PRECISE ECHO SOUNDING IN DEEP WATER

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IHB Note. *In view of the increasing importance to bathymetry of accurate determination of the velocity of sound at the present time, we think it useful to reprint the present article — quoted in the references for the preceding article — so that readers may be able to make a comparison between the arithmetical weighted mean and the harmonic mean methods.*

ABSTRACT

The advent of narrow-beam stabilized echo sounders and shipboard digital computers is revolutionizing bathymetry measurements in the deep ocean. New and more precise procedures for obtaining and correcting depth measurements are described, and the application of these methods aboard the USC&GS ship *Discoverer* is presented.

EQUIPMENT

The United States Coast and Geodetic Survey ship *Discoverer* is equipped with a Narrow-Beam Echo Sounder (NBES) designed and built by the Harris ASW Division of General Instrument Corp. The performance specifications were provided the corporation by the Coast and Geodetic Survey. Among the specifications was that this echo sounder is to project a 12 kHz narrow sound beam to be effectively $2\frac{2}{3}$ degrees total beam (3 dB) down). The sound beam is gyro stabilized to ± 1 degrees of the local gravity vertical within the limitations of ± 10 degrees pitch and ± 20 degrees roll. The depth resolution is ± 1 fathom at 4 000 fathoms. The sounding is displayed on a digital display to the nearest whole fathom, as well as on the conventional analog readout, a McKiernan-Terry Corp. Mark XV Precision Depth Recorder (PDR). The digital display of the NBES aboard the *Discoverer* was adjusted to provide an automatic correction for the average draft of the transducers.

The Data Acquisition System (DAS) of the *Discoverer* is a Westinghouse Prodac 510 processor utilizing a UNIVAC 1218 computer. The system is designed to collect, process, display, and store environmental data such as bathymetry, gravity, magnetics, wind speed and direction, and air and surface water temperatures; control data such as ship's course and speed, and position; and on-station data which includes water temperature, salinity, and velocity of sound as a function of depth.

OPERATING PROCEDURE

Prior to departure on a cruise, anticipated values of the velocity of sound are provided to the Coast and Geodetic Survey by the National Oceanographic Data Center. Computations are made from historical data using the empirical equation of W. D. WILSON [1].

The values provided to the ship are divided into applicable geographic zones. As the survey progresses from zone to zone, the values of the velocity of sound are changed to conform with the particular area of operations. An example of the geographic zones for a project is shown in figure 1.

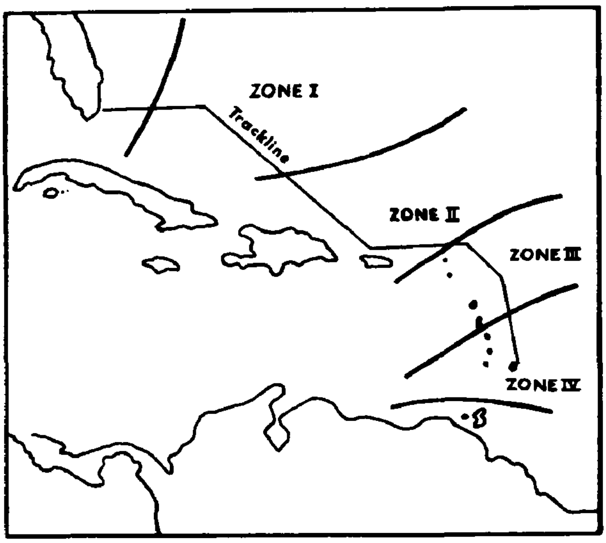

FIG. 1. — Geographic zones for velocity corrections. Corrections to soundings, as read from the sounding instrument, are changed as the trackline progresses from zone to zone.

NARROW-BEAM ECHO SOUNDING [2]

In this paper, the term *sounding* means the uncorrected reading of the echo sounder; *depth* means the vertical distance from the water surface to the bottom. The term *automatic depth input* as used in the description of the data acquisition system means *automatic sounding input.*

The narrow-beam echo sounder projects a signal at a repetition rate which is a function of the depth. If the water depth is in the range of 0-400 fathoms, a signal is projected once every second; if the depth is 400-800 fathoms, the signal is projected every 2 seconds, etc. This echo sounder is designed to receive the projected signal before the next sound burst is triggered.

