546.5	1 535.5	+ 11.0
75	1 541.2	1 536.4	+ 4.8
100	1 539.6	1 534.3	+ 5.3
150	1 537.3	1 537.2	+ 0.1
200	1 530.4	1 530.1	+ 0.3
250	1 525.0	1 524.8	+ 0.2
300	1 524.4	1 524.2	+ 0.2
400	1 521.8	1 521.5	+ 0.3
Date : 18 Sept. 1961 Time : 0700 Local Position : 24° 18′ N Lat. 77° 28′ W Long.			
0	1 545.9	1 545.7	+ 0.2
10	1 545.9	1 525.7	+ 20.2
20	1 545.8	1 538.3	+ 7.5
30	1 545.9	1 528.0	+ 17.9
50	1 546.1	1 533.0	+ 13.1
75	1 544.7	1 535.2	+ 9.5
100	1 540.5	1 537.1	+ 3.4
150	1 538.2	1 537.8	+ 0.4
200	1 531.1	1 530.8	+ 0.3
250	1 525.3	1 525.0	+ 0.3
300	1 524.1	1 524.2	— 0.1
400	1 521.3	1 521.2	+ 0.1
Date : 18 Sept. 1961 Time : 1200 Local Position : 24° 18′ N Lat. 77° 28′ W Long.			
0	1 545.9	1 545.8	+ 0.1
10	1 546.0	1 546.0	0
20	1 545.9	1 546.0	— 0.1
30	1 546.1	1 546.1	0

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
50	1 544.2	1 544.6	— 0.4
75	1 543.4	1 543.5	— 0.1
100	1 539.9	1 539.9	0
150	1 537.6	1 537.1	+ 0.5
200	1 530.8	1 531.0	— 0.2
250	1 525.7	1 525.6	+ 0.1
300	1 524.4	1 524.2	+ 0.2
400	1 522.2	1 522.0	+ 0.2

Date : 18 Sept. 1961
Time : 1902 Local
Position : 24° 18′ N Lat. 77° 28′ W Long.

0	1 546.8	1 546.7	+ 0.1
10	1 546.4	1 546.4	0
20	1 546.5	1 545.5	+ 1.1
30	1 546.3	1 546.3	0
50	1 546.6	1 546.4	+ 0.2
75	1 544.4	1 544.1	+ 0.3
100	1 540.6	1 540.6	0
150	1 538.3	1 538.3	0
200	1 531.7	1 531.4	+ 0.3
250	1 525.0	1 525.2	— 0.2
300	1 523.9	1 523.9	0
400	1 521.4	1 521.2	+ 0.2
500	1 517.1	1 517.4	— 0.3
600	1 511.1	1 511.5	— 0.4
700	1 503.3	1 504.0	— 0.7
800	1 499.0	1 498.8	+ 0.2
900	1 491.5	1 492.3	+ 0.2
1 000	1 489.2	1 489.3	— 0.1

Date : 19 Sept. 1961
Time : 0055 Local
Position : 24° 18′ N Lat. 77° 28′ W Long.

0	1 546.1	1 546.1	0
10	1 546.0	1 545.9	+ 0.1
20	1 546.2	1 546.1	+ 0.1
30	1 546.0	1 546.0	0
50	1 546.0	1 546.0	0
75	1 544.1	1 544.0	+ 0.1
100	1 540.1	1 540.1	0
150	1 537.8	1 537.8	0
200	1 531.6	1 530.9	— 0.3
250	1 525.6	1 525.4	+ 0.2
300	1 524.4	1 524.1	+ 0.3
400	1 521.8	1 521.7	+ 0.1

Date : 19 Sept. 1961
Time : 0700 Local
Position : 24° 18′ N Lat. 77° 28′ W Long.

0	1 545.9	1 545.8	+ 0.1
10	1 546.0	1 546.1	— 0.1
20	1 545.9	1 546.0	— 0.1
30	1 546.0	1 546.0	0
50	1 546.3	1 545.7	+ 0.6
75	1 546.1	1 545.7	+ 0.4
100	1 540.4	1 540.2	+ 0.2
150	1 538.5	1 538.3	+ 0.2
200	1 532.3	1 531.9	+ 0.4
250	1 525.7	1 525.3	+ 0.4
300	1 523.9	1 523.7	+ 0.2
400	1 521.1	1 521.0	+ 0.1