The first wave form of the returning sound pulse that exceeds a preset threshold level is used to measure the elapsed traveltime of the projected signal. The time count, which began with the trigger pulse, is stopped when the trend of the amplitude of this wave form is reversed (see figure 2). The elapsed time is converted to fathoms and is displayed on the digital readout.

The mark on the precision depth recorder begins after the returning signal exceeds a preset threshold level, but before the amplitude is reversed, and lingers past the point of amplitude reversal until the threshold level is again reached. This produces a mark on the graphic recorder which varies from light to dark to light again as the signal passes. The change in density is not discernible to the eye. This implies that the digital sounding is not necessarily coincident with the leading edge of the mark on the recorder. This is illustrated in figure 2.

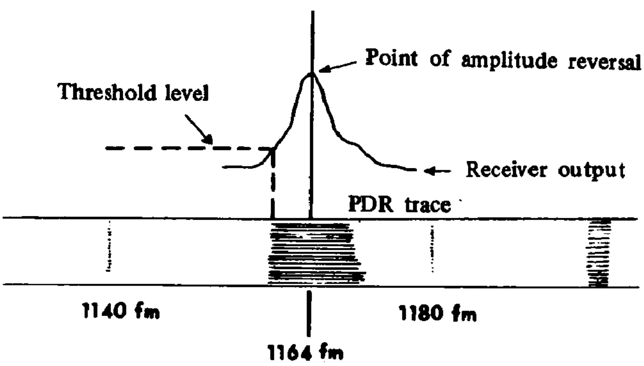

FIG. 2. — Superposition of the oscilloscope trace of the detected, filtered, and amplified receiver output over a section of PDR trace.

The difference in digital and analog values depicted in figure 2 was taken from a test conducted aboard the *Discoverer.* The 3-fathom draft correction was subtracted from the digital value prior to the comparison. The apparent difference in soundings may be due to many factors among which are bottom slope, paper distortion, and instrumental error. It should be recognized that a 1-fathom difference will occur if the time from the threshold to amplitude reversal is 2.5 milliseconds.

The digital value, with the draft correction, is automatically read into the data acquisition system when automatic depth input (ADI) is initialized. For the sake of continuity, the digital readings are used to obtain soundings whenever the narrow-beam echo sounder is in operation.

The narrow-beam echo sounder is a gated instrument. The gating switch is divided into ranges of 400 fathoms. This provides coordination with the scales on the precision depth recorder. If this switch is set at a range less than the sounding, the digital readings become erratic. If the setting is greater, the digital readings remain correct; however, the signal-to-noise ratio will decrease. A time-varied-gain (TVG) effectively provides greater receiver sensitivity with increasing depth.

The echo sounder gating provides positive identification of the correct 400-fathom multiple, hence scale checks on the precision depth recorder are not necessary with the narrow-beam echo sounder operation. Scale checks may be easily accomplished on the Narrow-Beam Echo Sounder — Precision Depth Recorder by switching to the 0- to 4000-fathom scale on the graphic recorder; the gain on the Precision Depth Recorder usually must be reduced during this operation.

The recording procedure is as follows : At the prescribed intervals, the sounding is read from the echo sounder digital display, and written on the graphic recorder trace for cross reference on the appropriate time mark. If automatic depth input is initialized in the data acquisition system, the sounding record is checked as the survey progresses. Manual entry requires check scanning at a later time.

DATA REDUCTION

Reduction of the soundings is accomplished by the data acquisition system on a real-time basis. The reading of the echo sounder is entered into the system either manually or automatically; manual entry is necessary when operating conditions require the manual override of the time-varied-gain. After processing for the velocity of sound, the depth is displayed on a Nixie tube readout, printed on the hydrographic and geophysical report typeouts, and stored on magnetic tape.

Definitions of sounding velocity [3] and echo sounder depth [4] are now in order. Sounding velocity (Sv) is the weighted mean (Mn) of the velocity of sound (Vs) with depth (Z); that is, integrated velocity from the surface to the stated depth. Echo sounder depth (Z_s) is the sounding the instrument will read in a water column whose sounding velocity is not identical with the instrumental velocity of 800 fathoms per second.

The computer corrects the sounding for acoustic velocity in the following manner : The entered reading of the echo sounder is converted to time by dividing by the instrumental velocity of 800 fathoms per second. The computer then searches a listing of sounding velocity versus echo sounder depth; a linear interpolation is performed between the tabulated values for the applicable sounding velocity. The corrected depth is calculated by multiplying the sounding velocity by time.

The sounding velocity may be derived from the basic equation for the weighted mean [5] of any parameter :

$$Mn = \frac{\sum_{i=1}^{i=n} X_i Q_i}{\sum_{i=1}^{i=n} X_i} \quad (1)$$

where Q_i is any variable and X_i is the interval over which Q_i is applicable.

In order to determine the mean velocity from the surface to a stated depth, it is assumed that linearity exists between the point sources of the data as shown in figure 3.

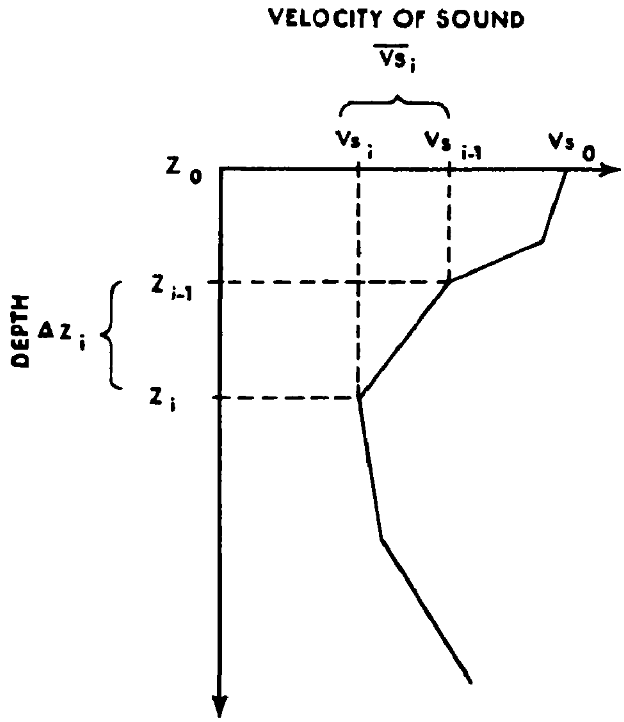

FIG. 3. — Point to point distribution of velocity of sound versus depth.

Consider the case of Z_i to Z_{i-1}, the mean velocity can be written :

$$\frac{Vs_i + Vs_{i-1}}{2} = \overline{Vs}_i = Q_i$$

The bounded interval over which this value applies is :

$$Z_i - Z_{i-1} = \Delta Z_i = X_i$$

Z_i must always be greater than Z_{i-1}.

Substituting into equation (1) :

$$Mn = \frac{\sum_{i=1}^{i=n} \Delta Z_i \overline{Vs}_i}{\sum_{i=1}^{i=n} \Delta Z_i} = Sv_n \quad (2)$$

The denominator when expanded :

$$\sum_{i=1}^{i=n} \Delta Z_i = \Delta Z_1 + \Delta Z_2 + \Delta Z_3 + \cdots + \Delta Z_n$$
$$= Z_1 - Z_0 + Z_2 - Z_1 + Z_3 - Z_2 + \cdots + Z_n - Z_{n-1}$$
$$= - Z_0 + (Z_1 - Z_1) + (Z_2 - Z_2) + \ldots + Z_n$$
$$= - Z_0 + Z_n$$

but Z_0, the surface = 0, therefore

$$\sum_{i=1}^{i=n} \Delta Z_i = Z_n$$

Rewriting (2)

$$Sv_n = \frac{\sum_{i=1}^{i=n} \overline{V}s_i \, \Delta Z_i}{Z_n}$$

$$= \frac{1}{Z_n} \sum_{i=1}^{i=n} \overline{V}s_i \, \Delta Z_i \tag{3}$$

The summation is from Z = 0, the surface, to Z = *n*, the depth to which the integration is desired. The function Vs is continuous on the closed interval $0 \leqslant Z_i \leqslant Z_n$, hence the definite integral exists, and the equation may be written :

$$Sv = \frac{1}{Z} \int_0^Z \overline{V}s dz \tag{4}$$

The integral is evaluated numerically be means of the trapezoidal rule. The entering arguments of Vs and Z are the tabulated values at the standard oceanographic depths. The standard oceanographic depths are enumerated in appendix 1. The average velocity of sound (Vs) is calculated for the standard oceanographic layers. An example of these calculations is shown in appendix 1. A graphic illustration of sounding velocity, velocity of sound, and instrumental velocity is shown in figure 4.