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
Date : 1 Oct. 1961 Time : 2220 Local Position : 24° 42′ N Lat. 76° 15′ W Long.			
0	1 545.3	1 545.6	— 0.3
10	1 545.6	1 545.8	— 0.2
20	1 545.7	1 545.8	— 0.1
30	1 545.9	1 545.9	0
50	1 546.1	1 546.4	— 0.3
75	1 543.8	1 544.1	— 0.3
100	1 539.0	1 539.1	— 0.1
150	1 533.0	1 533.1	— 0.1
200	1 527.4	1 527.4	0
250	1 524.6	1 524.7	— 0.1
300	1 523.5	1 523.4	+ 0.1
400	1 522.8	1 522.8	0
500	1 520.9	1 520.7	+ 0.2
600	1 514.6	1 515.0	— 0.4
700	1 505.8	1 506.8	— 1.0
Date : 2 Oct. 1961 Time : 0910 Local Position : 24° 42′ N Lat. 76° 15′ W Long.			
10	1 545.4	1 545.5	— 0.1
20	1 545.7	1 545.6	+ 0.1
30	1 546.0	1 546.0	0
50	1 546.5	1 546.8	— 0.3
75	1 541.8	1 542.2	— 0.4
100	1 538.5	1 538.9	— 0.4
150	1 534.1	1 533.9	+ 0.2
200	1 527.7	1 528.2	— 0.5
250	1 525.0	1 524.9	+ 0.1
300	1 523.9	1 523.8	+ 0.1
400	1 523.1	1 523.0	+ 0.1
Date : 3 Oct. 1961 Time : 1500 Local Position : 24° 42′ N Lat. 76° 15′ W Long.			
0	1 545.7	1 545.0	— 0.3
10	1 545.5	1 545.7	— 0.2
20	1 545.6	1 545.8	— 0.2
30	1 545.8	1 546.0	— 0.2
50	1 546.7	1 546.9	— 0.2
75	1 541.3	1 541.4	— 0.1
100	1 537.7	1 537.8	— 0.1
150	1 531.3	1 531.3	0
200	1 526.4	1 526.5	— 0.1
250	1 525.1	1 524.9	+ 0.2
300	1 524.3	1 524.2	+ 0.1
400	1 522.5	1 522.4	+ 0.1
Date : 4 Oct. 1961 Time : 0921 Local Position : 24° 42′ N Lat. 76° 15′ W Long.			
0	1 547.4	1 545.3	+ 2.1
10	1 545.6	1 545.7	— 0.1
20	1 545.7	1 545.8	— 0.1
30	1 545.9	1 546.1	— 0.2
50	1 546.4	1 546.4	0
75	1 543.9	1 543.8	+ 0.1
100	1 538.9	1 538.9	0
150	1 531.7	1 531.8	— 0.1
200	1 527.5	1 527.4	+ 0.1
250	1 525.4	1 525.2	+ 0.2
300	1 524.3	1 524.4	— 0.1
400	1 522.6	1 522.4	+ 0.2

Depth m	Sound Velocity Computed m/s	Sound Velocity Measured m/s	Difference m/s
Date : 6 Oct. 1961 Time : 1027 Local Position : 24° 28′ N Lat. 76° 32′ W Long.			
0	1 546.0	1 546.4	— 0.4
10	1 546.2	1 546.6	— 0.4
20	1 546.4	1 546.8	— 0.4
30	1 546.5	1 547.0	— 0.5
50	1 547.1	1 547.3	— 0.2
75	1 545.6	1 546.7	— 0.1
100	1 538.6	1 538.5	+ 0.1
150	1 532.8	1 532.6	+ 0.2
200	1 527.6	1 527.6	0
250	1 524.6	1 524.7	— 0.1
300	1 523.7	1 523.1	+ 0.6
400	1 522.8	1 522.2	+ 0.6
500	1 519.0	1 519.1	+ 0.1
600	1 511.7	1 511.5	— 0.2
Date : 6 Oct. 1961 Time : 1500 Local Position : 24° 14′ N Lat. 76° 23′ W Long.			
10	1 545.7	1 545.8	— 0.1
20	1 545.7	1 546.0	— 0.3
30	1 545.8	1 546.2	— 0.4
50	1 546.0	1 546.4	— 0.4
75	1 544.2	1 544.4	— 0.2
100	1 539.7	1 539.3	+ 0.4
150	1 534.1	1 533.5	+ 0.6
200	1 528.0	1 527.4	+ 0.6
250	1 525.0	1 524.5	+ 0.5
300	1 524.0	1 523.7	+ 0.3
400	1 523.0	1 522.9	+ 0.1
500	1 519.3	1 519.5	— 0.2
600	1 511.5	1 512.2	— 0.7

REFERENCES

[1] Alexiou, Arthur G. : Conducting Underwater Surveys with a Multi-Purpose Instrument, *Instrument Society of America Journal,* Vol. 8, Number 12, December 1961.

[2] Wilson, W. D. : Speed of Sound in Sea Water as a Function of Temperature, Pressure and Salinity *Journal of the Acoustical Society of America,* Vol. 32, Number 10, June 1960.