Computer programming of sounding velocity is accomplished by substituting into equation (3) the expressions for Vs_i and ΔZ_i above, and developing the following algorithm :

$$Sv = \frac{1}{2Z_n} \sum_{i=1}^{i=n} (Z_i - Z_{i-1}) (Vs_i + Vs_{i-1}) \tag{5}$$

The echo sounder depth (Z_s) is derived from the basic equation : Distance = time (T) × speed. For an instrument calibrated for a standard speed of sound in sea-water of 800 fathoms per second :

$$Z_s = T \times 800 \text{ fm/s}$$
$$= T \times 1463.04 \text{ m/s} \tag{6}$$

The metric conversion is based on the U.S. Survey Foot which by definition equals 1200/3937 metre exactly.

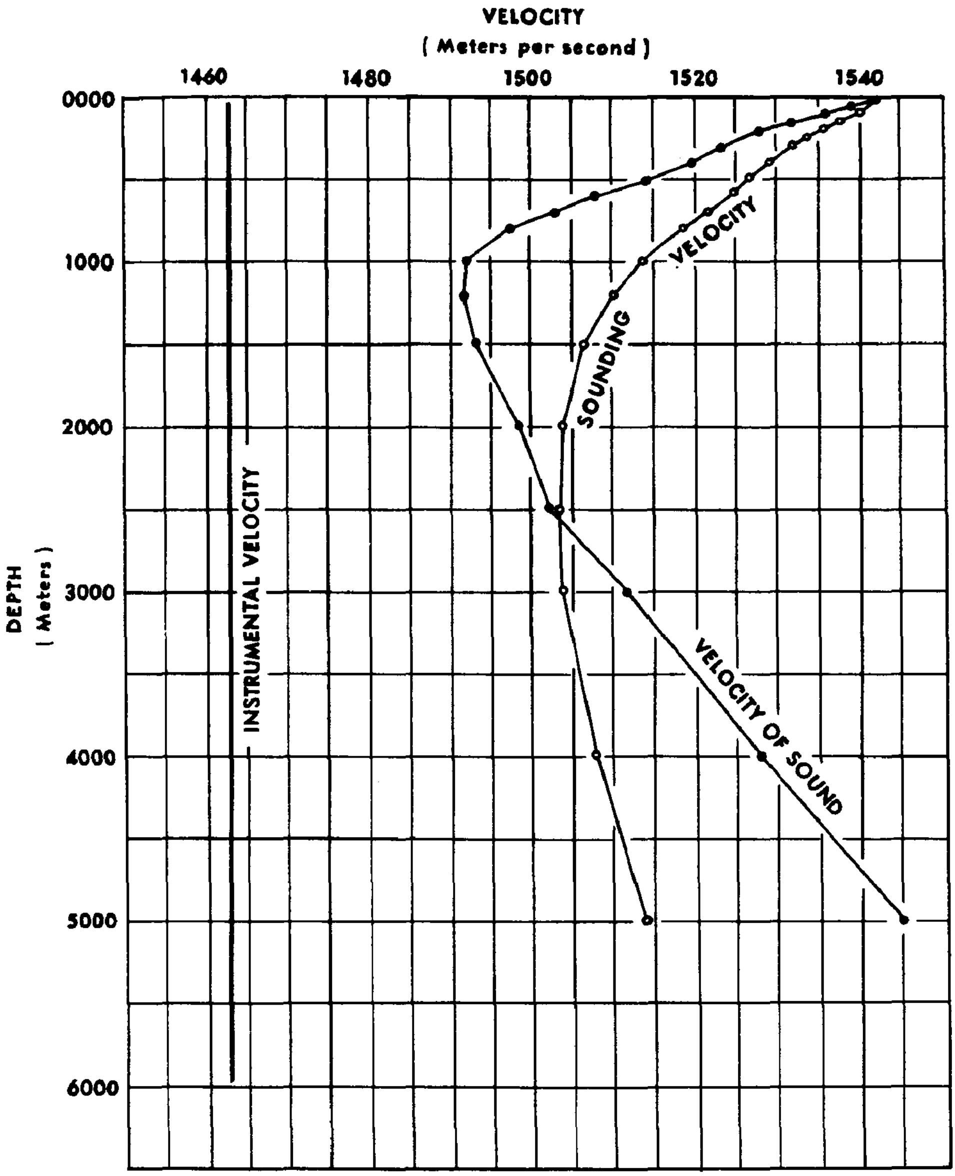

FIG. 4. — Velocity as a function of depth.

True depth (*) (Z_t) has the same relationship to time :

$$Z_t = T \times S\nu \tag{7}$$

Solving the simultaneous equation for echo sounder depth :

$$Z_s = \frac{Z_t \times 1463.04}{S\nu} \tag{8}$$

The sounding velocity in equation (8) is the applicable value for the true depth. These calculations are shown in the example in appendix 1.

(*) "True depth" is understood to mean precise in the theoretical sense; the accuracy of the value is not implied.

An example of the computer listing for the calculations in appendix 1 is shown in appendix 2. A gradient is applied to best fit the historical data beyond the deepest tabulated value.

The original data acquisition system programming would not allow the numerical value of the depth to exceed the value of the sounding velocity in the listing. Effectively this meant that the gradient had to be linear from 1500 metres to the bottom. The data acquisition system software was changed to correct this situation.

The use of sounding velocity computations is a computer application of the basic method of hand corrections outlined in Pub. 20-2, Hydrographic Manual [6]. Sounding velocity computations have been used aboard the *Discoverer* since she went into operation in July 1967. The refinement of interpolating with echo sounder depth as the entering argument, as suggested by RYAN and GRIM [7], is now in effect.

LIMITATIONS IN SHOAL WATER

The procedure of adding the draft of the transducers to the echo sounder depth prior to processing the sounding for acoustic velocity will introduce an error in shoal water. It is desired to keep all errors less than ½ of 1 percent of the depth. That is :

$$0.5\,\% = \%\,\text{error} = \frac{Z_c - Z_t}{Z_t} \times 100 \qquad (9)$$

where Z_c is the computed depth. The true depth and the computed depth may be written in the following form :

$$Z_t = \left[\frac{Z_s}{1463} \times Sv \right] + d \qquad (10)$$

$$Z_c = \frac{Z_s + d}{1463} \times Sv \qquad (11)$$

where d is the draft of the transducers in metres.

Substituting equations (10) and (11) into equation (9) and solving for echo sounder depth, it can be stated that an error that exceeds ½ of 1 percent of the depth will be introduced if :

$$Z_c \leqslant d \left[200 - \frac{294063}{Sv} \right] \qquad (12)$$

Consider the case of a Class I Oceanographic Survey Vessel whose draft is approximately 6 metres. If the sounding velocity is a rather high 1 542 metres per second, an error that exceeds ½ of 1 percent of the depth will be introduced when the fathometer depth equals 55.8 metres (30.5 fathoms).

Due to signal blanking, the narrow-beam echo sounder is not usable in depths less than 40 fathoms. Furthermore, current project instructions require the use of a shoal water echo sounder in depths less than 100 fathoms. Hence, the narrow beam sounder coupled with the data acquisition system will not under even these extreme conditions, inadvertently introduce this error.

FUTURE REFINEMENTS

Many of the refinements suggested by Ryan and Grim [8] in area surveys recognize the fact that off-line postsurvey processing is necessary. On-line, real-time processing depends on the use of historical data. This is an obvious shortcoming of the *Discoverer*'s method. It must be recognized, however, that a practical limit may have been reached with the present sate-of-the-art that warrants additional equipment and processing uneconomical.

A compiler language program for the Westinghouse Prodac 500 of the sounding velocity and fathometer depth is given as appendix 3. This program can be adopted to provide on-station, real-time, calculation of these parameters for multisensor data input, as well as off-line processing of historical data or Nansen cast data. The addresses in the program were arbitrarily chosen and will have to be changed for use with the present data acquisition system on-station programs; the scale factors (B4 for velocity of sound, and B0 for depth) conform to the scaling in the present system on-station program. This scaling satisfies the accuracy of the data input.

CONCLUSION

This report represents a cohesion of ideas into a working system. The equipment and methods presented will reduce the labor of processing, and improve the accuracy of deepwater soundings.

REFERENCES

[1] Wilson, W. D. : Equation for speed of sound in sea water. *Journal of the Acoustical Society of America,* Vol. **32,** p. 1357, 1960.

[2] Technical Manual, Narrow-beam Echo sounder, Vol. **1,** System Description, General Instrument Corp.

[3] Sverdrup, H. U., Johnson, M. W. and Fleming, R. H. : The Oceans, Prentice-Hall, Englewood Cliffs, N.J., p. 79f, 1942.

[4] RYAN, T. V. and GRIM, P. J. : A new technique for echo sounding corrections. *International Hydrographic Review*, Vol. **XLV**, No. 2, pp. 41-58 (1968).

[5] JAMES, G. and JAMES, R. C., Editors, Mathematics Dictionary, Van Nostrand, Princeton, New Jersey, p. 380, 1949.

[6] JEFFERS, K. B. : Hydrographic Manual, Publication 20-2, U.S. Coast and Geodetic Survey, Washington, D.C., p. 182 ff, 1960.

[7] RYAN, T. V. and GRIM, P. J. : *Op. cit.*, ref. [4].

[8] *Ibid.*

APPENDIX 1

Z_t	Vs	ΔZ	$\overline{Vs}$	$\Delta Z \times \overline{Vs}$	$\Sigma\Delta Z \times \overline{Vs}$	$Sv = \frac{\Sigma\Delta Z \times \overline{Vs}}{Z_t}$	$Z_t = \frac{Z_t \times 1463.04}{Sv}$
0	1542.0					(1542.0)	0
		10	1542.1	15421			
10	1542.2				15421	1542.1	9.5
		10	1541.9	15419			
20	1541.6				30840	1542.0	19.0
		10	1541.2	15412			
30	1540.7				46252	1541.7	28.5
		20	1539.8	30796			
50	1538.8				77048	1541.0	47.5
		25	1538.2	38455			
75	1537.5				115503	1540.0	71.3
		25	1536.6	38415			
100	1535.8				153918	1539.2	95.0
		50	1533.7	76685			
150	1531.6				230603	1537.4	142.7
		50	1529.8	76490			
200	1527.9				307093	1535.5	190.6
		50	1526.4	76320			
250	1524.8				383413	1533.7	238.5
		50	1523.9	76195			
300	1523.0				459608	1532.0	286.5
		100	1521.2	152120			
400	1519.5				611728	1529.3	382.7
		100	1516.8	151680			
500	1514.1				763408	1526.8	479.1
		100	1510.8	151080			
600	1507.6				914488	1524.1	576.0
		100	1505.2	150520			
700	1502.7				1065008	1521.4	673.1
		100	1500.0	150000			
800	1497.3				1215008	1518.8	770.6
		200	1494.6	298920			
1000	1492.0				1513928	1513.9	966.4
		200	1491.8	298360			
1200	1491.6				1812288	1510.2	1162.5
		300	1492.3	447690			
1500	1493.0				2259978	1506.7	1456.5
		500	1495.6	747800			
2000	1498.3				3007778	1503.9	1945.7
		500	1500.2	750100			

NOTE. — Z_t is the standard oceanographic depth in meters. Vs and Sv are in meters per second.

Z_t	Vs	ΔZ	$\overline{Vs}$	$\Delta Z \times \overline{Vs}$	$\Sigma \Delta Z \times \overline{Vs}$	$Sv = \frac{\Sigma \Delta Z \times \overline{Vs}}{Z_t}$	$Z_t = \frac{Z_t \times 1463{,}04}{Sv}$
2500	1502.2				3757878	1503.2	2433.2
		500	1507.0	753500			
3000	1511.7				4511378	1503.8	2918.7
		1000	1519.7	1519700			
4000	1527.7				6031078	1507.8	3881.3
		1000	1536.2	1536200			
5000	1544.7				7567278	1513.5	4833.3

APPENDIX 2

Interpolation		Computer Listing
Sv	Z_s	DVP(*)
1542.0	0	1542/0000/
1541.0	47.5	1541/0048/
1540.0	71.3	1540/0071/
1539.0	100.3	1539/0100/
1535.0	203.9	1535/0204/
1532.0	286.5	1532/0286/
1529.0	394.3	1529/0394/
1527.0	471.4	1527/0471/
1524.0	579.6	1524/0580/
1521.0	688.1	1521/0688/
1519.0	763.1	1519/0763/
1514.0	962.4	1514/0962/
1510.0	1179.3	1510/1179/
1507.0	1481.7	1507/1482/
1504.0	1928.2	1504/1928/
1503.2	2433.4	1503/2433/
1504.0	2966.8	1504/2967/
1508.0	3914.7	1508/3915/
1513.0	4749.5	1513/4750/

$$\text{Gradient} = \frac{V_2 - V_1}{Z_2 - Z_1} = \frac{1513.5 - 1507.8}{4833.3 - 3881.3} = +\,0.00599$$

G/+.00599/

(*) The computer listing will accept integers only for the values of sounding velocity and echo-sounder depth. To minimize error, interpolations for integer values of sounding velocity are performed; only values of echo-sounder depth are rounded to the nearest meter.

The program will accept up to nineteen points in the form of four-digit numbers. The left column of the computer listing is the sounding velocity; the right column is the depth. The gradient is applied at depths greater than 4 750 meters.

APPENDIX 3

Address	Instruction	Remarks
33333	ELC 1234	arbitrary non-zero constant
33334	JLZ 3344	
33335	STZ 3410	clear register
33336	STZ 3411	Do
33337	STZ 3412	Do
33340	STZ 3413	Do
33341	ELC 0	
33342	ENB 3341	
33343	STB 3333	3333 ELC 0
33344	ENL 3411	Vs_{t-1} scaled B4
33345	JLZ 3367	
33346	ADD 6010	+ Vs_t scaled B4
33347	STL 3414	$Vs_t + Vs_{t-1}$
33350	ENL 6011	Z_t scaled B0
33351	SUB 3410	$- Z_{t-1}$ scaled B0
33352	JLN 3402	
33353	JLZ 3402	
33354	MPL 3414	x $Vs_t + Vs_{t-1}$
33355	ADA 3412	+ Σ
33356	STU 3413 }	$\Sigma(Z_t - Z_{t-1})(Vs_t + Vs_{t-1})$ scaled B4
33357	STL 3412 }	
33360	ELC 2	
33361	MPL 6011	x Z_t
33362	STL 3416	$2Z_t$
33363	ENL 3412	
33364	ENU 3413	
33365	DIV 3416	÷ $2Z_t$
33366	STL 3415	= $S\nu$ scaled B4
33367	ENL 6010	
33370	STL 3411	new Z_{t-1}
33371	ENL 6011	
33372	STL 3410	new Vs_{t-1}
33373	ENL 3415	
33374	RSL 4	
33375	STL 3420	= $S\nu$ scaled B0
33376	ELC 2667	$2667_8 = 1463_{10}$
33477	MPL 6011	x Z_t
33400	DIV 3420	÷ $S\nu$ scaled B0
33401	STL 3417	= Z_s scaled B0
33402	1000	STOP

Program Input Addresses

36010	Vs_t scaled B4	input from the multisensor
36011	Z_t scaled B0	during on-station operations

List of Mnemonics

Mnemonic	Meaning
ELC	Enter AL with constant Y
JLZ	Jump on (AL) zero to Y
STZ	Set (Y) to 0
ENB	Enter B with (Y)
STB	Store (B) in Y
ADD	Add (Y) to (AL)
STL	Store (AL) in Y
ENL	Enter AL with (Y)
SUB	Subtract (Y) from (AL)
JLN	Jump on (AL) negative to Y
MPL	Multiply (AL) by (Y)
ADA	Add (Y + 1 , Y) to (A)
STU	Store (AU) in Y
ENU	Enter AU with Y
DIV	Divide (A) by (Y)
RSL	Right shift (AL) by *k* positions
Where	AL is the lower accumulator AU is the upper accumulator A is the AU and AL (36 bit word) B is the B register (Y) is the contents of Y Y is the address